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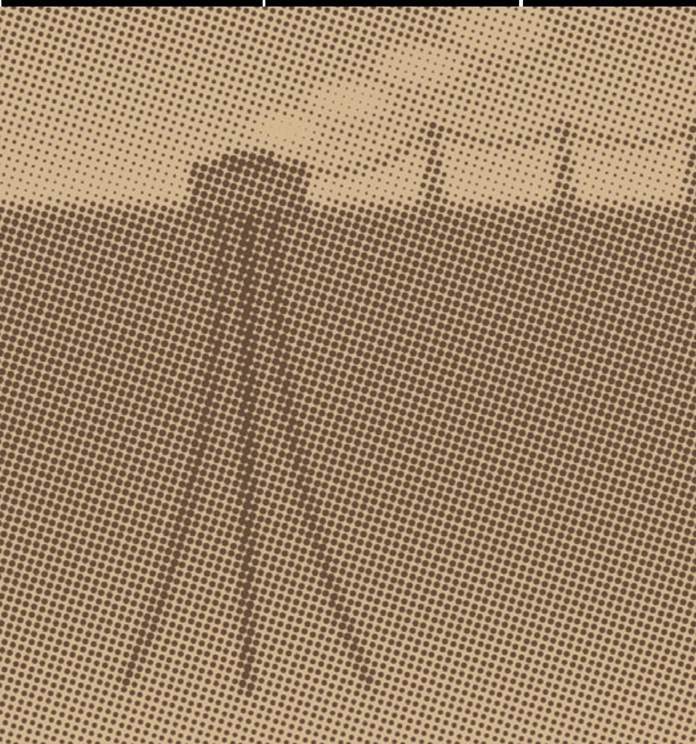

Stefan Hirschberg, Stefan Wiemer,
Peter Burgherr (eds.)

Energy from the Earth

Deep Geothermal as a Resource for the Future?

vdf

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TA-SWISS 62/2015

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Bibliographic Information published by
Die Deutsche Nationalbibliothek
Die Deutsche Nationalbibliothek lists this publication in the Internet
at http://dnb.d-nb.de.

The study was supported by the Swiss Federal Office of Energy SFOE, the Commission for Technology and Innovation CTI, and the Swiss Academy of Engineering Sciences SATW.

Cover images:
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ISBN 978-3-7281-3654-1 (print version)

Download open access:
ISBN 978-3-7281-3655-8 / DOI 10.3218/3655-8

www.vdf.ethz.ch
verlag@vdf.ethz.ch

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Disclaimer

Roles of the various institutes in the TA-SWISS study on deep geothermal energy:

The different scientific institutes represented by the authors cooperated as competence centers in the present TA-SWISS study energy to contribute their expert knowledge on deep geothermal energy. The authors, and thus their institutions, cooperated as scientific advisors to work out the recommendations. The study and its recommendations are the common product of all the authors and groups, but they do not necessarily represent the official positions of their individual institutions.

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Acronyms

ACC – American Chemistry Council
ATLASIS – Advanced Traffic Light and Assessment System for Induced Seismicity
ATLS – Adaptive Traffic Lights Systems
ATSDR – Agency for Toxic Substances and Disease Registry
ARIA – Analysis Research and Information on Accidents
BC – British Columbia
BFE – Bundesamt für Energie
BHT – Bottom Hole Temperature
BLEVES – Boiling Liquid Expanding Vapor Explosion
BOP – Blowout Preventer
CA – California
CCEM – Competence Center Energy and Mobility
CCES – Competence Center Environment and Sustainability
CCPS – Center for Chemical Process Safety
CCS – Carbon Capture and Storage
CHF – Swiss Franc
CO_2 – Carbon Dioxide
DC – Direct Current
DFN – Discrete Fracture Networks
ECOS – Earthquake Catalogue of Switzerland
EGS – Enhanced Geothermal System
EIA – Energy Information Administration
EJ – Exajoules
EM – electromagnetic
ENSAD – Energy-related Severe Accident Database
EPA – Environmental Protection Agency
EPM – Equivalent Porous Medium
ERNS – Emergency Response Notification System
ETHZ – Eidgenössische Technische Hochschule Zürich
EU – European Union
EUR – Euro
FACTS – Failure and Accidents Technical Information System
FKPE – Forschungskollegium Physik des Erdkörpers
GEISER – Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs
GETEM – Geothermal Electricity Technology Evaluation Model
GSHAP – Global Seismic Hazard Assessment Program
GMS – Geomechanical Seed Model
GtV – Geothermal Association
GW/GWh – Gigawatt/Gigawatt hour
GWh_t – Kilowatt hour of thermal heat
GWeyr – Gigawatt electric year
HCl – Hydrochloric Acid
HDR – Hot Dry Rock
HF – Hydrogen Fluoride
HRT – High Resolution Temperature logging
HSC – Health and Safety Commission

HSE – Health and Safety Executive
HSELINE – Health and Safety Executive Information Services
H_2S – Hydrogen Sulfide
HT – Hydraulic Testing
HTPF – Hydraulic Testing on Preexisting Fractures
ICFT – Initial Closed–Loop Flow test
IEA – International Energy Agency
IEAGHG – International Energy Agency Greenhouse Gas R&D Programme
IPCC – Intergovernmental Panel on Climate Change
KCl – Potassium Chloride
km – kilometer
kW/kWh – Kilowatt/Kilowatt hour
kWh_e/kWh_t – Kilowatt hour of electricity/Kilowatt hour of thermal heat
l – liter
InSAR – Interferometric Synthetic Aperture Radar
ISO – International Organization for Standardization
LCA – Life Cycle Assessment
LCI – Life Cycle Inventory
LCIA – Life Cycle Impact Assessment
LCOE – Levelized Cost of Electricity
LOTs – Leak–off tests
LTFT – Long-term Flow Test
LWD – Logging while Drilling
MCDA – Multi-Criteria Decision Analysis
MD – Measured Depth (depth measured along borehole trajectory from wellhead)
MHAIDS – Major Hazards Accidents and Incidents
MHIDAS – Major Hazard Incident Data Service
MPa – Mega Pascal
MT – magnetotelluric
MWD – Measurement while Drilling
MW/MWh – Megawatt/Megawatt hour
MWh_e/MWh_t –Megawatt hour of electricity/Megawatt hour of thermal heat
NAGRA – National Cooperative for the Disposal of Radioactive Waste
NE – Northeast
NH_3 – Ammonia
NH_4Cl – Ammonium Chloride
NIMBY – Not In My Backyard
NRC – National Response Center
NRC – National Research Council
NW – Northwest
NZZ – Neue Zürcher Zeitung
O_2 – Oxygen
OECD – Organisation for Economic Co-operation and Development
OEHHA – Office of Environmental Health Hazard Assessment
OSH – Occupational Safety and Health
ORC – Organic Rankine Cycle
PAB – Project Advisory Board
PBR – Polished Bore Receptacle

PC – Permo-carboniferous
PDC – polycrystalline diamond compact
PGA – Peak Ground Acceleration
PGV – Peak Ground Velocity
Pp – Pore pressure
PSHA – Probabilistic Seismic Hazard Assessment
PSI – Paul Scherrer Institute
PSRA – Probabilistic Seismic Risk Assessment
R&D – Research and Development
RFP – Request for Proposal
ROP – Rate of Penetration
RPM – Revolution per Minute
SCCER – Swiss Competence Centers for Energy Research
SE – Southeast
SED – Swiss Seismological Service
SECURE – Security of Energy Considering its Uncertainty, Risks and Economic implications
SFOE – Swiss Federal Office of Energy
SGFZ – St. Gallen Fracture Zone
S_{hmax} – maximum principal horizontal stress magnitude
S_{hmin} – minimum principal horizontal stress magnitude
Sv – Vertical Stress
SW – Southwest
TA – Tages-Anzeiger
TA-SWISS – Centre for Technology Assessment
TJ – Terajoule
TWh – Terawatt hour
TWh_e – Terawatt hour of electricity
TVD – True Vertical Depth
UBA – Umweltbundesamt
UK – United Kingdom
URG – Upper Rhine Graben
US/USA – United States of America
USD – US Dollar
USDOE – United States of America Department of Energy
VFS – Verband Fernwärme Schweiz (Swiss District Heating Association)
VSP – Vertical Seismic Profiling
WOB – Weight on Bit
WP – Work Package
XLOT – Extended Leak-off Tests
°C – degrees Celsius
2D – Two-Dimensional
3D – Three-Dimensional

Executive Summary

Geothermal energy offers the prospect of supplying base-load power in a decentralized fashion, while remaining heat can be used in district heating networks or industrial processes. No electric power is currently generated from deep geothermal energy sources within Switzerland that is available to end consumers – despite the large resource potential.

Study Background and Goals

The new Swiss energy policy requires energy efficiency to be substantially improved, the proportion of fossil fuels in the energy supply to be considerably reduced, and nuclear power to be phased out, while meeting highly ambitious climate protection targets. One of the core implications of the new energy policy is the need for a massive increase of the use of renewable sources for electricity generation.

In this context, the Swiss Federal Office of Energy (SFOE) estimates that deep geothermal energy could contribute 4–5 TWh per year to electricity generation in Switzerland by 2050, which would be a substantial contribution to a projected annual power need in 2050 of 60 TWh. Geothermal energy is attractive because of the very large scale of the resource, its expected relatively low CO_2 emissions, and its reliable, all-day domestic availability. However, the future contribution of deep geothermal energy is subject to major uncertainties due to its novel and unproven nature within Switzerland.

The longer term opportunities of geothermal energy nevertheless provide a powerful incentive to find an answer to the following questions: how much of this resource can be exploited and at what economic cost? What are the environmental and risk-related externalities that the public must be willing to bear? How does its overall performance compare to competing energy resources? And will the regulatory framework and public acceptance be sufficient to allow geothermal energy to provide a significant contribution?

The current TA-SWISS project attempts to answer these questions in a comprehensive and balanced way. An interdisciplinary evaluation approach facilitates comparison with other technologies and supports stakeholder decision-making. There are no perfect energy solutions, but understanding deep geothermal's strengths and weaknesses will provide some initial structured indications of the role this energy source might play within the future Swiss energy mix.

Study Focus, Content and Organization

The focus of the current study is on electricity generation, although the potential and importance of heat production for suitable sectors is emphasized whenever appropriate. Though the main emphasis is on geothermal energy in Switzerland, the methodology used and many insights are of broader interest.

The main value of the current work is a comprehensive review of the state of the art. In some areas this was based on partner expertise and the available knowledge base (e.g. the status of resource data, technology data and regulation). In other sectors new quantitative results have been generated. Emphasis has been given to relatively unexplored areas such as the assessment of Swiss resources, economics, ecology, risks, regulatory framework and public acceptance. But the research work also highlighted key areas such as reservoir engineering, where further advances in technology are essential.

The study includes, among other topics:

- resource analysis;
- evaluation of lessons learned from reservoir creation in petrothermal projects;
- review of drilling technologies, both current and emerging;
- development and application of a new model for cost estimation;
- quantification of environmental impact based on Life Cycle Assessment (LCA) with direct coupling to the cost estimation model;
- risk evaluations and lessons learned from induced earthquakes;
- review of regulatory issues and potential solutions;
- analysis of the treatment of geothermal energy in the media;
- investigation of the attitudes to and positions on geothermal energy of Swiss stakeholders and citizens in a broader social context, and
- limited Multi-Criteria Decision Analysis (MCDA) involving comparison of technologies and mapping of the impact of stakeholder preferences.

This study has formed the basis for subsequent recommendations for policy and further research.

The study was conducted by a research consortium with broad multi-disciplinary competences. The participants included the Paul Scherrer Institute (PSI; coordinator of the study), the Swiss Federal Institute of Technology Zurich (ETHZ), Zurich University of Applied Sciences (ZHAW) and University of Stuttgart/Dialogik. More than 30 researchers from these organizations contributed to the project. The study established an intensive interaction with the recently established Swiss Competence Center (SCCER) on Supply of Electricity, which has created synergies for the parallel development of a deep geothermal roadmap for Switzerland.

Basic Technological Options

Conventional (i.e. hydrothermal) geothermal resources rely on the interplay of three factors:

- High temperatures in the subsurface, which given today's energy conversion technology implies more than 100 °C and consequently depths greater than 3 km as temperatures rise with increasing depth.
- Presence of water-bearing geological formations or structures.
- Adequate generation of hot water for economically viable and sustainable electricity generation on the surface.

Current experience suggests that the concurrence of all three factors in one location is rare in Switzerland, and hence there is a low probability of hydrothermal plants being able to make a substantial contribution to electricity supply.

An alternative type of technology for extracting heat from deep hot rocks are Enhanced or Engineered Geothermal Systems (EGS), commonly referred to as petrothermal systems in German-speaking countries. Unlike hydrothermal systems, these systems do not require the presence of hot fluid reservoirs at depth. The basic concept is to engineer a heat exchanger between two or more boreholes drilled into the target rock mass. This is accomplished by conducting high-rate cold water injections at pressure into deep underground to promote reservoir stimulation and improve permeability of the rock mass between the wells, so that they are linked by many flow paths that access a large volume of rock. The permeability enhancement process has been demonstrated to be effective in field projects, but is still not currently well enough understood to permit optimization. Gaining greater understanding of these processes and their dependence upon geological conditions, together with the controlling of the seismicity that accompanies the operations, represent the principal challenges to bringing the technology to maturity. Once the heat exchanger has been constructed, water can be circulated around a loop and the heat contained in it extracted and converted into electrical energy using appropriate conversion technologies on the surface.

Petrothermal systems (EGS) are therefore the ultimate goal of a successful, long-term development of Switzerland's geothermal resources, because the resource potential is vast. But due to the technical challenges that are still present, EGS has not reached sufficient maturity to be economically viable in the market place. Still, since 2006, when the issue of seismic hazard rose to prominence due to small earthquakes generated during reservoir creation operations at the Basel EGS site that were felt by the local population, a number of countries such as the USA, Iceland, Germany, France and Australia have continued to make progress in the development of the technology.

Resources and Reserves

Geothermal energy has specific advantages that open up a wide range of opportunities. To put geothermal resources and their potential into perspective, it is instructive to keep in mind that Switzerland's total energy demand for 2013 was around 896 Petajoule (896 X 10^{15} J).

Switzerland has an abundance of geothermal resources. The inferred heat in place in rocks at depths between 3 and 10 km is of the order of 10^{23} J, or 100 thousand times higher than Switzerland's 2013 energy demand, and heat is continuously being replenished from below. With knowledge gained from future exploration programs, some of the theoretical assumed resources will ultimately become quantifiable resources. When modifying factors (i.e. technical, economic, marketing, legal, environmental, land-use-related, social and governmental aspects), which directly affect the likelihood of commercial use are also considered, then these resources will in turn become proven reserves. Incorporating these modifying factors, and further constraints arising from technical and operational risks given the current state of knowledge, the potentially usable potential is reduced by many orders of magnitude.

However, rather than starting with the postulated but highly uncertain potential to be implemented by 2050, investigations have concentrated on the respective prerequisites for meeting the target of Swiss energy strategy. Thus, the production target for geothermal electricity generation of 4–5 TWh per year by 2050 can only be met if the plants can reach their capacity and cost goals. This in turn will depend upon finding, characterizing and developing geothermal resources, which also includes demonstrating the capability to construct suitable heat exchangers that support commercially adequate flow rates and production lifetimes, as well as controlling the risk of induced seismicity at a socially acceptable level.

Needs and Prospects for Technological Advancements

While technical feasibility is fundamentally proven, a number of technological developments must take place to enable EGS to be deployed in a sustainable manner that balances social well-being, environmental protection, generation of profits and value added. In general, exploration technologies have not yet been applied on a regional basis in Switzerland. Hence there has not yet been any systematic proof as to which resources are ultimately to be classified as reserves. Geothermal drilling technology has been (and continues to be) mostly adapted from the oil and gas industry and is regarded as mature in many respects, but development in the oil and gas sector is still very active. Drilling is by far the largest cost component of developing a geothermal reservoir, and it follows that reduced drilling costs will have a great impact on the commercial viability of geothermal projects. Costs remain high partly because tailored rapid drilling methods are still at the research stage, and partly because there is a lack of standardization and experience in Switzerland. The costs of hydraulic stimulation are a smaller proportion of total costs, but improvements here can also have high paybacks on flow rates and well life. The achievable depth and reliability for subsurface pumps are also active areas of research. EGS surface power generation plant technology is generally mature but there are prospects for incremental improvements in thermal efficiency, and optimizing design and operation for combined production of electricity and heat. The greatest challenge in deploying EGS technology in Switzerland and worldwide lies in mastering the creation of the subsurface heat exchanger, and in controlling the associated seismicity.

Given the seemingly limited opportunities for developing hydrothermal resources in Switzerland (i.e. finding and accessing aquifers or formations that contain large quantities of mobile water) significant power generation can only come from solving the geological engineering challenge of developing EGS technology. The focus on power generation from deep geothermal resources should not hinder development of shallower resources for direct use applications (e.g. to cover the heat demand from households, industry, agriculture, aquaculture). The requisite temperatures of 60 °C or more are already found in favorable locations at depths of 1.5 km and below. Exploration of such reservoirs would add further to the probable and proven geothermal heat resources of Switzerland.

Economics

Economic analysis of geothermal energy shows that the average cost of power generation can vary significantly based on a range of factors, some of which still entail major uncertainties, such as well costs and reservoir life. The Swiss reference base case has an estimated average power generation cost of 35 Swiss cents/kWh, but the fluctuation between the Swiss good and poor reference cases ranges from 18 to 61 Swiss cents/kWh, respectively. Well-related costs remain the overwhelmingly dominant cost component and cause most of the cost uncertainty. The main sources of uncertainty include not just the cost of drilling, but also the number of wells necessary for exploration, confirmation and production, and the well life before re-drilling is required. There is significant room for incremental reduction of conventional drilling costs before revolutionary new drilling technologies would be necessary to achieve further appreciable cost reductions. The effect of possible sales of waste heat has been shown to be very important for the average cost – in the base case this reduces the average cost from 35 to 14 Swiss cents/kWh. An industry review of the potential district heating market shows that if this potential could be fully achieved by 2050 and was fully served by the waste heat from geothermal power generation, then slightly over 5 TWh/a of electricity could be generated at the lower cost made possible by the heat sales. The clear benefit of heat sales on plant economics does create a tension between the necessary proximity to heat markets and the desirable distance from a population sensitive to potential induced seismicity, noise and visual impact on the landscape. At the current state of the art the generation costs of geothermal electricity are 3 to 5 times too high for customers in Switzerland. Sales of waste heat will only decrease in importance if the well costs can be very significantly reduced. But even if the district heating market potential is not met solely by geothermal power, the heat market is still large enough to offer a significant learning curve for reducing geothermal costs. A credible path exists to commercial viability if the technological, engineering and safety challenges can be overcome.

Environmental Performance

The environmental impact of deep geothermal plants in Switzerland was estimated by means of a Life Cycle Assessment (LCA). This method only covers normal operation, i.e. it does not consider potential accidents that need to be addressed separately. Indicators factored into environmental performance include: climate change, human toxicity, particulate matter formation, ionizing radiation, water and metal depletion. The environmental impact of deep geothermal power plants is lower than or in the same range as those from other new renewable energy options considered in Switzerland for a future electricity mix, even when considering the relatively high uncertainties of some parameters used in determining the performance of future geothermal plants. The estimated emissions of greenhouse gases are between 8 and 46 g CO_2-eq/kWh depending on the choice of technological and operational parameters. This means that geothermal energy is practically CO_2-free. The drilling phase has the greatest impact on the overall environmental burden. Surface plants, choice of the working fluid and reservoir stimulation all play minor roles in most impact categories. Based on environmental policy goals, and climate protection in particular, it is definitely worthwhile considering geothermal energy as a potential part of the future electricity mix.

Uncertainties, Risks and Potentials for their Mitigation

The sheer extent of the geothermal resource presents major opportunities for power generation and heat production, but development is subject to a number of significant limiting factors. The identification of hydrothermal resources suffers mostly from a severe lack of exploration of Switzerland’s deep subsurface formations. Political decisions have already been made to remedy that situation, following a number of initiatives by members of the Swiss Parliament. Unfortunately, current exploration technology lacks the potential to predict the permeability structure and the state of tectonic pre-loading of the subsurface rock and may therefore be of limited use for geothermal applications. The technology for developing hydrothermal systems, however, is mature. Thus, where such systems can be identified, they can be developed, subject to environmental and regulatory safeguards.

By contrast, EGS technology is not mature and requires a program of basic research before it is ready for large-scale deployment. Over the past 40 years, several large-scale prototype systems have been built in various geological situations, and these have provided encouraging proof of concept. However, it has so far proved difficult to construct a heat exchanger on the requisite scale (> 500 m well separation) and with the requisite properties to allow commercial flow rates, without the benefit of pre-existing, highly-permeable structures within the target rock (i.e. fracture zones and faults), such as at the Soultz EGS site in France. A lesson learned from previous projects is that no two rock formations are identical, and that it is necessary to 'work with' the rock formation in developing the multiple hydraulic linkages between the wells that constitute the heat exchanger. For commercial systems with a production lifetime of tens of years, the wells should be no less than 500 m apart, and the net flow between them should sweep a fracture area of the order of several km^2, contained within a rock volume of the order of 0.1 to 0.2 km^3.

A further consideration for developing deep geothermal systems is the risk of triggering earthquakes that are felt by the local population. Experience to date in Switzerland shows that this is a concern for both EGS and hydrothermal systems. It is clear that the subsurface must be developed in a manner that keeps the seismic risk to people, the environment and material assets to as low a level as reasonably practicable. For EGS technology, managing induced seismicity during the process of creating the heat exchanger and in the subsequent 20-30-year operational period is one of the outstanding issues besides the ability to create a fracture network capable of decades-long supply of hot water. In view of the seismic risks, obtaining the appropriate insurance could be a factor having a substantial impact on the economics of geothermal energy.

In addition to the pronounced seismic risks, there are a number of standard operational risks such as harmful geofluids or drilling-related hazards which are certainly not uncommon in the oil, gas and mining industries. These risks should be managed by appropriate regulations and operational practices that meet stringent industry standards, and strict regulatory enforcement. The current study also addressed the risks of accidents due to blowouts and selected hazardous substances. Risk indicators for different types of consequences (fatalities, etc.) are quite low, but they are not negligible. Blowout risk poses a higher risk to human health, whereas releases of hazardous chemicals mostly impact the environment.

Detailed sensitivity studies that address the major factors driving project development cost suggest that a substantial reduction of the cost could be achieved through standardization of drilling practices, which should be possible once more experience in drilling deep geothermal wells is gained. Similarly, learning how to safely create the subsurface heat exchanger in a cost effective manner is crucial for commercial viability. Optimizing the design and the geometry of the heat exchanger to yield maximum fluid circulation without a rapid break-through of cold water to the production well(s) is also seen as a major area for investigation. Economic risks can be further reduced by creating opportunities to sell the heat left after electricity generation – this would provide a significant upside to the project economics and is a major incentive for private investors to enter and develop the geothermal business. An additional enabling step for the development of a Swiss-wide geothermal business is a national geothermal data system where resource data, utilization data, operational and environmental rules, regulations and standards, end-customer demand for power and heat, and the corresponding supply infrastructure are centrally managed.

Legal Aspects

The existing legal and regulatory framework of Switzerland's individual cantons does not constitute an insurmountable barrier to geothermal development. While transferring the legal and regulatory authority to a federal entity seems at first sight attractive and has a large potential to expedite the development of geothermal energy, this does not appear to be politically feasible. Nevertheless, cantonal laws or legal procedures governing the subsurface exist and enable the development of geothermal resources, although they are rarely tailored to geothermal energy. An exploration permit to find geothermal resources that is issued by cantonal authorities does not necessarily confer an automatic right to a subsequent development license or concession to exploit the geothermal resource. This is a disadvantage for the exploration permit holder who has invested in the exploration and has actually found a geothermal resource. Similarly, it is not clear in some cantons whether granting a development license or a concession is subject to a public tender process. While some cantons comply with the federally mandated "coordination model" that ensures consistency in obtaining a wide range of permits from various authorities, only very few cantons have implemented the "concentration model." Here, one cantonal authority would coordinate and streamline the entire approval process with all other relevant authorities and finally issue the permits on a package basis. A key enabler for the development of the subsurface in general, and for geothermal energy in particular, is the inclusion of the subsurface in Cantonal Structure Plans and Land Use Planning – the critical tool of cantonal administrations for designating zones and areas on the surface and in regions of the subsurface where geothermal energy may be developed. As of 2014 a number of governmental and national Council initiatives are under way to develop and implement a legal framework to speed up the approval process. These must however be balanced with cantonal sovereignty and, for example, the unintended consequences if zoning exemptions were used excessively. Various cantons have implemented a range of rules and regulations for the exploration and development of deep geothermal resources. The adoption of proven practices is seen as an essential, low-cost way to achieve an optimal legal framework. While the federal government and administration does not have any meaningful authority to regulate geothermal energy, it is in the best position to create a kind of "soft" legislation by advising and assisting by setting up a federal platform (without any legal authority) that aids cantons in implementing and enforcing relevant acts, ordinances and guidelines.

Public Opinion and Risk Perception

The social acceptability of deep geothermal energy revolves to no small degree around public perceptions. Analyzing results from social focus groups, the social media and newspaper articles allows the formulation of content-related arguments or so-called frames. One frame centers on arguments related to Switzerland's energy strategy: "deep geothermal energy could contribute to the implementation of Switzerland's energy strategy", or "deep geothermal energy is an unrealistic option". A second frame looks at the risks: the uncertainties and risks on the one hand and a perception that risks may be kept under control on the other. A third frame deals with technology, which can have benefits and be successful or, alternatively, is perceived as mostly problematic and doomed to failure. Finally, a fourth frame focuses on cost – again, a struggle between affordability and high expense. There are many indications that public perception is highly volatile, with many people being extremely ambivalent. The early stages of geothermal development – despite the comparatively strong public responses to the projects in St. Gallen (2013) and Basel (2006/2007) – did not lead to fixed public views. Subsurface activities may be associated with concepts such as "tampering with nature," a very unlikely but highly destructive seismic event, or the visibility of the engineering infrastructures (tall derricks of drilling rigs). Communicating the complexity of managing the "invisible" deep subsurface relies on highly abstract expert knowledge that is often difficult to communicate well to lay people. Because of their highly dynamic nature and the way arguments are used, social media and media articles can serve as early warning signals of shifting public opinion. So far, social media have largely and persistently ignored deep geothermal energy (even after St. Gallen). When it is reported, deep geothermal energy enjoys a more neutral and positive sentiment among the Swiss public.

Industry and science have special roles in the public discourse. Currently, industry is the stakeholder focused on the potential, while scientists emphasize the risks and uncertainties. Both groups would benefit from communicating a more balanced view: industry could actively address risks and uncertainties, while scientists could also focus on potential and existing risk reduction strategies.

Integration of Environment, Economy, Risks and Security of Supply

As part of the integration analysis a limited Multi-Criteria Decision Analysis (MCDA) was carried out. MCDA provides an aggregated measure of the performance which allows the comparison of a range of alternative energy options with regard to environmental, economic, social and security of supply criteria while incorporating the preferences of the different stakeholders. MCDA supports informed decision-making, and may guide the public debate and participative processes. While MCDA shows the relative strengths and weaknesses of the various alternatives, it does not provide a definitive ranking of the technologies, but rather illustrates the sensitivity of the ranking to the subjective preferences of the respective stakeholders. The analysis, while limited to current technologies, covered the major new renewable energies of interest for Switzerland (including photovoltaics, wind power and biogas).

Generally, the MCDA conducted in this study confirms that geothermal systems combining electricity generation with heat production perform clearly better than those generating electricity only. Overall, a preference profile with a balanced weighting of the fundamental sustainability criteria and an emphasis on climate protection, minimization of human toxicity, metal depletion, risks (other than induced seismicity) and security of supply, is most favorable for geothermal energy. However, a preference profile with a balanced weighting of the fundamental sustainability criteria and an emphasis on water depletion and induced seismic risks, disfavors geothermal energy.

Selected Recommendations

The study provides a relatively large number of recommendations for politics and science. The most essential recommendations are summarized below:

- It is advisable to direct the attention of decision-makers and stakeholders towards the potentially important role of geothermal energy in an increasingly decentralized electricity supply system with a high proportion of renewables that are only intermittently available. Geothermal energy is one of few “new” renewable options that could supply base-load power to the market and thus substantially contribute to security of supply. The future potential role of geothermal energy in Switzerland needs to be addressed in the context of the overall energy supply system.
- Electricity from deep geothermal plants exhibits favorable environmental performance under normal operating conditions. From the environmental point of

view, and with particular regard to climate protection, geothermal energy is an attractive potential contributor to the future Swiss energy mix and deserves to be seriously considered.

- Further promotion of geothermal energy production is necessary to scale up the market. This will motivate companies to increase their R&D efforts for geothermal well drilling, which in turn will reduce the risks and costs of geothermal power generation. Possible promotional measures could include further discovery and characterization of heat sources, technology development and demonstration projects, in addition to the current risk guarantees and feed-in remuneration.
- Given the huge uncertainty about the potential geothermal reserves in Switzerland, a major use-inspired research initiative coupled to a program of pilot and demonstration projects is needed to enable the construction of petrothermal systems that meet commercial performance targets.
- It would be a significant advance to link the locations of geological potential, political regulation, population (or sensitivity to seismicity), and heat markets to the economic model within a GIS framework, so that we can map out the resulting costs of geothermal electricity generation and show where the best potential locations may be, considering all these factors.
- Seismicity risks can be assessed and mitigated, but not eliminated. The success rate and economic viability of deep geothermal energy depends largely on the level of seismic risk that stakeholders are willing to take. In this context society needs to consider and decide which level of risk is acceptable.
- Research and the ability to forecast induced seismicity have advanced considerably over recent years, on the basis of projects funded by the scientific community and industry. These efforts need to be continued over the next few years. The most urgent need is for validation of the emerging modeling tools and risk reduction strategies. Future pilot and demonstration projects are key to these validation efforts. Additionally, many of the processes relevant for induced seismicity are scale-invariant and can also be studied in small-scale underground laboratories. Multidisciplinary research combining geoscience, technical disciplines and IT is necessary to solve the problem of efficient reservoir creation while limiting seismic risks.
- Use of the Swiss subsurface is regulated by the cantons. This creates certain difficulties for the potential operators of geothermal plants. A homogeneous regulatory framework (e.g. a concentration model) or a federal regulatory competence centre could contribute to simplifying and accelerating the process.
- Some cantons have adopted a concentration model in which one authority coordinates the content of the various permits and issues them on a package basis. In this model, the decision to grant a license also includes all permits and rulings by other authorities. This solution is effective and convenient. In any case, in processing a license application many issues generally need to be addressed that also affect other permits. Such a model would serve to speed up procedures and facilitate communication with those to whom a ruling is addressed.
- In principle, it is the responsibility of the cantons to issue regulations concerning use of the subsurface. Such regulations must include the following provisions: responsi-

bilities, types of use, compulsory expropriation, exploitation permits, procedures, human and material resources, liability, coordination with other permits, fees, enforcement, and legal protection.

- The entire process of planning, siting, and implementing geothermal projects must be closely followed by a carefully planned, continuously monitored, and precisely evaluated process of public and stakeholder engagement. Characterization of sites based on social criteria (i.e., regarding specific needs, collaboration with the communities) could certainly complement the technical site characterization for future (pilot) projects.

Media attention is largely driven by spectacular events with news value, such as earthquakes. This could influence the public perception of deep geothermal energy and might shift people's attention towards negative arguments. Deep geothermal projects should therefore include communication and public participation from an early stage. Communication should be transparent and openly address opportunities as well as challenges including risks and strategies to reduce them. It is crucial here that the information provided is clear, easy to understand and well balanced.

Zusammenfassung

Die Geothermie als Energieträger eröffnet die Perspektive einer dezentralen Stromversorgung für den Grundlastbereich, bei gleichzeitiger Nutzung der Abwärme in Fernwärmenetzen und als Prozesswärme für Industriebetriebe. Derzeit wird in der Schweiz mit Tiefengeothermie noch kein Strom für Endverbraucher erzeugt – obwohl ein grosses Ressourcenpotenzial vorhanden ist.

Hintergrund und Ziele der Studie

Die neue schweizerische Energiepolitik sieht eine erhebliche Verbesserung der Energieeffizienz, eine deutliche Verringerung des Anteils fossiler Brennstoffe an der Energieversorgung sowie den Ausstieg aus der Kernenergie vor und setzt sich gleichzeitig überaus ehrgeizige Klimaschutzziele. Eine wesentliche Konsequenz der neuen Energiepolitik liegt daher in der Notwendigkeit, erneuerbare Energiequellen für die Stromerzeugung massiv auszubauen.

Das Bundesamt für Energie (BFE) geht in diesem Zusammenhang davon aus, dass die Tiefengeothermie in der Schweiz bis 2050 jährlich 4–5 TWh zur Stromerzeugung beisteuern könnte. Dies wäre ein substanzieller Beitrag zum für 2050 prognostizierten Strombedarf von 60 TWh im Jahr. Attraktiv wird die Geothermie durch das unerschöpfliche Vorhandensein ihrer Ressourcen, die voraussichtlich relativ geringe CO_2-Belastung sowie ihre zuverlässige Verfügbarkeit im Inland und rund um die Uhr. Allerdings ist der künftige Beitrag der Tiefengeothermie zurzeit noch mit grösseren Unsicherheiten behaftet, da sie sich als neuartige Energiequelle in der Schweiz erst noch bewähren muss.

Die längerfristigen Chancen, die mit der Nutzung der Erdwärme einhergehen, sind Anreiz genug, um auf folgende Fragen eine Antwort zu suchen: In welchem Ausmass ist diese Ressource nutzbar und welche wirtschaftlichen Kosten fallen dabei an? Welche ökologischen und risikobezogenen Externalitäten muss die Allgemeinheit in Kauf nehmen? Wie fällt die Gesamtleistung der Geothermie im Vergleich zu konkurrenzierenden Energiequellen aus? Erlauben es der Regulierungsrahmen und die Akzeptanz in der Öffentlichkeit, einen wesentlichen Teil des Energiebedarfs durch Geothermie zu decken?

Die vorliegende TA-SWISS-Studie versucht, diese Fragestellungen umfassend und ausgewogen zu beantworten. Ein interdisziplinärer Evaluierungsansatz ermöglicht es, Vergleiche zu anderen Technologien zu ziehen und so den Entscheidungsprozess der verschiedenen Interessensgruppen zu unterstützen. Die perfekte Energielösung gibt es nicht. Doch das Abwägen der Stärken und Schwächen der Tiefengeothermie liefert erste strukturierte Hinweise zur Rolle, die diese Energiequelle innerhalb des künftigen schweizerischen Energiemix in Zukunft spielen könnte.

Schwerpunkt, Inhalt und Organisation der Studie

Der Schwerpunkt der aktuellen Studie liegt auf der Stromerzeugung, für geeignete Bereiche werden auch das Potenzial und die Bedeutung der Wärmegewinnung hervorgehoben. Obwohl das Hauptaugenmerk der Geothermie in der Schweiz gilt, sind die verwendeten Methoden und die zahlreichen Erkenntnisse von breiterem Interesse.

Der Hauptverdienst des Projekts ist die umfassende Darstellung des derzeitigen Forschungsstandes. In einigen Bereichen wurde dabei auf das Expertenwissen von Partnern und auf vorhandene Wissensgrundlagen zurückgegriffen (z. B. für den Status von Ressourcendaten, Technologiedaten und Regulierung), in anderen wurden neue quantitative Ergebnisse erarbeitet. Besonderes Gewicht wurde auf noch relativ unerforschte Gebiete gelegt, wie die Beurteilung der schweizerischen Ressourcen, die Wirtschaftlichkeit, die Ökologie, die Risiken, den Regulierungsrahmen und die öffentliche Akzeptanz. Ebenfalls berücksichtigt wurden schliesslich Schlüsselbereiche wie die Reservoirtechnik, wo weitere technologische Fortschritte erzielt werden müssen.

Die Studie umfasst unter anderem folgende Themen:

- Ressourcenanalyse
- Evaluierung der Erkenntnisse, die in petrothermalen Projekten beim Anlegen von Reservoirs gewonnen werden konnten. Analyse aktueller und neuartiger Bohrtechnologien
- Entwicklung und Anwendung eines neuartigen Kostenkalkulationsmodells
- Quantifizierung der Umweltauswirkungen anhand eines Life Cycle Assessments (LCA) mit direkter Ankoppelung an das Kostenkalkulationsmodell
- Risikoevaluierungen und Erkenntnisse aus induzierten Erdbeben
- Analyse der Regulierungsthemen und mögliche Lösungsansätze
- Analyse des Umgangs mit dem Thema Geothermie in den Medien
- Erforschung der Standpunkte und der Meinungen von verschiedenen Interessensgruppen zum Thema Geothermie sowie von Bürgerinnen und Bürgern in einem breiteren gesellschaftlichen Kontext
- Begrenzte Multikriterien-Entscheidungsanalyse (MCDA) mit Technologievergleich und Darstellung der Auswirkungen von Interessensgruppenpräferenzen

Die Studie bildete die Grundlage für anschliessende Empfehlungen an die Politik und für weitere Forschungsvorhaben.

Durchgeführt wurde die Studie von einem Forschungskonsortium mit breiten multidisziplinären Kompetenzen. Zu den Beteiligten gehörten das Paul Scherrer Institut (PSI; Koordination der Studie), die Eidgenössische Technische Hochschule Zürich (ETHZ), die Zürcher Hochschule für Angewandte Wissenschaften (ZHAW) und die Universität Stuttgart/ Dialogik. Mehr als 30 Forscherinnen und Forscher aus den genannten Einrichtungen leisteten Projektbeiträge. Die Studie führte zudem zu einer intensiven Zusammenarbeit mit dem vor Kurzem gegründeten Energiekompetenzzentrum für Strombereitstellung SCCER (Swiss Competence Center on Supply of Electricity). Aus diesen Kontakten haben sich Synergien für die parallele Entwicklung einer Tiefengeothermie-Roadmap für die Schweiz ergeben.

Grundlegende technologische Optionen

Konventionelle (d. h. hydrothermale) Erdwärmeressourcen basieren auf dem Zusammenwirken von drei Faktoren:

- hohe Temperaturen im Untergrund, die angesichts der heutigen Energietechnik bei mindestens 100 °C liegen müssen; dies bedingt somit Tiefen von mehr als 3 Kilometern, da die Temperatur mit zunehmender Tiefe steigt
- Vorhandensein von wasserführenden geologischen Formationen oder Strukturen
- ausreichende Erzeugung von heissem Wasser für eine wirtschaftlich tragfähige, nachhaltige Stromerzeugung an der Oberfläche

Aktuelle Erfahrungen deuten darauf hin, dass das gleichzeitige Vorhandensein aller drei Faktoren an einem Standort in der Schweiz nur selten gegeben ist. Von daher ist die Wahrscheinlichkeit gering, dass hydrothermale Anlagen einen substanziellen Beitrag zur Stromerzeugung leisten können.

Eine alternative Technologieform zur Extraktion von Wärme aus tiefen, heissen Gesteinsschichten stellen EGS-Verfahren (*Enhanced* oder *Engineered Geothermal Systems*) dar, die im deutschsprachigen Raum als «petrothermale Systeme» bezeichnet werden. Anders als hydrothermale Systeme benötigen die petrothermalen in der Tiefe keine Reservoire für heisse Flüssigkeiten. Das Grundkonzept besteht in der Anlage eines Wärmeübertragers (Wärmetauschers) zwischen zwei oder mehreren Bohrlöchern, die in den Zielbereich des Gesteins gebohrt werden. Erreicht wird dies durch umfangreiche Injektionen von kaltem Wasser unter Druck in tiefe Gesteinsschichten, um so die Reservoirstimulation und die Verbesserung der Gesteinsdurchlässigkeit zwischen den Bohrlöchern zu fördern. Damit sind diese durch vielfältige Fliesswege über ein grosses Gesteinsvolumen miteinander verbunden. Das Verfahren zur Verbesserung der Gesteinsdurchlässigkeit hat sich bei Feldversuchen als effektiv erwiesen, wird derzeit aber noch nicht hinreichend verstanden, um eine Optimierung zu ermöglichen. Weitere Erkenntnisse über solche Prozesse und ihre Beeinflussung durch geologische Bedingungen zu gewinnen, bleibt deshalb – zusammen mit der Kontrolle der Seismizität, die mit dem Betrieb einhergeht – die wichtigste Herausforderung, um die Technik zur Marktreife führen zu können. Sobald der Wärmeübertrager installiert ist, kann Wasser in einem Kreislauf zirkulieren und die darin enthaltene Wärme extrahiert und mithilfe geeigneter Energieumwandlungstechnologien an der Oberfläche in elektrische Energie umgewandelt werden.

Petrothermale Systeme (EGS) sind daher das Endziel für eine erfolgreiche langfristige Erschliessung der schweizerischen Geothermieressourcen, denn das Ressourcenpotenzial ist immens. Doch angesichts der noch bestehenden technischen Probleme gelten die EGS-Systeme nicht als genügend ausgereift, um am Markt bestehen zu können. Seit 2006 beim Anlegen des Reservoirs für das Basler EGS-Projekt eine Serie von kleineren, für die örtliche Bevölkerung jedoch spürbaren Erdstössen ausgelöst wurde und die Möglichkeit seismischer Risiken die Öffentlichkeit alarmierte, ist die technische Entwicklung in mehreren Ländern wie den USA, Island, Deutschland, Frankreich und Australien allerdings weiter vorangeschritten.

Ressourcen und Reserven

Die Geothermie bietet als Energieträger spezifische Vorteile, wodurch sich vielfältige Möglichkeiten eröffnen. Um sich die Grössenordnung der geothermalen Ressourcen und ihr

Potenzial verdeutlichen zu können, ist es aufschlussreich zu wissen, dass der gesamte Energiebedarf der Schweiz im Jahr 2013 bei rund 896 Petajoule (896×10^{15} J) lag.

Die Schweiz verfügt über riesige geothermale Ressourcen. Die in Tiefen zwischen 3 und 10 Kilometern im Gestein gespeicherte Wärmemenge dürfte in einer Grössenordnung von 10^{23}J liegen – das ist hunderttausendmal mehr als der Energiebedarf im Jahr 2013. Dazu kommt, dass die Wärmespeicher aus der Tiefe ständig wieder aufgefüllt werden. Das durch weitere Explorationsprogramme gewonnene Know-how wird dazu führen, dass verschiedene dieser theoretisch vermuteten Ressourcen genau quantifizierbar werden. Berücksichtigt man zudem Einflussfaktoren (wie technische, wirtschaftliche, vermarktungsspezifische, rechtliche, ökologische, landnutzungsbezogene, gesellschaftliche und staatliche Aspekte), die sich direkt auf die Wahrscheinlichkeit einer kommerziellen Nutzung auswirken, so werden aus diesen Ressourcen wiederum sogenannte nachgewiesene Reserven. Die Einbeziehung dieser Einflussfaktoren und weiterer Beschränkungen, die sich aufgrund von technischen und operativen Risiken ergeben, reduziert das vermutete Potenzial – zumindest nach heutigem Wissensstand – um mehrere Grössenordnungen.

Statt von einem Potenzial auszugehen, von dem höchst ungewiss ist, ob es bis 2050 überhaupt genutzt werden könnte, konzentriert sich die vorliegende Untersuchung auf die Voraussetzungen, die für das Erreichen der Ziele der schweizerischen Energiestrategie notwendig sind. Demnach kann das für 2050 anvisierte Ziel einer geothermalen Stromerzeugung von 4–5 TWh im Jahr nur dann umgesetzt werden, wenn die Anlagen ihre Kapazitäts- und Kostenvorgaben erfüllen können. Dies wiederum hängt von einer erfolgreichen Erkundung, Charakterisierung und Erschliessung von geothermalen Ressourcen ab. Dazu gehört auch der Nachweis, dass geeignete Wärmeübertrager konstruiert werden können: Sie müssen einerseits eine kommerziell ausreichende Durchflussrate und Betriebslebensdauer aufweisen und es andererseits ermöglichen, das Risiko der induzierten Seismizität auf einem gesellschaftlich akzeptablen Niveau zu halten.

Erfordernisse und Perspektiven des technologischen Fortschritts

Obschon die grundlegende technische Machbarkeit nachgewiesen ist, müssen noch eine Reihe technologischer Entwicklungen stattfinden, damit petrothermale Systeme nachhaltig so eingesetzt werden können, dass dabei ein ausgewogenes Verhältnis zwischen gesellschaftlichem Nutzen, Umweltschutz, Gewinnerzielung und Wertschöpfung erreicht wird. Im Allgemeinen sind in der Schweiz regional noch keine Explorationstechnologien eingesetzt worden. Deshalb liegt bislang auch noch kein systematischer Nachweis dazu vor, welche Ressourcen letztlich als Reserven einzustufen sind. Die in der Geothermie verwendete Bohrtechnologie wurde hauptsächlich (und wird auch heute noch) aus der Öl- und Gasförderung übernommen und gilt in vielerlei Hinsicht als ausgereift, wobei die Entwicklung im Öl- und Gassektor weiterhin energisch vorangetrieben wird. Bohrungen stellen die bei weitem wichtigste Kostenkomponente beim Anlegen eines Geothermiereservoirs dar, so dass sich eine Reduzierung der Bohrkosten erheblich auf die wirtschaftliche Machbarkeit von Geothermieprojekten auswirkt. Das hohe Kostenniveau ist darauf zurückzuführen, dass passgenaue schnelle Bohrmethoden zum einen erst noch erforscht werden müssen und es zum andern in der Schweiz an Standards und Erfahrung mangelt. Die Kosten der hydraulischen Stimulation machen den geringeren Teil der Gesamtkosten aus, doch auch hier können sich Verbesserungen erheblich auf die Durchflussraten und die Nutzungsdauer der Bohrlöcher auswirken. Ebenso stellen die erreichbare Tiefe und die Zuverlässigkeit von Tiefpumpen wichtige Forschungsbereiche dar.

Die Stromerzeugungstechnologie, die bei petrothermalen Anlagen an der Oberfläche eingesetzt wird, gilt im Allgemeinen als ausgereift. Durch schrittweise Verbesserungen könnte der Wirkungsgrad weiter gesteigert und die Konstruktion für eine Kraft-Wärme-Kopplung optimiert werden. Die grösste Herausforderung beim Einsatz von petrothermalen Systemen in der Schweiz und weltweit besteht darin, die Schaffung eines Wärmeübertragers im Untergrund zu beherrschen und die damit verbundene Seismizität zu kontrollieren.

Angesichts der anscheinend beschränkten Möglichkeiten der Erschliessung von hydrothermalen Ressourcen in der Schweiz (d. h. Auffinden und Nutzung von Aquiferen oder Formationen mit grossen Mengen mobilisierbarem Wasser) kann ein nennenswerter Anteil der Geothermie an der Stromerzeugung nur dann erfolgen, wenn es gelingt, die geologisch-technischen Herausforderungen der EGS-Technik zu meistern. Der Schwerpunkt auf die Stromerzeugung durch Tiefengeothermie sollte jedoch die Erschliessung oberflächennaher Ressourcen zur direkten Nutzung (z. B. zur Deckung des Wärmebedarfs von Haushalten und Industriebetrieben, in der Landwirtschaft und Aquakultur) nicht hemmen. Die dafür erforderlichen Temperaturen von 60 °C und mehr sind an günstigen Standorten bereits in Tiefen von 1,5 km zu finden. Eine Exploration dieser Reservoire würde die wahrscheinlichen und nachgewiesenen geothermalen Wärmeressourcen der Schweiz weiter vergrössern.

Wirtschaftlichkeit

Die Wirtschaftlichkeitsanalyse der Geothermie zeigt, dass die durchschnittlichen Stromerzeugungskosten aufgrund einer Reihe von Faktoren erheblich schwanken können; diese sind teilweise mit grossen Unsicherheiten behaftet, so beispielsweise die Bohrlochkosten und die Reservoirnutzungsdauer. Bei der Bezugsbasis liegen die durchschnittlichen Kosten der Stromproduktion in der Schweiz bei 35 Rappen/kWh, wobei die Schwankungsbreite zwischen positiven und negativen Vergleichsfällen eine Spanne von 18 bis 61 Rappen/kWh umfasst. Bohrlochbezogene Kosten sind noch immer die alles beherrschende Kostenkomponente, die gleichzeitig für die grösste Unsicherheit bei der Kostenberechnung sorgt. Dazu gehören nicht nur die Bohrkosten, sondern auch die Anzahl der für die Exploration, Bestätigung und Förderung erforderlichen Bohrlöcher sowie deren Nutzungsdauer, bis neue Bohrlöcher angelegt werden müssen. Für eine schrittweise Senkung der konventionellen Bohrkosten besteht noch erheblicher Spielraum, bevor neue, revolutionäre Bohrtechnologien zum Einsatz kommen müssten, um eine weitere nennenswerte Kostenreduktion zu erreichen. Ein möglicher Verkauf der Abwärme würde die Durchschnittskosten nachweislich deutlich reduzieren – in der Bezugsbasis würde der Durchschnittspreis von 35 auf 14 Rappen/kWh sinken. Eine Branchenanalyse für den potenziellen Fernwärmemarkt zeigt, dass bei einer vollständigen Ausschöpfung dieses Potenzials bis 2050 und einer vollständigen Deckung des Bedarfs durch Abwärme aus der Geothermie-Stromerzeugung jährlich etwas über 5 TWh Strom dank Abwärmebonus zu tieferen Kosten produziert werden könnten. Der klare betriebswirtschaftliche Nutzen des Abwärmeverkaufs steht allerdings in einem Spannungsfeld zwischen der benötigten räumlichen Nähe zu den Wärmeabnehmern und der gewollten Distanz zu Anwohnern, die sensibel auf induzierte Seismizität, Lärm und Eingriffe in das Landschaftsbild reagieren könnten. Beim aktuellen Stand der Technik sind die Produktionskosten für Geothermiestrom für Abnehmer in der Schweiz drei- bis fünfmal zu hoch. Der Abwärmeverkauf verliert erst dann an Bedeutung, wenn die Bohrlochkosten wesentlich gesenkt werden können. Doch selbst wenn das Marktpotenzial für Fernwärme nicht allein durch Geothermiestrom gedeckt wird, ist der Wärmemarkt gross genug, um in Bezug auf die Reduktion der Geothermiekosten einen bedeutenden Lernprozess zu ermöglichen. Ein glaubwürdiger Weg zur wirtschaftlichen Tragfähigkeit ist dann gegeben, wenn die technologischen, ingenieurtechnischen und sicherheitsbezogenen Herausforderungen gemeistert werden.

Ökobilanz

Die Umweltauswirkungen der Tiefengeothermie in der Schweiz wurden mithilfe eines Life Cycle Assessments (LCA) abgeschätzt. Diese Methode bezieht sich jedoch nur auf den Normalbetrieb und berücksichtigt keine möglichen Störfälle; diese wären gesondert zu bewerten. Zu den in der Ökobilanz berücksichtigten Indikatoren gehören: Klimawandel, Toxizität für den Menschen, Feinstaubbildung (Partikel), ionisierende Strahlung, Wasser- und Metallverbrauch. Die Umweltauswirkungen der Stromerzeugung durch Tiefengeothermie sind geringer oder liegen auf demselben Niveau wie bei anderen neuen erneuerbaren Energien, die für den künftigen Energiemix der Schweiz in Frage kommen. Dies gilt übrigens auch dann, wenn man die relativ starken Unwägbarkeiten bei einigen Parametern berücksichtigt, die zur Bestimmung der Bilanz von künftigen Geothermieanlagen herangezogen wurden. So liegen die geschätzten Treibhausgasemissionen je nach technischen und betrieblichen Parametern zwischen 8 und 46 g CO_2-Äquivalenten pro kWh. Damit ist Geothermiestrom praktisch CO_2-frei. Die Bohrphase wirkt sich am stärksten auf die ökologische Gesamtbilanz aus. Die Oberflächenanlagen, die Wahl des Arbeitsmediums und die Reservoirstimulation spielen in den meisten Umweltkategorien nur eine untergeordnete Rolle. Mit Blick auf die umweltpolitischen Zielsetzungen und insbesondere den Klimaschutz sollte die Geothermie als Energieträger im künftigen Strommix daher definitiv in Betracht gezogen werden.

Unsicherheiten, Risiken und Potenziale für deren Begrenzung

Der schiere Umfang der Geothermieressourcen bietet gewaltige Chancen für die Stromerzeugung und die Wärmegewinnung. Allerdings unterliegt ihre Erschliessung bedeutenden begrenzenden Faktoren. Die Identifikation von hydrothermalen Ressourcen wird vor allem durch erhebliche Defizite in der Exploration der Tiefenformationen in der Schweiz erschwert. Politische Entscheidungen, um hier Abhilfe zu schaffen, wurden dank einer Reihe von Initiativen des Schweizer Parlaments bereits getroffen. Leider fehlt der heutigen Explorationstechnik noch die Möglichkeit, die Durchlässigkeit und die tektonische Vorspannung des Tiefengesteins vorherzusagen, was ihren Nutzen für geothermale Anwendungen begrenzt. Die Technologie zur Erschliessung hydrothermaler Ressourcen ist hingegen ausgereift. Sobald es gelingt, entsprechende Vorkommen zu identifizieren, können diese vorbehaltlich allfälliger umwelt- und aufsichtsrechtlicher Auflagen erschlossen werden.

Demgegenüber sind die EGS-Verfahren für petrothermale Systeme noch keineswegs ausgereift und erfordern ein Grundlagenforschungsprogramm, bevor eine grossflächige Anwendung möglich wird. In den vergangenen 40 Jahren wurden mehrere umfangreiche Prototypensysteme in unterschiedlichen geologischen Szenarien errichtet, die ermutigende Machbarkeitsnachweise geliefert haben. Allerdings hat sich die Konstruktion eines genügend grossen Wärmeübertragers (mit einem Abstand zwischen den Bohrlöchern von > 500 m), der die Voraussetzungen für ausreichende kommerzielle Durchflussraten erfüllt, bislang als schwierig erwiesen, wenn nicht bereits hochpermeable Formationen im Zielbereich des Gesteins (d. h. Risse und Klüfte) vorhanden waren, wie dies beispielsweise am EGS-Standort Soultz in Frankreich der Fall ist. Aus vorangehenden Projekten weiss man inzwischen, dass es keine zwei identischen Felsformationen gibt und dass daher mit der jeweiligen Formation «gearbeitet» werden muss, um durch zahlreiche hydraulische Verbindungen zwischen den Bohrlöchern einen Wärmeübertrager anzulegen. Für kommerzielle Systeme mit einer Nutzungsdauer von einigen Dutzend Jahren sollten die Bohrlöcher mindestens 500 m auseinanderliegen, wobei die Nettoströmung zwischen ihnen einen Kluftbereich von mehreren Quadratkilometern mit einem Gesteinsvolumen in der Grössenordnung von 0,1 bis 0,2 km^3 durchlaufen sollte.

Ein weiterer Gesichtspunkt bei der Entwicklung der Tiefengeothermie ist das Risiko, dass für die lokale Bevölkerung spürbare Erdstösse ausgelöst werden. Die bislang in der Schweiz gemachten Erfahrungen zeigen, dass dies sowohl bei petrothermalen als auch hydrothermalen Systemen geschehen kann. Klar ist, dass der Untergrund so erschlossen werden muss, dass das seismische Risiko für Mensch, Umwelt und Sachwerte so gering wie praktikabel gehalten wird. Bei den EGS-Verfahren bleibt einer der wichtigsten problematischen Punkte die Steuerung der induzierten Seismizität während dem Anlegen des Wärmeübertragers und der anschliessenden 20 bis 30-jährigen Betriebsperiode sowie die Fähigkeit, ein Rissenetz zu kreieren, das über Jahrzehnte heisses Wasser liefern kann. Angesichts der seismischen Risiken einen angemessenen Versicherungsschutz sicherzustellen, könnte sich ebenfalls erheblich auf die Wirtschaftlichkeit der Geothermie als Energieträger auswirken.

Zusätzlich zu den ausgeprägten seismischen Risiken besteht eine Reihe von üblichen betrieblichen Risiken, z. B. aufgrund von schädlichen Arbeitsmedien oder bohrbezogenen Gefahren, wie sie in der Öl-, Gas- und Bergbauindustrie keineswegs ungewöhnlich sind. Diese Risiken sollten durch eine geeignete Regulierung und Betriebspraxis gesteuert werden, welche strengen Branchenstandards genügt und aufsichtsrechtlich stringent durchgesetzt wird. Die vorliegende Studie hat sich auch mit der Gefahr von Störfällen aufgrund von Blowouts und gewissen Gefahrenstoffen befasst. Dabei sind die Risikomessgrössen für verschiedene Folgekategorien (z. B. Opferzahlen etc.) gering, aber nicht vernachlässigbar. Die Gefahr von Blowouts stellt ein erhöhtes Risiko für die menschliche Gesundheit dar, während die Freisetzung von chemischen Gefahrenstoffen vor allem die Umwelt belastet.

Detaillierte Sensivitätsanalysen, die die wesentlichen Kostenfaktoren der Entwicklung von EGS-Projekten untersuchen, deuten darauf hin, dass durch eine Standardisierung der Bohrpraktiken eine erhebliche Kostenreduktion erreicht werden könnte. Möglich wird dies, sobald mehr Erfahrungen beim Anlegen von Bohrlöchern für die Tiefengeothermie vorliegen. Ebenso ist die Entwicklung von kosteneffektiven Methoden für die Installation des unterirdischen Wärmeübertragers Voraussetzung für die wirtschaftliche Machbarkeit. Wie sich die Auslegung und Geometrie des Wärmeübertragers optimieren lässt, um eine maximale Flüssigkeitszirkulation ohne rasche Einbrüche von kaltem Wasser in die Produktionsbrunnen zu erreichen, bleibt ebenfalls ein wichtiger Forschungsbereich. Die wirtschaftlichen Risiken können weiter abgefedert werden, indem Möglichkeiten für den Abwärmeverkauf geschaffen werden. Dies würde die Wirtschaftlichkeit der Projekte signifikant steigern und wäre ein wesentlicher Anreiz für privatwirtschaftliche Investoren, sich am Geothermiegeschäft und seiner Entwicklung zu beteiligen. Ein weiterer wesentlicher Schritt für den Aufbau einer landesweiten Geothermiebranche wäre ein nationales Geothermie-Datensystem, in dem Ressourcen- und Nutzungsdaten, Betriebs- und Umweltauflagen, Regularien und Standards, Strom- und Wärmebedarf der Endkunden sowie die entsprechende Versorgungsinfrastruktur zentral verwaltet würden.

Rechtliche Aspekte

Der bestehende gesetzliche und aufsichtsrechtliche Rahmen in den einzelnen Schweizer Kantonen stellt für die Entwicklung der Geothermie kein grundsätzliches Hindernis dar. Eine Übertragung der rechtlichen und aufsichtsrechtlichen Zuständigkeit an eine Bundesbehörde erscheint zwar auf den ersten Blick attraktiv und könnte die Erschliessung der Geothermie potenziell deutlich beschleunigen, dürfte jedoch politisch kaum durchzusetzen sein. Es existieren durchaus kantonale Gesetze und rechtliche Verfahren über die Nutzung des Untergrunds, die die Erschliessung von Geothermieressourcen ermöglichen, wenngleich sie selten auf die Geothermie abgestimmt sind. Eine Explorationskonzession für die Suche nach Geothermieressourcen, wie sie von den kantonalen Behörden erteilt wird, begründet keinen automatischen Anspruch auf eine anschliessende Nutzungskonzession, um gefundene Geothermieressourcen ausbeuten zu können. Dies stellt eine Benachteiligung des Inhabers der Explorationskonzession dar, der in die Exploration investiert hat und tatsächlich fündig geworden ist. Genauso ist es in einigen Kantonen unklar, ob die Erteilung einer Nutzungsbewilligung oder Konzession nur durch eine öffentliche Ausschreibung erfolgen kann. Einige Kantone richten sich zwar nach dem «Koordinationsmodell» des Bundes, das bei der Beantragung einer Vielzahl von Bewilligungen bei unterschiedlichen Behörden eine gewisse Einheitlichkeit sicherzustellen sucht. Doch nur sehr wenige Kantone haben das «Konzentrationsmodell» umgesetzt. Dabei koordiniert und vereinfacht eine kantonale Behörde den gesamten Genehmigungsprozess mit allen anderen zuständigen Behörden und erteilt am Ende die Bewilligungen gebündelt. Ein wichtiger Wegbereiter für die Erschliessung des Untergrunds im Allgemeinen und der Geothermie im Besonderen ist die Einbeziehung des Untergrunds in die kantonalen Struktur- und Richtpläne, welche wesentliche Instrumente der kantonalen Behörden für die Raumplanung an der Oberfläche und in Bereichen des Untergrunds darstellen, in denen geothermale Energieträger erschlossen werden sollen. Im Jahr 2014 wurde eine Reihe von Initiativen des Bundes und des Nationalrats auf den Weg gebracht, um einen Rechtsrahmen für eine Beschleunigung des Bewilligungsverfahrens zu schaffen. Dabei muss jedoch mit Blick auf kantonale Souveränitätsrechte und die beispielsweise unbeabsichtigten Folgen einer übermässigen Erteilung von Ausnahmeregelungen gegenüber den Richtplänen eine sorgfältige Abwägung stattfinden. Mehrere Kantone haben verschiedene Vorschriften und Regelungen für die Exploration und Erschliessung von tiefen Geothermieressourcen erlassen. Die Übernahme von Praktiken, die sich bewähren, gilt als ein entscheidender und kostengünstiger Weg, um einen optimalen rechtlichen Rahmen zu finden. Der Bund hat zwar keine wesentlichen Kompetenzen, um die Geothermie als Energieträger zu regulieren. Er ist jedoch geradezu prädestiniert, durch Beratung und durch die unterstützende Einrichtung einer Bundesplattform (ohne rechtliche Zuständigkeit) eine Art «weiche» Gesetzgebung zu schaffen und so den Kantonen bei Umsetzung und Vollzug ihrer jeweiligen Massnahmen, Verordnungen und Richtlinien tatkräftig zur Seite zu stehen.

Öffentliche Meinung und Risikowahrnehmung

Die gesellschaftliche Akzeptanz der Tiefengeothermie hängt nicht unwesentlich von der öffentlichen Wahrnehmung ab. Durch die Analyse von Daten aus gesellschaftlichen Fokusgruppen, den sozialen Medien und Zeitungsartikeln können inhaltsbezogene Argumente bzw. sogenannte «Frames» abgeleitet werden. Ein solcher Frame konzentriert sich beispielsweise auf Argumente im Zusammenhang mit der Energiestrategie der Schweiz: «Die Tiefengeothermie könnte zur Umsetzung der Energiestrategie der Schweiz beitragen», oder: «Die Tiefengeothermie ist keine realistische Option». Ein zweiter Frame betrifft die Risiken:

Auf der einen Seite werden die Unwägbarkeiten und Risiken hervorgehoben. Auf der anderen Seite überwiegt die Wahrnehmung, dass die Risiken beherrschbar sind. Ein dritter Frame behandelt die Technologie, die einerseits als nützlich und erfolgversprechend, andererseits aber vor allem als problembehaftet und zum Scheitern verurteilt dargestellt wird. Schliesslich wird in einem vierten Frame die Kostenfrage beleuchtet: Ist die Geothermie erschwinglich oder mit zu hohen Aufwendungen verbunden? Vieles deutet darauf hin, dass die öffentliche Wahrnehmung erheblichen Schwankungen unterliegt, da viele Menschen überaus ambivalent eingestellt sind. Die frühe Entwicklungsphase der Geothermie hat trotz des vergleichsweise starken öffentlichen Echos auf die Projekte in St. Gallen (2013) und Basel (2006/2007) zu keinem eindeutigen Meinungsbild in der Öffentlichkeit geführt. Aktivitäten unter der Erde werden oft mit Vorstellungen wie einer «Einmischung in die Natur», einem äusserst unwahrscheinlichen, aber auch sehr zerstörerischen Beben oder mit der Sichtbarkeit technischer Anlagen (hohe Gerüste von Bohrtürmen) in Verbindung gebracht. Die Komplexität des Umgangs mit der «unsichtbaren» Tiefe beruht auf überaus abstraktem Expertenwissen, das sich oft nur schwer an Laien vermitteln lässt. Aufgrund ihrer starken Dynamik und der Art, wie Argumente darin verwendet werden, können soziale Medien und Beiträge in den traditionellen Medien als Frühwarnsignale für ein Umschlagen des öffentlichen Meinungsbilds dienen. Bislang haben die sozialen Medien die Tiefengeothermie (selbst nach St. Gallen) weitestgehend und beharrlich ignoriert. Wird darüber berichtet, so fällt die Einstellung der schweizerischen Öffentlichkeit gegenüber der Tiefengeothermie eher neutral bis positiv aus.

Der Industrie und der Wissenschaft kommen besondere Rollen im öffentlichen Diskurs zu. Die Industrie betont derzeit als Interessensgruppe das Potenzial der Tiefengeothermie, die Wissenschaft hingegen die Risiken und Unsicherheiten. Bei beiden Gruppen wäre ein ausgewogenerer Standpunkt hilfreich für die Kommunikation: Die Industrie könnte Risiken und Unsicherheiten aktiv ansprechen, während Wissenschaftler ebenso auf mögliche oder bestehende Strategien zur Risikominderung hinweisen könnten.

Integration von Umwelt, Wirtschaftlichkeit, Risiken und Versorgungssicherheit

Im Rahmen der Integrationsanalyse wurde eine begrenzte Multikriterien-Entscheidungsanalyse (MCDA) durchgeführt. Eine MCDA bietet aggregierte Kennzahlen für einen Vergleich der verschiedenen alternativen Energieträger mit Blick auf ökologische, wirtschaftliche, gesellschaftliche und die Versorgungssicherheit betreffende Kriterien; gleichzeitig werden die Präferenzen der verschiedenen Interessensgruppen berücksichtigt. Sie unterstützt eine mündige Entscheidungsfindung und kann in öffentlichen Debatten und partizipativen Prozessen als Orientierungshilfe dienen. Durch die MCDA werden zwar die relativen Stärken und Schwächen der verschiedenen Alternativen aufgezeigt, doch es wird keine abschliessende Einstufung der Technologien vorgenommen. Vielmehr macht die MCDA die Sensitivität des Rankings gegenüber den subjektiven Präferenzen der jeweiligen Interessensgruppen deutlich. Die Analyse umfasste die wichtigsten neuen erneuerbaren Energien, die für die Schweiz von Interesse sind (einschliesslich Photovoltaik, Windenergie und Biogas), wobei sie sich auf vorhandene Technologien beschränkte.

Insgesamt bestätigt die im Rahmen dieser Studie durchgeführte MCDA, dass geothermale Systeme, die Stromerzeugung und Wärmegewinnung kombinieren, deutlich besser abschneiden als eine reine geothermale Stromerzeugung. Betrachtet man ein Präferenzprofil mit einer ausgewogenen Gewichtung der grundlegenden Nachhaltigkeitskriterien und einem Schwerpunkt auf Klimaschutz, Minimierung von Humantoxizität, Metallverbrauch und Risiken (unter Aussparung der induzierten Seismizität) sowie Versorgungssicherheit, so schneidet die Geothermie in der Gesamtschau am besten ab. Ein Präferenzprofil mit einer ausgewogenen Gewichtung der grundlegenden Nachhaltigkeitskriterien und einem Schwerpunkt auf Wasserverbrauch und induzierter Seismizität erweist sich hingegen als ungünstig für die Geothermie.

Ausgewählte Empfehlungen

Die Studie umfasst eine relativ grosse Anzahl Empfehlungen für Politik und Wissenschaft. Im Folgenden werden die wichtigsten davon zusammengefasst:

- Das Augenmerk der Entscheidungsträger und Interessensgruppen sollte auf die potenziell wichtige Rolle der Geothermie in einer zunehmend dezentralisierten Stromversorgung mit einem hohen Anteil von nur zeitweilig verfügbaren erneuerbaren Energien gelenkt werden. Die Geothermie stellt dabei eine der wenigen «neuen» erneuerbaren Optionen dar, die am Strommarkt für die Grundlastversorgung in Frage kommen und damit wesentlich zur Versorgungssicherheit beitragen könnten. Die künftige potenzielle Rolle der Geothermie in der Schweiz muss daher im Kontext des gesamten Energieversorgungssystems gesehen werden.
- Strom aus Tiefengeothermieanlagen weist unter normalen Betriebsbedingungen eine günstige Umweltbilanz auf. Aus ökologischer Sicht und besonders mit Blick auf den Klimaschutz könnte die Geothermie einen attraktiven Beitrag zum künftigen Energiemix der Schweiz leisten und verdient es daher, ernsthaft in Betracht gezogen zu werden.
- Eine weitere Förderung der Geothermieproduktion ist jedoch notwendig, um den Markt zu verbreitern. Dies wird Unternehmen motivieren, ihre Forschungs- und Entwicklungsanstrengungen für das Anlegen von geothermischen Bohrungen zu verstärken, wodurch sich wiederum die Risiken und Kosten der geothermalen Stromerzeugung verringern lassen. Mögliche Förderbereiche könnten neben den aktuellen Risikogarantien und den Einspeisevergütungen die weitere Erkundung und Charakterisierung von Wärmequellen sowie die Technologieentwicklung und Demonstrationsprojekte sein.
- Angesichts der erheblichen Unsicherheit über die potenziellen Geothermiereserven der Schweiz ist eine umfangreiche nutzungsgetriebene Forschungsinitiative in Verbindung mit einem Programm aus Pilot- und Demonstrationsprojekten erforderlich, um den Bau eines petrothermalen Systems, das kommerzielle Leistungsanforderungen erfüllt, zu ermöglichen.
- Ein erheblicher Fortschritt würde erzielt, wenn sich Standorte mit geologischem Potenzial mit der politischen Regulierung, den Anliegen der Bevölkerung (in Bezug auf Seismizität) und den Wärmemärkten innerhalb des GIS-Rahmens zu einem ökonomischen Modell verbinden liessen. Damit wäre es möglich, die Kosten der geothermalen Stromerzeugung besser zu kalkulieren sowie darzustellen, wo sich unter Berücksichtigung aller Faktoren die Standorte mit dem höchsten Potenzial befinden.

- Die Erdbebenrisiken können bewertet und kontrolliert, nicht aber ausgeschlossen werden. Die Erfolgsquote und die wirtschaftliche Machbarkeit der Tiefengeothermie hängt wesentlich davon ab, welches seismische Risiko die verschiedenen Interessensgruppen zu tragen bereit sind. Die Gesellschaft muss in diesem Zusammenhang prüfen und entscheiden, welches Risikoniveau akzeptabel erscheint.
- Die Erforschung und die Fähigkeit zur Prognostizierung von induzierter Seismizität haben in den vergangenen Jahren aufgrund von Projekten, die von der wissenschaftlichen Gemeinschaft und der Industrie finanziert wurden, erhebliche Fortschritte gemacht. Diese Bemühungen müssen in den kommenden Jahren weitergeführt werden. Der dringendste Bedarf besteht bei der Validierung neuer Modellierungstools und Risikominderungsstrategien. Künftigen Pilot- und Demoprojekten fällt dabei eine wesentliche Rolle zu. Hinzu kommt, dass viele für die induzierte Seismizität relevante Verfahren skaleninvariant sind und auch in kleinen Untergrundlabors untersucht werden können. Um die Frage einer effizienten Reservoirbildung unter Begrenzung der Erdbebenrisiken lösen zu können, ist eine multidisziplinäre Forschung nötig, die Geowissenschaften, technische Disziplinen und Informatik verbindet.
- Die Nutzung des Untergrunds wird in der Schweiz von den Kantonen reguliert. Daraus ergeben sich für die potenziellen Betreiber von Geothermieanlagen gewisse Schwierigkeiten. Ein homogener Regulierungsrahmen (z. B. ein Konzentrationsmodell) oder ein Kompetenzzentrum des Bundes könnten zur Vereinfachung und Beschleunigung der Verfahren beitragen.
- Einige Kantone haben ein Konzentrationsmodell entwickelt, bei dem eine Behörde den Inhalt der verschiedenen Bewilligungen koordiniert und diese gebündelt erteilt. In diesem Modell werden mit dem Entscheid zur Vergabe einer Konzession auch alle Bewilligungen und Entscheide der übrigen Behörden erteilt. Diese Lösung ist effektiv und praktisch. Bei der Bearbeitung eines Konzessionsgesuchs müssen in der Regel ohnehin zahlreiche Fragen behandelt werden, die auch für andere Bewilligungen von Belang sind. Durch ein solches Modell würden sich die Verfahren beschleunigen und die Kommunikation mit den Adressaten der Entscheide vereinfachen lassen.
- Grundsätzlich obliegt es den Kantonen, die Nutzung des Untergrunds zu regulieren. Dabei müssen folgende Aspekte geregelt werden: Verantwortlichkeiten, Nutzungstypen, Zwangsenteignungen, Nutzungsbewilligungen, Verfahrensschritte, Personal- und Sachressourcen, Haftung, Wechselwirkungen mit anderen Bewilligungen, Gebühren, Vollzug und Rechtsschutz.
- Der gesamte Prozess der Planung, Standortwahl und Umsetzung von Geothermieprojekten muss eng begleitet werden durch eine Einbindung aller Interessensgruppen und der Öffentlichkeit, die sorgfältig geplant, fortlaufend überwacht und genau evaluiert wird. Die Charakterisierung von Standorten anhand von gesellschaftlichen Kriterien (in Bezug auf besondere Anforderungen und die Zusammenarbeit mit den Gemeinden) könnte dabei die technische Standortcharakterisierung bei künftigen (Pilot-)Projekten ergänzen.
- Das Medieninteresse wird hauptsächlich durch spektakuläre Ereignisse mit Nachrichtenwert bestimmt, beispielsweise durch Erdbeben. Dadurch kann die öffentliche Wahrnehmung der Tiefengeothermie beeinflusst werden und das

Augenmerk der Menschen auf negative Argumente gelenkt werden. Tiefengeothermieprojekte sollten daher frühzeitig den Aspekt der Kommunikation und der öffentlichen Partizipation berücksichtigen. Die Kommunikation sollte transparent und offen Chancen und Herausforderungen ansprechen, inklusive Risiken und Strategien zu deren Verringerung. Dabei ist entscheidend, dass die Information klar, einfach verständlich und ausgewogen ist.

Résumé

La géothermie en tant que source d'énergie ouvre la perspective d'un approvisionnement en électricité décentralisé pour le domaine de la charge de base. De plus, la chaleur résiduelle peut être utilisée dans des réseaux de chauffage à distance et comme chaleur destinée à des processus industriels. A l'heure actuelle en Suisse, on ne produit pas encore d'électricité pour le consommateur final au moyen de la géothermie profonde, même s'il existe un potentiel important au vu des ressources.

Contexte et objectifs de l'étude

La nouvelle politique énergétique de la Suisse prévoit une amélioration sensible de l'efficacité énergétique, une diminution notable de la part des combustibles fossiles dans l'approvisionnement énergétique, ainsi qu'une sortie du nucléaire. Dans le même temps, les objectifs à réaliser en matière de protection du climat sont ambitieux. Une conséquence majeure de la nouvelle politique énergétique est donc la nécessité de développer massivement les énergies renouvelables pour la production d'électricité.

Dans ce domaine, l'Office fédéral de l'énergie (OFEN) estime que la géothermie profonde pourrait fournir quatre à cinq térawattheures (TWh) par an à la Suisse à l'horizon 2050. Elle contribuerait ainsi de manière substantielle aux besoins en énergie, estimés à 60 TWh par an d'ici au milieu du siècle. L'attrait de la géothermie réside dans la disponibilité inépuisable de ses ressources, dans les émissions de CO_2 relativement faibles susceptibles d'être générées et dans le fait qu'elle offre une source d'énergie fiable en Suisse même, disponible à toute heure. Néanmoins, la contribution que la géothermie profonde pourrait apporter à l'avenir ne va pas sans susciter bon nombre d'interrogations, car il s'agit d'une source d'énergie nouvelle en Suisse, et qui doit encore faire ses preuves.

La perspective des opportunités que recèle l'exploitation de la chaleur terrestre à long terme exerce cependant un puissant attrait, qui incite à trouver des réponses aux questions suivantes : Dans quelle mesure cette ressource est-elle exploitable, et quels sont les coûts économiques occasionnés ? Quels effets externes sur le plan de l'environnement et des risques la collectivité doit-elle être disposée à supporter ? Quel est le bilan de la géothermie en général par rapport aux sources d'énergies concurrentes ? Enfin, compte tenu du cadre réglementaire et du niveau d'acceptation du public, sera-t-il possible de couvrir une part essentielle des besoins énergétiques avec la géothermie ?

Le projet TA-SWISS actuel entend répondre à ces questions dans le cadre d'une démarche complète et équilibrée. Une approche d'évaluation interdisciplinaire permet une comparaison avec d'autres technologies et soutient le processus de décision des différents groupes d'intérêts. Lorsqu'il est question d'énergie, la solution parfaite n'existe pas. Cependant, l'examen des forces et faiblesses de la géothermie profonde permet de tirer de premières conclusions structurées sur le rôle que cette source d'énergie pourra jouer dans le bouquet énergétique suisse à l'avenir.

Objet principal, contenu et organisation de l'étude

L'étude actuelle porte principalement sur la production d'électricité, même si le potentiel et l'importance de la production de chaleur pour des secteurs spécifiques sont également soulignés. L'attention est portée essentiellement à la géothermie en Suisse, bien que la méthodologie employée et les nombreux enseignements tirés revêtent un intérêt plus général.

Le but premier du projet est de faire le point sur l'état actuel de la recherche. Dans quelques domaines, le savoir-faire de partenaires et Ia base de connaissances disponible ont été mis à profit (p. ex. pour dresser l'état des lieux des données sur les ressources, des données technologiques et de la réglementation). Dans d'autres domaines, des résultats quantitativement nouveaux ont été générés. A cet égard, certains secteurs qui n'avaient encore guère fait l'objet de recherches, tels que l'évaluation des ressources de la Suisse, la rentabilité, l'aspect écologique, les risques, le cadre réglementaire et l'acceptation par le public, ont notamment retenu l'attention. Cependant, des domaines clés, tels que la technique de développement du réservoir, où des progrès technologiques sont encore nécessaires, figurent également au centre de la recherche.

L'étude couvre notamment les thèmes suivants :

- Analyse des ressources
- Evaluation des enseignements tirés de la création de réservoirs dans les projets pétrothermaux
- Analyse de techniques de forage actuelles et novatrices
- Développement et application d'un modèle de calcul des coûts innovant
- Quantification de l'impact environnemental au moyen d'une analyse du cycle de vie (ACV) mise en relation directe avec le modèle de calcul des coûts
- Evaluation des risques et enseignements tirés des secousses sismiques induites
- Analyse des thèmes liés à la réglementation et des approches de solution possibles
- Analyse de la façon dont le thème de la géothermie est abordé dans les médias
- Examen des points de vue et des positions sur le thème de la géothermie chez les groupes d'intérêts et les citoyens suisses dans un contexte social élargi
- Analyse multicritère d'aide à la décision d'envergure limitée avec comparaison des technologies et exposé des conséquences des préférences formulées par les groupes d'intérêts

L'étude a jeté les bases de recommandations formulées à l'intention des milieux politiques et d'autres projets de recherche.

L'étude a été réalisée par un groupe de recherche doté de larges compétences multidisciplinaires. Parmi les participants figuraient notamment l'Institut Paul Scherrer (PSI, coordinateur de l'étude), l'Ecole polytechnique fédérale de Zurich (EPFZ), l'Université des sciences appliquées de Zurich (ZHAW) et l'Université de Stuttgart/Dialogik. Plus de 30 chercheurs et chercheuses issus des établissements mentionnés ont contribué à la réalisation du projet. L'étude a également permis une intégration étroite du tout nouveau Centre de compétences suisse pour la recherche énergétique (Swiss Competence Center for Energy Research, SCCER), créant ainsi des synergies en vue du développement parallèle d'un agenda en matière de géothermie profonde pour la Suisse.

Options technologiques fondamentales

Les ressources conventionnelles disponibles sous forme de chaleur souterraine (autrement dit hydrothermales) reposent sur l'interaction de trois facteurs :

- Des températures élevées dans le sous-sol, qui doivent atteindre au moins 100 °C au vu des techniques énergétiques actuelles, et de conséquence des profondeurs supérieures à 3 km, puisque la température croît à mesure que la profondeur augmente
- La disponibilité de formations géologiques ou de structures aquifères
- Un volume d'eau chaude suffisant pour une production de courant rentable et durable en surface

Les expériences faites à ce jour montrent que la disponibilité simultanée de ces trois facteurs sur un site n'est que rarement donnée en Suisse. Il est donc peu probable que des installations hydrothermales puissent contribuer de manière substantielle à la production de courant électrique.

Une forme de technologie alternative à l'extraction de la chaleur des couches rocheuses inférieures et chaudes est le système géothermique stimulé ou SGS *(Enhanced Geothermal System, EGS)*, couramment appelé « système pétrothermal ». Contrairement aux systèmes hydrothermaux, les systèmes pétrothermaux n'ont pas besoin de collecteurs dans le sous-sol profond pour recueillir les fluides brûlants. Le concept de base consiste en la construction d'un échangeur de chaleur entre deux ou plusieurs puits de forage creusés dans la roche à l'endroit voulu. Des injections massives d'eau froide sous pression dans les couches inférieures de la roche permettent de stimuler les réservoirs et d'améliorer la perméabilité de la roche entre les trous de forage, afin que ceux-ci soient reliés par des nombreux canaux traversant un volume de roche important. Le processus d'amélioration de la perméabilité de la roche s'est avéré efficace dans les essais sur le terrain, mais il manque pour l'heure une compréhension étendue du phénomène, qui permette de l'optimiser. Le défi majeur pour que la technologie arrive à maturité réside dans la collecte de nouveaux enseignements sur les processus de ce type et dans la réponse à la question de savoir dans quelle mesure ils sont influencés par les conditions géologiques, ainsi que dans le contrôle de la sismicité induite par l'exploitation. Dès que l'échangeur de chaleur est installé, l'eau peut se déplacer à l'intérieur d'un circuit et la chaleur qu'elle contient être extraite et, à l'aide de technologies de conversion de l'énergie appropriées, être transformée en courant électrique en surface.

Les systèmes pétrothermaux (SGS) sont donc le but final pour une intégration réussie, sur le long terme, des ressources géothermiques dont dispose la Suisse, car le potentiel de ressources dans ce domaine est considérable. Toutefois, étant donné les problèmes techniques qui subsistent encore, les systèmes SGS n'ont pas encore atteint un degré de maturité suffisant pour s'assurer une place sur le marché. Depuis que le thème des dangers sismiques s'est retrouvé au centre de l'attention en 2006, à l'occasion de secousses sismiques de moindre envergure, mais qui ont pu être ressenties par la population locale, déclenchées lors de la mise en place du réservoir pour le projet SGS de Bâle, de nouvelles avancées techniques ont été réalisées dans plusieurs pays, tels que les Etats-Unis, l'Islande, l'Allemagne, la France et l'Australie.

Ressources et réserves

La géothermie en tant que source d'énergie présente des avantages spécifiques, qui ouvrent la voie à de multiples possibilités. Pour illustrer l'ordre de grandeur des ressources géothermales et leur potentiel, il est judicieux de faire remarquer que l'ensemble des besoins énergétiques de la Suisse en 2013 s'est élevé à quelque 896 pétajoules (896×10^{15} J).

La Suisse dispose de gigantesques ressources géothermiques. La quantité de chaleur qu'on estime stockée dans la roche à une profondeur située entre 3 et 10 km est de l'ordre de 10^{23} J – ce qui équivaut à cent mille fois les besoins énergétiques de l'année 2013. De plus, les accumulateurs de chaleur en profondeur se remplissent perpétuellement. Le savoir-faire acquis par de nouveaux programmes d'exploration permettra de quantifier finalement quelques-unes des ressources qui, jusqu'à présent, ne pouvaient qu'être évaluées sur le plan théorique. Si on tient en outre compte de facteurs d'influence (tels que les aspects techniques, économiques, en lien avec la commercialisation, juridiques, environnementaux, liés à l'aménagement du territoire, sociaux et étatiques) qui se répercutent directement sur la probabilité d'une utilisation commerciale, ces ressources constituent ce qu'on appelle des réserves prouvées. Le potentiel présumé est sensiblement réduit par l'intégration de ces facteurs d'influence et d'autres restrictions liées aux risques techniques et opérationnels, si on considère l'état actuel des connaissances.

Toutefois, plutôt que de prendre pour point de départ un potentiel dont on ne sait absolument pas s'il pourra être exploité de manière réaliste d'ici à 2050, on s'est focalisé sur l'analyse des conditions nécessaires à la réalisation des objectifs énoncés dans le cadre de la stratégie énergétique suisse. Selon celle-ci, le but visé pour 2050 d'une production de courant par géothermie de 4 à 5 TWh par an ne pourra être atteint que si les installations peuvent remplir les prescriptions qui leur ont été fixées en termes de capacité et de coûts. Pour y parvenir, elles sont tributaires de la réussite de la prospection, de l'identification et de la mise en valeur des ressources géothermales. Il faut à cet effet également attester de la capacité à construire des échangeurs de chaleur adéquats, qui affichent un débit et une durée d'exploitation suffisants et qui permettent dans le même temps de maintenir le risque de sismicité induite à un niveau qui soit acceptable pour la société.

Besoins et perspectives de progrès technologiques

Même si la faisabilité de la technique fondamentale est démontrée, une série de developpements technologiques est encore nécessaire pour que les systèmes pétrothermaux puissent être utilisés sur le long terme et pour qu'un équilibre puisse être trouvé entre utilité pour la société, protection de l'environnement, rentabilité et création de valeur. D'une façon générale, aucune technologie d'exploration n'a encore été utilisée en Suisse sur le plan régional. C'est pourquoi jusqu'à présent, nul n'a encore démontré de manière systématique quelles ressources doivent être classées comme étant des réserves. La technologie de forage employée en géothermie a été (et continue à être) principalement empruntée au secteur de l'extraction de pétrole et de gaz naturel et est considérée à bien des égards comme étant arrivée à maturité, quoique le développement du secteur pétrolier et gazier bénéficie encore d'un puissant moteur de développement. Les forages représentent, et de loin, la principale composante en termes de coûts dans la création d'un réservoir géothermique, de sorte qu'une réduction des coûts de forage influe sensiblement sur la faisabilité économique des projets de géothermie. Le niveau élevé des coûts est dû, d'une part, au fait que des recherches doivent encore être menées sur des méthodes de forage rapides et précises et, d'autre part, à l'absence en Suisse de normes et d'expérience en la matière. Les coûts de la stimulation hydraulique représentent une faible part des coûts généraux, mais ici aussi, des améliorations peuvent influer fortement sur le débit des fluides et sur la durée d'utilisation des puits de forage. De même, la profondeur pouvant être atteinte et la fiabilité des pompes de sondage sont des domaines de recherche importants. La technologie de production d'électricité utilisée dans les installations pétrothermales en surface est généralement considérée comme étant parvenue à maturité. Néanmoins, des améliorations progressives permettraient d'augmenter encore le rendement et d'optimiser la construction en vue d'une production combinée d'électricité et de chaleur. Le principal défi dans le recours aux systèmes pétrothermaux en Suisse et ailleurs dans le monde réside dans la maîtrise de la création d'un échangeur de chaleur en sous-sol et dans le contrôle de la sismicité qui l'accompagne.

Au vu des possibilités apparemment limitées de valoriser des ressources hydrothermales en Suisse (autrement dit, la capacité à trouver et exploiter des aquifères ou des formations recelant d'importants volumes d'eau mobilisable), la géothermie ne représentera une part significative de la production d'électricité que si on apporte une réponse aux défis de la technologie SGS sur le plan géophysique. La priorité de la production d'électricité par la géothermie profonde ne devrait cependant pas faire perdre de vue la possibilité de valoriser les ressources proches de la surface en vue d'une utilisation directe (p. ex. pour couvrir un besoin en chauffage de ménages ou d'exploitations industrielles, dans l'agriculture ou l'aquaculture). Les températures nécessaires à cet effet, de 60 °C et plus, se trouvent dans les sites favorables déjà à des profondeurs de 1,5 km, voire moins. Une exploration de ces réservoirs permettrait d'accroître encore les ressources de chaleur géothermale probables ou prouvées en Suisse.

Rentabilité

L'analyse de rentabilité de la géothermie montre que les coûts moyens de production d'électricité peuvent fluctuer fortement en fonction d'une série de facteurs. Or, de grandes incertitudes entourent quelques-uns de ces facteurs, notamment le coût lié aux puits de forage et la durée d'utilisation du réservoir. Les coûts moyens de production d'électricité en Suisse, soit 35 cts/kWh, servent de référence, même si la fourchette de fluctuation entre les valeurs les plus faibles et les plus élevées va, pour la Suisse, de 18 à 61 cts/kWh. Les coûts liés aux puits de forage demeurent la composante principale en matière de coûts, et en même temps l'élément du calcul le plus aléatoire. Doivent être pris en compte non seulement les coûts de forage des puits, mais aussi le nombre de puits nécessaire pour l'exploration, la confirmation et l'extraction, ainsi que la durée d'utilisation avant que de nouveaux puits ne doivent être creusés. Il existe encore une marge de manœuvre considérable pour réduire progressivement les coûts de forage conventionnels, avant que de nouvelles technologies de forage révolutionnaires permettent d'atteindre une nouvelle réduction notable des coûts. Une éventuelle vente de la chaleur dégagée aurait un impact sensible et avéré sur les coûts moyens. Le prix moyen pour la valeur de référence baisserait ainsi de 35 à 14 cts/kWh. Une analyse par secteur pour le marché potentiel du chauffage à distance montre quant à elle qu'en exploitant pleinement le potentiel d'ici à 2050 et en couvrant intégralement les besoins par la chaleur résiduelle issue de la production d'électricité par géothermie, ce bonus généré par les rejets thermiques permettrait une baisse de coût sur un volume de courant d'un peu plus de 5 TWh. L'utilité évidente sur le plan économique de la vente de la chaleur résiduelle crée cependant un champ de tension entre l'exigence d'une proximité géographique avec les consommateurs de chaleur et une distance souhaitée par rapports aux habitants, pour lesquels la sismicité induite, le bruit et l'impact sur le paysage pourraient être des thèmes sensibles et susciter des réactions négatives. Selon l'état actuel de la technique, les coûts de production sont tels que le courant électrique issu de la géothermie coûte entre trois et cinq fois trop cher au consommateur suisse. La vente de la chaleur résiduelle ne perdrait de son importance que si les coûts liés aux puits de forage pouvaient être sensiblement réduits. Reste que même si le courant électrique issu de la géothermie ne suffit pas à lui seul à couvrir le potentiel du marché pour le chauffage à distance, le marché de la chaleur utilisée pour le chauffage est suffisamment vaste pour permettre des étapes d'apprentissage aboutissant à une réduction des coûts de la géothermie. Un chemin crédible vers la viabilité commerciale est amorcé dès lors que les défis technologiques, pratiques et en matière de sécurité peuvent être surmontés.

Bilan environnemental

L'impact sur l'environnement de la géothermie profonde en Suisse a été évalué à l'aide d'une analyse du cycle de vie (ACV). Cette méthode se réfère toutefois uniquement à l'exploitation normale et ne tient pas compte des éventuels incidents, qui devraient être évalués à part. Les indicateurs pris en compte dans le bilan écologique sont notamment les suivants: le changement climatique, la toxicité pour l'homme, la production de particules fines, le rayonnement ionisant, la consommation d'eau et de métal. Les répercussions sur l'environnement de la production d'électricité par la géothermie sont moindres ou équivalentes à celles d'autres énergies renouvelables envisagées pour le mix énergétique de la Suisse à l'avenir ; cela reste d'ailleurs valable même si on tient compte des incertitudes relativement marquées de certains paramètres pris en compte dans le calcul du bilan des futures installations de géothermie. Ainsi, les émissions de gaz à effet de serre sont estimées, en fonction de paramètres techniques et d'exploitation, entre 8 et 46 g d'équivalent CO_2 par kWh. La production d'électricité par géothermie se fait donc pratiquement sans émission de CO_2. La phase de forage influe le plus sur le bilan écologique global. Les installations en surface, le choix du fluide de travail et la stimulation du réservoir ne jouent qu'un rôle secondaire en ce qui concerne la plupart des critères environnementaux. Au vu des objectifs de politique environnementale et en particulier de la protection du climat, la géothermie devrait donc être définitivement prise en compte en tant que source d'énergie dans le mix d'électricité à l'avenir.

Incertitudes, risques et potentiels de limitation des risques

Le volume des ressources géothermales à lui seul offre des opportunités considérables pour la production d'électricité et de chaleur. Cependant, leur valorisation est sujette à des facteurs limitatifs importants. Les lacunes notables dans l'exploration des formations en profondeur en Suisse, en particulier, compliquent l'identification des ressources hydrothermales. Grâce à une série d'initiatives de parlementaires suisses, des décisions politiques visant à remédier à cet état de fait ont d'ores et déjà été prises. Malheureusement, la technique d'exploration utilisée actuellement ne permet pas encore de prédire la perméabilité et les contraintes tectoniques d'une roche plutonique et son utilité dans un contexte de la géothermie est de ce fait limitée. La technologie de valorisation des ressources hydrothermales est, quant à elle, parvenue à maturité. Par conséquent, dès qu'on arrive à identifier des gisements correspondants, ceux-ci peuvent être exploités, si les conditions environnementales et le pouvoir de surveillance le permettent.

Par contre, les procédures SGS pour les systèmes pétrothermaux ne sont pas encore parvenues à maturité, loin s'en faut, et un programme de recherche fondamentale est nécessaire avant qu'une application à grande échelle ne soit possible. Au cours des quatre dernières décennies, plusieurs prototypes complets de systèmes ont été élaborés, qui impliquaient différents scénarios géologiques et ont apporté des preuves encourageantes de la faisabilité du concept. Cependant, la construction d'un échangeur de chaleur de taille suffisante (avec un intervalle entre les puits de forage supérieur à 500 m), remplissant les conditions d'un débit de fluide suffisant sur le plan commercial, s'est avérée compliquée jusqu'à présent, à moins que des formations hautement perméables dans la zone cible de la roche (autrement dit les failles et les anfractuosités) soient déjà disponibles, comme c'était le cas notamment sur le site SGS de Soultz-sous-Forêts en France. Grâce aux projets mentionnés ci-dessus, on sait désormais qu'il n'y a pas deux formations rocheuses identiques et que, de ce fait, il faut « travailler » avec la formation à disposition pour créer un échangeur de chaleur au moyen d'innombrables liaisons hydrauliques entre les puits de forage. Pour les systèmes commerciaux ayant une durée d'utilisation de quelques dizaines d'années, les puits de forage devraient être éloignés les uns des autres d'au moins 500 m. Ce faisant, le flux net entre eux devrait parcourir une zone de fracturation de plusieurs kilomètres carrés avec un volume de roche de l'ordre de 0,1 à 0,2 km^3.

Un autre aspect dans le développement de la géothermie profonde est le risque que des secousses sismiques pouvant être ressenties par la population locale soient déclenchées. Les expériences faites à ce jour en Suisse montrent que celles-ci peuvent se produire avec les systèmes aussi bien pétrothermaux qu'hydrothermaux. Une chose est claire: le sous-sol doit être valorisé de manière à ce que le risque sismique demeure aussi faible que possible pour l'homme, l'environnement et les biens matériels. Dans le débat sur les processus SGS, la gestion de la sismicité induite pendant la construction de l'échangeur de chaleur et au cours de la période d'exploitation qui s'ensuit, d'une durée de 20 à 30 ans, compte autant que la capacité de créer un réseau de failles à même de fournir de l'eau chaude pendant des décennies. La question de savoir comment offrir une protection et des garanties d'assurance adaptées contre les risques sismiques pourrait avoir des répercussions considérables sur la rentabilité de la géothermie en tant que source d'énergie.

En plus des risques sismiques marqués, il existe une série de risques habituels liés à l'exploitation, p. ex. en raison des fluides de travail nocifs ou des dangers liés au forage, qui n'ont rien d'inhabituel dans l'industrie pétrolière, gazière ou minière. Ces risques devraient être gérés par une réglementation et une pratique d'exploitation appropriées, répondant à des normes rigoureuses pour la branche et soumises à une stricte surveillance. La présente étude s'est également intéressée au danger d'incidents lié aux éruptions (blowouts) et à une sélection de substances dangereuses. A cet égard, les valeurs de risque mesurées pour différentes catégories (p. ex. nombre de victimes) sont faibles, mais non négligeables. Le danger des éruptions représente un risque accru pour la santé humaine, tandis que la libération de substances chimiques dangereuses fait craindre avant tout des conséquences pour l'environnement.

Des analyses de sensibilité plus détaillées, qui mettent en lumière les facteurs de coûts essentiels dans le développement des projets, montrent qu'une standardisation des pratiques de forage pourrait permettre de réduire sensiblement les coûts. Cela deviendra possible dès qu'un plus grand bagage d'expériences dans la création de puits de forage pour la géothermie profonde aura été constitué. Le développement de méthodes rentables pour l'installation de l'échangeur de chaleur souterrain est également une condition préalable pour assurer la faisabilité économique. Un autre domaine de recherche important s'intéresse à la manière d'optimiser la configuration et la géométrie de l'échangeur de chaleur pour obtenir une circulation maximale des fluides sans pénétration rapide d'eau froide dans les puits de production. Les risques économiques peuvent être encore atténués en créant des opportunités de vente de la chaleur résiduelle. Cela créerait des marges de manœuvre significatives pour la rentabilité des projets et une incitation majeure pour encourager les investisseurs du domaine privé à miser sur le secteur de la géothermie et son évolution. Un autre levier pour le développement d'une branche de la géothermie à l'échelle de la Suisse serait un système national de données sur la géothermie, qui centraliserait les données sur les ressources et leur utilisation, les conditions d'exploitation et les exigences en matière de protection de l'environnement, les réglementations et les normes, les besoins en électricité et en chaleur des clients finaux, ainsi que l'infrastructure d'approvisionnement correspondante.

Aspects juridiques

Le cadre légal et de surveillance actuel des différents cantons suisses ne constitue pas en soi un obstacle pour le développement de la géothermie. Un transfert de la compétence légale et de surveillance à une autorité fédérale semble certes intéressant au premier abord et pourrait permettre d'accélérer sensiblement la valorisation de la géothermie, mais il ne semble guère pouvoir être imposé sur le plan politique. Il existe des lois et des procédures juridiques cantonales portant sur l'utilisation du sous-sol qui permettent la valorisation des ressources géothermiques, même si elles ne sont que rarement conçues dans l'optique de la géothermie. Un permis d'exploration pour la recherche de ressources géothermiques octroyé par les autorités cantonales ne donne pas automatiquement droit par la suite à une concession d'utilisation permettant d'exploiter les ressources géothermiques ainsi trouvées. Le titulaire d'un permis d'exploration, qui a investi dans l'exploration et effectivement réussi dans sa quête, est dès lors désavantagé. De même, dans certains cantons, il n'est pas clairement défini si l'attribution d'une autorisation d'utilisation ou d'une concession peut uniquement se faire dans le cadre d'un appel d'offres public. Quelques cantons s'inspirent certes des « principes de coordination » de la Confédération, qui visent à garantir une certaine uniformité de la demande de bon nombre d'autorisations auprès de différentes autorités. Mais rares sont les cantons qui ont appliqué le « modèle de la concentration ». Celui-ci prévoit qu'une autorité cantonale coordonne et simplifie l'ensemble du processus d'autorisation avec toutes les autres autorités compétentes et qu'en fin de compte, les autorisations sont octroyées de manière groupée. Un facteur clé pour la valorisation du sous-sol d'une façon générale et pour la géothermie en particulier est l'intégration du sous-sol dans les plans structurels et les plans directeurs cantonaux, qui représentent des instruments essentiels des autorités cantonales pour l'aménagement du territoire à la surface et dans les secteurs du sous-sol qui doivent renfermer des sources d'énergie géothermales. En 2014, une série d'initiatives de la Confédération et du Conseil national ont été mises en route afin de créer un cadre juridique pour une accélération de la procédure d'autorisation. Ce faisant, il convient d'examiner attentivement les droits de souveraineté cantonaux et notamment les conséquences inattendues d'une émission excessive de réglementations dérogatoires par rapport aux plans directeurs. Plusieurs cantons ont édicté différentes prescriptions et réglementations concernant l'exploration et la valorisation des ressources par la géothermie profonde. Le recours à des pratiques qui ont fait leurs preuves est considéré comme une voie avantageuse et décisive pour définir un cadre légal optimal. La Confédération ne dispose certes pas de compétences centrales pour réglementer la géothermie en tant que source d'énergie. Cependant, il lui revient naturellement, par le conseil et par la mise en place d'une plateforme fédérale à titre de mesure de soutien (sans compétence légale), d'édicter une sorte de législation « molle » et, ainsi, de se tenir activement aux côtés des cantons dans la mise en œuvre de leurs mesures, ordonnances et directives respectives.

Opinion publique et perception du risque

L'acceptation par la société de la géothermie profonde dépend pour beaucoup de la perception qu'en a l'opinion publique. L'analyse de données provenant de groupes de travail au sein de la société, des médias sociaux et d'articles de journaux permet de déduire des arguments quant au contenu, qui sont regroupés en tableaux de données *(data frames)*. Un tableau de ce type se concentre par exemple sur des arguments liés à la stratégie énergétique de la Suisse: « La géothermie profonde pourrait contribuer à la mise en œuvre de la stratégie énergétique de la Suisse », ou: « La géothermie profonde n'est pas une option réaliste ». Un deuxième tableau concerne les risques: D'une part, les impondérables et les risques sont mis en lumière. D'autre part, la perception qui prévaut est que les risques sont maîtrisables. Un troisième tableau traite de la technologie, qui d'un côté est qualifiée d'utile et de porteuse d'avenir et, de l'autre, est dépeinte comme problématique et vouée à l'échec. Enfin, un quatrième tableau porte sur la question des coûts: la géothermie est-elle abordable ou la facture est-elle trop élevée? Bien des choses laissent à penser que la perception du public est sujette à des fluctuations considérables, car nombreux sont les indécis. La phase de développement précoce de la géothermie, malgré un écho relativement fort dans le public lors des projets réalisés à St-Gall (2013) et à Bâle (2006/2007), n'a pas débouché sur un point de vue univoque au sein de l'opinion publique. Les activités souterraines sont souvent associées à des représentations telles qu'une « ingérence dans la nature », un tremblement de terre très destructeur, certes extrêmement improbable, ou à des installations techniques dans le champ visuel (hauts échafaudages des tours de forage). La communication au sujet de la gestion complexe de la profondeur « invisible » repose sur un savoir d'experts hautement abstrait, qui est difficile à transmettre à des profanes. En raison de leur fort dynamisme et de la manière dont ils utilisent les arguments, les médias sociaux et les contributions dans les médias traditionnels peuvent servir de signaux d'alerte précoce d'un repli de l'opinion publique. Jusqu'à présent, les réseaux sociaux ne se sont guère intéressés à la géothermie profonde (même après l'épisode de St-Gall). Lorsque le sujet y est abordé, l'état d'esprit de l'opinion publique suisse vis-à-vis de la géothermie profonde va de plutôt neutre à positif.

L'industrie et le monde scientifique ont un rôle particulier à jouer dans le débat public. L'industrie, en tant que partie prenante, souligne actuellement le potentiel, tandis que les milieux scientifiques mettent en avant les risques et les incertitudes. Dans les deux groupes, un point de vue équilibré serait utile pour la communication: l'industrie pourrait aborder activement les risques et les impondérables, tandis que les scientifiques pourraient mettre également l'accent sur des stratégies possibles ou existantes visant à réduire les risques.

Intégration de l'environnement, de la rentabilité, des risques et de la sécurité de l'approvisionnement

Dans le cadre de l'analyse d'intégration, une analyse multicritère d'aide à la décision d'envergure limitée a été réalisée. Une analyse multicritère fournit des indicateurs agrégés pour comparer les différentes sources d'énergie alternatives selon des critères écologiques, économiques, sociaux et en matière de sécurité de l'approvisionnement ; dans le même temps, les préférences des différents groupes d'intérêts sont prises en compte. Elle aide à prendre une décision en connaissance de cause et peut offrir des points de repère lors de débats publics et de processus participatifs. L'analyse multicritère montre certes les points forts et les faiblesses relatifs des différentes alternatives, mais ne dresse pas de classement définitif des technologies. L'analyse multicritère met plutôt en exergue la sensibilité du classement en raison des préférences subjectives des différents groupes d'intérêts. L'analyse a inclus les principales nouvelles énergies renouvelables qui revêtent un intérêt pour la Suisse (notamment l'énergie photovoltaïque, l'énergie éolienne et le biogaz), tout en se limitant aux technologies actuellement disponibles.

D'une façon générale, l'analyse multicritère réalisée dans le cadre de la présente étude confirme que les systèmes géothermaux qui combinent production d'énergie et de chaleur sont bien mieux accueillis qu'une installation géothermale ne produisant que de l'électricité. Si on considère un profil de préférences avec une pondération équilibrée des critères de durabilité fondamentaux en mettant l'accent sur la protection du climat, la minimisation de la toxicité pour l'homme, la consommation de métal et les risques (sans inclure la sismicité induite), ainsi que la sécurité de l'approvisionnement, la géothermie arrive en tête dans l'aperçu général. Un profil de préférences avec une pondération équilibrée des critères de durabilité fondamentaux mettant l'accent sur la consommation d'eau et la sismicité induite se révèle quant à lui peu avantageux pour la géothermie.

Sélection de recommandations

L'étude comprend un nombre relativement élevé de recommandations destinées aux milieux politiques et scientifiques. Les principales recommandations sont résumées ci-dessous:

- L'attention des décideurs et des groupes d'intérêts devrait être portée sur le rôle potentiellement important de la géothermie dans un approvisionnement électrique de plus en plus décentralisé avec une part importante d'énergies renouvelables qui ne sont disponibles que sur une base temporaire. La géothermie représente dans ce contexte une des rares options renouvelables « nouvelles » qui entrent en ligne de compte sur le marché de l'électricité pour la charge de base et pourraient donc contribuer de façon essentielle à la sécurité de l'approvisionnement. Le rôle futur potentiel de la géothermie en Suisse doit donc être représenté dans le contexte du système d'approvisionnement énergétique dans son ensemble.
- Le courant électrique issu des installations de géothermie profonde affiche, dans des conditions d'exploitation normales, un bilan écologique favorable. Du point de vue de la préservation de l'environnement et en particulier de la protection du climat, la géothermie pourrait apporter une contribution attrayante au mix énergétique de la Suisse à l'avenir et mérite donc d'être sérieusement envisagée.

- Il est toutefois nécessaire de continuer à encourager la production géothermique, afin d'étendre le marché. Ainsi, des entreprises seront incitées à renforcer leurs efforts de recherche et de développement en vue de procéder à des forages géothermiques, ce qui contribuera à réduire les risques et les coûts de la production d'électricité par géothermie. Des domaines d'intervention possibles, outre les garanties actuelles contre les risques et la rétribution du courant injecté, pourraient être la prospection et l'identification de sources de chaleur, ainsi que le develop-pement de technologies et des projets de démonstration.
- Etant donné l'incertitude notable quant aux réserves géothermiques potentielles de la Suisse, une initiative de recherche étendue axée sur l'utilisation en lien avec un programme constitué de projets pilotes et de démonstration est nécessaire pour permettre la construction d'un système pétrothermal qui remplisse les exigences commerciales en matière de performance.
- Si les sites recelant un potentiel géologique s'unissaient pour former un modèle économique tenant compte de la réglementation politique, des demandes de la population (par rapport à la sismicité) et des marchés de la chaleur dans le cadre du SIG, cela représenterait un progrès considérable. Les coûts de la production d'électricité géothermique pourraient ainsi être mieux calculés et on pourrait représenter où se trouvent les sites dotés du plus fort potentiel, compte tenu de tous les facteurs.
- Les risques sismiques peuvent être évalués et contrôlés, mais pas éliminés. Le taux de réussite et la faisabilité économique de la géothermie profonde dépendent essentiellement du risque sismique que les différents groupes d'intérêts sont disposés à courir. Dans ce contexte, la société doit analyser et décider quel niveau de risque lui paraît acceptable.
- La recherche et la capacité à prédire la sismicité induite ont considérablement progressé ces dernières années grâce à des projets financés par la communauté scientifique et les milieux industriels. Ces efforts doivent être poursuivis ces prochaines années. Le besoin le plus pressant se situe dans la validation de nouveaux outils de modélisation et de stratégies de réduction des risques. Les projets pilotes et de démonstration à venir joueront un rôle essentiel à cet égard. S'y ajoute le fait que bon nombre des procédés liés à la sismicité induite ne varient pas et peuvent aussi faire l'objet de recherches dans de petits laboratoires souterrains. Pour savoir comment former efficacement un réservoir tout en limitant les risques de séisme, une recherche multidisciplinaire est nécessaire, qui implique les sciences de la terre, des disciplines techniques et l'informatique.
- En Suisse, l'utilisation du sous-sol est réglementée par les cantons, ce qui ne va pas sans poser un certain nombre de difficultés aux exploitants potentiels d'installations géothermiques. Un cadre réglementaire homogène (p. ex. un modèle de la concentration) ou un centre de compétences de la Confédération pourrait contribuer à simplifier et à accélérer les procédures dans ce domaine. Le rôle futur potentiel de la géothermie en Suisse doit donc être représenté dans le contexte du système d'approvisionnement énergétique dans son ensemble.
- Quelques cantons ont développé un modèle de la concentration dans lequel une autorité coordonne le contenu des différentes autorisations et les octroie de façon

groupée. Dans ce modèle, en même temps que la décision d'attribution d'une concession, toutes les autorisations et décisions des autres autorités sont également accordées. Cette solution est efficace et pratique. Lors de l'examen d'une demande de concession, généralement de nombreuses questions doivent de toute manière être examinées, lesquelles sont également pertinentes pour les autres autorisations. Un modèle de ce type permettrait d'accélérer les procédures et de simplifier la communication avec les destinataires des décisions.

- De manière générale, il incombe aux cantons de réglementer l'utilisation du sous-sol. Ce faisant, les aspects suivants doivent être réglés: les compétences, les types d'utilisation, les expropriations, les autorisations d'utilisation, les étapes de procédure, les ressources humaines et matérielles, la responsabilité, les interactions avec les autres autorisations, les émoluments, l'exécution et la sécurité juridique.
- L'ensemble du processus de planification, de choix du site et de mise en œuvre de projets de géothermie doit être étroitement accompagné par une implication de tous les groupes d'intérêts et de l'opinion publique qui soit soigneusement planifiée, surveillée en continu et évaluée avec précision. L'identification des sites sur la base de critères sociaux (tenant compte des exigences particulières et en collaboration avec les communes) pourrait compléter la définition technique de sites lors de futurs projets (pilotes).

L'intérêt des médias dépend principalement d'événements spectaculaires, qui recèlent une valeur informative, tels que les tremblements de terre. La perception de la géothermie peut ainsi être influencée et l'attention du public portée sur des arguments négatifs. Les projets de géothermie profonde devraient donc inclure à un stade précoce l'aspect de la communication et de la participation de l'opinion publique. La communication devrait aborder de façon transparente et ouverte les opportunités et les défis, y compris les risques et les stratégies visant à les atténuer. Ce faisant, il est essentiel que les informations soient claires, aisément compréhensibles et équilibrées.

Sintesi propositiva

La geotermia si prospetta come fonte di approvvigionamento decentralizzato di energia di base e offre al contempo la possibilità di utilizzare il calore residuo per approvvigionare reti di teleriscaldamento e attività industriali. Nonostante l'elevato potenziale di risorse, attualmente in Svizzera non si utilizza ancora la geotermia di profondità per erogare energia elettrica agli utenti finali.

Contesto e obiettivi dello studio

La nuova politica energetica svizzera prevede un netto miglioramento dell'efficienza energetica, una consistente riduzione della quota dei combustibili fossili nell'approvvigionamento energetico e l'abbandono dell'energia atomica, il tutto da conciliarsi con obiettivi molto ambiziosi di tutela del clima. Ciò richiede necessariamente un impiego assai più massiccio di energie rinnovabili nella produzione di elettricità.

In questa prospettiva l'Ufficio federale dell'energia (UFE) stima che entro il 2050 la geotermia di profondità potrebbe fornire 4–5 TWh di energia elettrica l'anno, apportando un contributo sostanziale alla copertura del fabbisogno di elettricità complessivo che, per il 2050, si prevede di 60 TWh annui. La geotermia si prospetta una soluzione allettante per l'inesauribilità delle sue risorse, la disponibilità costante e sicura delle stesse sul territorio federale ed emissioni di CO_2 relativamente modeste. Ciò non toglie che il futuro contributo della geotermia di profondità sia ancora gravato da grandi incertezze, poiché in Svizzera questa nuova fonte di energia deve ancora affermarsi e conquistarsi fiducia.

Le opportunità a lungo termine dischiuse dall'impiego dell'energia geotermica offrono un forte stimolo alla ricerca di risposte alle seguenti domande: in che misura è utilizzabile questa risorsa e quali costi economici comporta? Quali esternalità deve essere disposta a sostenere la comunità in termini di ecologia e rischi? Come risulta nel complesso la geotermia al confronto con le fonti energetiche concorrenti? Sarà possibile istituire un quadro normativo e un clima di consenso sufficienti a consentire di coprire una parte fondamentale del fabbisogno energetico con la geotermia?

L'attuale progetto di TA-SWISS cerca di dare una risposta esauriente ed equilibrata a questi quesiti. L'approccio valutativo interdisciplinare permette di condurre un raffronto con altre tecnologie e agevola i vari gruppi di interesse nel processo decisionale. La soluzione energetica perfetta non esiste, ma un'indagine sui punti di forza e di debolezza della geotermia di profondità può fornire una prima indicazione strutturata sul ruolo che questa fonte di energia sarà in grado di svolgere all'interno del futuro mix energetico svizzero.

Focus, contenuto e organizzazione dello studio

Lo studio è incentrato sulla produzione di energia elettrica, sebbene evidenzi ove opportuno anche le potenzialità e l'importanza della produzione di energia termica. La prospettiva adottata è anzitutto quella della geotermia in Svizzera, ma i metodi impiegati e i risultati conseguiti sono di più ampio interesse.

Il valore primario del progetto risiede nella presentazione esaustiva dell'attuale stato di avanzamento della ricerca. Per alcune aree si è fatto ricorso al know-how dei partner e alle conoscenze di base disponibili (ad es. per quanto riguarda lo stato dei dati di fonte, dei dati tecnologici e della regolamentazione). Sono stati conseguiti nuovi risultati quantitativi in diversi settori e sono state prese in considerazione anche aree relativamente poco esplorate come la valutazione delle risorse svizzere, i fattori economici, l'ecologia, i rischi, il quadro normativo e il pubblico consenso, senza trascurare aree nodali dello stoccaggio energetico che richiedono ulteriori progressi tecnologici.

Lo studio affronta diversi temi, tra cui:

- analisi delle risorse,
- valutazione delle conoscenze raccolte dalla creazione di serbatoi in progetti petrotermali,
- analisi delle tecnologie di perforazione attuali e di nuova generazione,
- sviluppo e applicazione di un nuovo modello di calcolo dei costi,
- quantificazione degli impatti ambientali in base al Life Cycle Assessment (LCA) direttamente ancorato al modello di calcolo dei costi,
- valutazione dei rischi e delle esperienza raccolte nei sismi indotti,
- analisi di questioni normative e possibili spunti di soluzione,
- analisi della gestione del tema geotermia da parte dei media,
- studio degli atteggiamenti e delle posizioni assunti nei confronti della geotermia dai gruppi di interessi e dai cittadini svizzeri in un ampio contesto sociale e
- analisi multicriterio delimitata per scopo decisionale (MCDA) con raffronto delle tecnologie e mappatura dell'impatto delle preferenze dei gruppi di interesse.

Lo studio è valso da fondamento per le raccomandazioni ai soggetti politici e ulteriori ricerche.

È stato svolto da un consorzio di ricerca con ampie competenze multidisciplinari. Tra i partecipanti si annoverano il Paul Scherrer Institut (PSI; coordinamento dello studio), il Politecnico federale di Zurigo (ETHZ), la Scuola universitaria di scienze applicate di Zurigo (ZHAW) e l'Università di Stoccarda/Dialogik. Hanno contribuito al progetto oltre trenta ricercatori e ricercatrici degli istituti citati. Grazie allo studio è nato inoltre un fitto scambio con il neofondato Centro di competenze svizzero per l'approvvigionamento energetico SCCER (Swiss Competence Center on Supply of Electricity), da cui sono derivate sinergie per lo sviluppo in parallelo di una roadmap della geotermia di profondità per la Svizzera.

Opzioni tecnologiche di base

Le risorse geotermiche convenzionali (ossia idrotermali) si basano sulla combinazione di tre fattori:

- temperature elevate nel sottosuolo; l'odierna tecnologia energetica richiede valori non inferiori a 100 °C e, di conseguenza, profondità superiori a 3 km, poiché la temperatura aumenta all'aumentare della profondità,
- presenza di formazioni o strutture geologiche acquifere e
- sufficiente produzione di acqua calda per una produzione di energia elettrica economicamente accettabile e sostenibile in superficie.

Le esperienze attuali indicano che in Svizzera la concomitanza di questi tre fattori in un unico sito è rara. Pertanto è poco probabile che gli impianti idrotermali possano contribuire in modo sostanziale all'approvvigionamento elettrico.

Una forma alternativa di tecnologia per l'estrazione di calore dagli strati profondi e caldi delle rocce è rappresentata dai cosiddetti EGS (*Enhanced* o *Engineered Geothermal Systems*), conosciuti in area germanofona anche come "sistemi petrotermali". A differenza di quelli idrotermali, i sistemi di questo tipo non necessitano di serbatoi profondi di fluidi caldi. Si basano invece sulla realizzazione di uno scambiatore di calore tra due o più pozzi perforati nella massa interessata della roccia. Ciò avviene iniettando sotto pressione grandi quantità di acqua fredda negli strati profondi delle rocce per stimolare i serbatoi e migliorare la permeabilità della roccia tra i pozzi, affinché questi vengano collegati tra loro da numerose vie di scorrimento nell'ambito di un esteso volume roccioso. Il processo di aumento della permeabilità della roccia si è dimostrato efficace negli esperimenti sul campo, ma non è stato ancora compreso abbastanza da poterlo ottimizzare. Comprendere meglio tali processi e la loro dipendenza dalle condizioni geologiche nonché verificare la sismicità indotta collegata a tali operazioni sono le principali sfide da vincere per approdare a una tecnologia matura. Una volta installato lo scambiatore di calore, è possibile far circolare l'acqua in un circuito, estrarre il calore ivi contenuto e trasformarlo in energia elettrica negli impianti di superficie con l'ausilio di apposite tecnologie di conversione.

I sistemi EGS sono quindi il traguardo da raggiungere per poter sfruttare con efficacia e a lungo termine le fonti geotermiche svizzere, considerato l'enorme potenziale di tali risorse. Ma a causa di problemi tecnici irrisolti, i sistemi ESG non sono ancora considerati sufficientemente maturi per poter sopravvivere sul mercato. Eppure da quando fu sollevata la questione del rischio sismico in seguito alle scosse telluriche provocate dalla realizzazione del serbatoio per il progetto ESG di Basilea nel 2006 – scosse modeste, ma comunque percepite dalla popolazione locale –, lo sviluppo tecnologico è progredito in diversi Paesi come gli USA, l'Islanda, la Germania, la Francia e l'Australia.

Risorse e riserve

L'energia geotermica offre vantaggi peculiari che dischiudono un ampio raggio di possibilità. Per poter comprendere l'ordine di grandezza delle risorse geotermiche e il loro potenziale, è utile sapere che il fabbisogno energetico totale svizzero per il 2013 è stato di 896 Petajoule (896×10^{15} J).

La Svizzera dispone di immense fonti geotermiche. Nelle rocce site tra 3 e 10 km di profondità si presume che sia immagazzinata una quantità di calore dell'ordine di 10^{23} J, ovvero centomila volte maggiore del fabbisogno energetico svizzero del 2013, quanto meno ipotizzando che il serbatoio di calore in profondità venga costantemente rifornito. Il know-how raccolto grazie a ulteriori programmi esplorativi consentirà forse di convertire alcune delle risorse stimate in risorse quantificabili. Considerando inoltre i fattori d'incidenza che si ripercuotono direttamente sulla probabilità di sfruttamento commerciale (aspetti tecnici, economici, commerciali, giuridici, ecologici, di utilizzo del suolo, sociali e statali), le risorse quantificabili potranno divenire a propria volta risorse accertate. Tenendo conto di questi fattori d'incidenza nonché di ulteriori limitazioni legate a rischi tecnici e operativi, il potenziale presunto si riduce di vari ordini di grandezza.

Dunque anziché presupporre un potenziale che non sappiamo se potrà essere sfruttato entro il 2050, questo studio si concentra sull'analisi dei requisiti necessari a conseguire gli obiettivi fissati dalle strategie energetiche svizzere. L'obiettivo ivi contemplato di produrre 4–5 TWh di energia geotermica entro il 2050 potrà essere raggiunto solo se gli impianti saranno in grado di soddisfare determinati requisiti di spesa e capacità. Ciò dipenderà a sua volta da una ricognizione, una caratterizzazione e uno sfruttamento congrui delle fonti geotermiche; queste operazioni includono anche la capacità di costruire scambiatori di calore adatti, dotati di una portata e durata operativa sufficienti sotto l'aspetto commerciale, e la contemporanea gestione del rischio di sismicità indotta per portarla a un livello socialmente accettabile.

Necessità e prospettive del progresso tecnologico

Sebbene ne sia stata dimostrata la realizzabilità tecnica di principio, la tecnologia deve ancora compiere una serie di passi avanti affinché i sistemi EGS possano essere utilizzati in modo tanto sostenibile da instaurare un rapporto equilibrato tra benessere sociale, tutela del clima, generazione di profitti e di valore aggiunto. In Svizzera, in generale, non sono state finora impiegate tecnologie di esplorazione a livello regionale. Per questo motivo non è ancora stato possibile stabilire con indagini sistematiche quali risorse si possano considerare riserve vere e proprie. La tecnologia di perforazione impiegata nella geotermia è stata mutuata con adattamenti (e continua a esserlo) dall'industria del petrolio e del gas ed è considerata matura sotto molti aspetti, benché i citati settori di origine continuino a perseguirne energicamente lo sviluppo tecnologico. Il fattore di costo decisamente più gravoso nella creazione dei serbatoi geotermici è la perforazione: la riduzione di questa voce di spesa inciderebbe in modo consistente sulla sostenibilità economica dei progetti geotermici. L'elevato livello di spesa è dovuto in parte al fatto che i metodi rapidi per la perforazione di precisione non sono ancora stati sufficientemente studiati e in parte alla carenza di standard e di esperienza in Svizzera. Sebbene i costi di stimolazione idraulica rappresentino la parte minore del volume di spesa complessivo, miglioramenti su questo piano produrrebbero ritorni significativi in termini di portata e vita utile dei pozzi. Altrettanto importanti sono le ricerche su tematiche centrali come le profondità raggiungibili e l'affidabilità delle pompe di profondità. In generale la tecnologia di produzione di energia elettrica impiegata negli impianti EGS di superficie ha raggiunto uno stadio maturo, ma vi è ancora potenziale per incrementare gradualmente il rendimento termico nonché per ottimizzare la progettazione e l'operatività ai fini di produrre elettricità e calore con sistemi combinati. La più grande sfida che occorre vincere per impiegare i sistemi EGS in Svizzera e nel resto del mondo si prospetta nel creare uno scambiatore di calore nel sottosuolo e nel controllo della sismicità associata.

Poiché al momento le opportunità di sfruttare le fonti idrotermali svizzere (ossia di trovare falde acquifere o formazioni contenenti grandi quantità di acqua gravidica e accedervi) sono limitate, sarà possibile partecipare alla produzione di energia elettrica con una quota significativa di geotermia solo superando le difficoltà geologico-tecniche presentate dalla tecnologia EGS. Concentrare l'attenzione sulla produzione di energia elettrica mediante geotermia di profondità non deve tuttavia far perdere d'occhio la possibile fruizione di risorse più vicine alla superficie ai fini dello sfruttamento diretto (ad es. per la copertura del fabbisogno di calore nelle case e nelle industrie, nell'agricoltura e nell'acquacoltura). In siti favorevoli le temperature richieste di 60 °C e oltre sono ottenibili già a partire da 1,5 km di profondità. La prospezione di tali giacimenti accrescerebbe il numero delle fonti geotermiche di calore probabili e di quelle accertate nel territorio svizzero.

Rendimento economico

L'analisi delle performance economiche della geotermia dimostra che i costi medi di produzione dell'energia elettrica oscillano notevolmente in base a una serie di fattori, alcuni dei quali – come i costi di perforazione e la vita utile dei serbatoi – gravati da consistenti incertezze. Il valore medio di riferimento per il costo di produzione dell'energia elettrica in Svizzera è di 35 cent./kWh, con un'oscillazione positiva e negativa dei casi di riferimento compresa tra 18 e 61 cent./kWh. Le spese di perforazione rappresentano tuttora il fattore di costo di gran lunga predominante e, allo stesso tempo, più incerto. Oltre ai costi di esecuzione dei pozzi veri e propri, le spese comprendono anche i pozzi ausiliari necessari all'esplorazione, alla conferma e alla produzione dei pozzi effettivi e sono dipendenti dalla vita utile di questi ultimi, la cui vetustà richiede nuove perforazione. Vi sono ancora ampi margini per la riduzione graduale dei costi convenzionali di perforazione prima di dover ricorrere a nuove, rivoluzionarie tecnologie di perforazione per abbattere ulteriormente i costi. È dimostrato che l'eventuale vendita del calore residuo avrebbe una notevole ricaduta sui costi medi, il cui valore medio di riferimento scenderebbe da 35 a 14 cent./kWh. Un'analisi di settore del mercato potenziale del teleriscaldamento ha a sua volta dimostrato che se queste potenzialità venissero completamente sfruttate entro il 2050 e si raggiungesse una copertura totale del fabbisogno con il calore residuo di provenienza geotermica, si produrrebbe annualmente un quantitativo di energia elettrica di poco superiore a 5 TWh, godendo al contempo della riduzione dei costi consentita dal "bonus" del calore residuo. I chiari benefici economici procurati dalla vendita di detto calore generano tuttavia un conflitto fra la necessaria vicinanza fisica degli impianti ai mercati di cessione del calore e l'indesiderata prossimità degli stessi alla popolazione, sensibile alla sismicità indotta, al rumore e all'impatto paesaggistico. Allo stato attuale della tecnologia i costi di produzione sono ancora da tre a cinque volte troppo elevati per gli utenti svizzeri. La vendita del calore residuo perderà d'importanza solo se sarà possibile ridurre in modo significativo i costi dei pozzi. Ma anche se il mercato potenziale del teleriscaldamento non verrà coperto unicamente con l'energia elettrica geotermica, il mercato del riscaldamento è sufficientemente ampio da lasciar spazio a tentativi di riduzione dei costi geotermici. Una strada credibile per raggiungere la fattibilità commerciale può derivare soltanto dalla soluzione dei problemi tecnologici, ingegneristici e di sicurezza.

Valutazione ambientale

L'impatto ambientale della geotermia di profondità in Svizzera è stato valutato mediante un Life Cycle Assessment (LCA). Questo metodo, tuttavia, tiene in considerazione solo l'operatività normale, senza includere possibili casi di guasto che andrebbero valutati a parte. Tra gli indicatori considerati ai fini del bilancio ecologico sono compresi: cambiamento climatico, tossicità per le persone, formazione di particolato (polveri fini), radiazioni ionizzanti, consumo di acqua e metalli. L'impatto ambientale della produzione di energia elettrica tramite geotermia di profondità è di livello inferiore o equivalente a quello di altre nuove fonti rinnovabili prese in considerazione ai fini del futuro mix energetico svizzero; ciò vale anche tenendo conto dell'imponderabilità relativamente elevata di alcuni parametri considerati per stilare il bilancio dei futuri impianti geotermici.

Le emissioni di gas serra sono stimate tra 8 e 46 gr di CO_2 equivalente per kWh, a seconda che si utilizzino parametri tecnici o operativi. Ciò equivale a dire che l'elettricità geotermica è prodotta con emissioni praticamente nulle di CO_2. La fase di perforazione determina il maggiore impatto dell'intero bilancio ecologico. Gli impianti di superficie, la scelta del fluido vettore e la stimolazione dei serbatoi svolgono un ruolo subordinato nella maggioranza delle categorie di valutazione ecologica. Alla luce degli obiettivi di politica ambientale e segnatamente di tutela del clima, la geotermia deve quindi essere assolutamente tenuta in considerazione come fonte di energia all'interno del futuro mix energetico svizzero.

Incertezze, rischi e potenzialità di limitazione degli stessi

La vasta entità delle risorse geotermiche offre enormi opportunità per la produzione di energia e di calore, ma la loro fruizione è purtroppo soggetta a considerevoli fattori limitanti. L'individuazione delle fonti idrotermali è resa assai difficoltosa soprattutto dalla grave carenza di informazioni sul sottosuolo profondo svizzero, alla quale si sta già tentando di ovviare con decisioni politiche ottenute a seguito di una serie di iniziative del parlamento svizzero. Purtroppo le attuali tecniche esplorative non offrono la possibilità di prevedere la permeabilità e la pretensione tettonica del sottosuolo profondo, carenza che ne limita l'efficacia a scopi geotermici. La tecnologia per lo sviluppo dei sistemi idrotermali ha invece raggiunto lo stadio maturo. Quando dunque si identificano risorse adatte, queste possono essere sfruttate nel rispetto delle eventuali disposizioni ecologiche e di vigilanza.

Al contrario, le tecnologie richieste dai sistemi EGS non sono affatto mature e richiedono l'attuazione di un programma di ricerca di base prima di poter essere implementate su larga scala. Negli ultimi quarant'anni sono stati costruiti diversi prototipi di sistema in svariati scenari geologici, ottenendo prove di fattibilità incoraggianti. L'ostacolo più arduo si è invece rivelato essere la costruzione di uno scambiatore di calore sufficientemente grande (con una distanza tra i pozzi superiore a 500 m) che soddisfi i requisiti necessari a ottenere portate commerciali sostenibili senza ricorrere a strutture rocciose ad alta permeabilità preesistenti (ovvero fratture e fessure), come sono quelle del sito EGS di Soultz in Francia. Grazie ai progetti svolti in passato, si è capito che non esistono formazioni rocciose identiche e che quindi è necessario "lavorare" con quelle specifiche locali, creando uno scambiatore di calore tra i vari pozzi per mezzo di numerose connessioni idrauliche. Per ottenere impianti commerciali con una vita produttiva di decine di anni, i pozzi dovrebbero distare almeno 500 m l'uno dall'altro, collegati da una corrente netta equivalente a una frattura di diversi chilometri quadrati, ma contenuta in un volume roccioso di 0,1–0,2 km^3.

Nello sviluppo della geotermia di profondità va inoltre considerato il rischio di movimenti tellurici indotti percepibili dalla popolazione. Le esperienze sinora raccolte in Svizzera dimostrano che ciò può accadere sia con i sistemi EGS sia con quelli idrotermali. È evidente che il sottosuolo deve essere sfruttato in modo tale da contenere il rischio sismico per l'uomo, l'ambiente e le cose al livello più basso possibile, nei limiti della praticabilità. La capacità di controllare la sismicità indotta sia durante la creazione dello scambiatore di calore sia nel periodo operativo dei venti-trent'anni successivi è uno dei temi predominanti nella ricerca sulla tecnologia ESG, insieme a quello della creazione di una rete di fratture capaci di fornire acqua calda per decenni. Un'appropriata copertura assicurativa a fronte del rischio sismico potrebbe avere un impatto considerevole sulla redditività della geotermoelettricità.

Oltre ai notevoli rischi sismici, si rilevano una serie di rischi operativi più comuni come quelli rappresentati dai geofluidi nocivi e i pericoli connessi alle perforazioni, diffusi d'altronde anche nell'industria petrolifera, mineraria e del gas. Questi rischi dovrebbero essere gestiti con un'adeguata regolamentazione e prassi operative che sottostiano a severi standard di settore e vengano applicate con disposizioni di vigilanza tassative. Il presente studio ha inoltre affrontato temi quali i rischi di guasti dovuti a esplosioni e determinate sostanze nocive. Gli indicatori di rischio per varie categorie di conseguenze (ad es. incidenti mortali) sono ridotti ma non trascurabili. Il rischio di esplosione rappresenta un pericolo per la salute umana, mentre la fuoriuscita di sostanze nocive si ripercuote soprattutto sull'ambiente.

Dettagliate analisi di sensitività incentrate sui principali fattori di costo implicati dallo sviluppo del progetto indicano che la standardizzazione delle pratiche di perforazione potrebbe ridurre notevolmente i costi; sarà possibile attuarla con una maggiore esperienza nel campo della perforazione geotermica di profondità. Una condizione altrettanto importante ai fini della sostenibilità economica è lo sviluppo di metodi economicamente efficienti per installare scambiatori di calore in profondità.

Un ulteriore, fondamentale argomento di ricerca è la questione di come ottimizzare la progettazione e la geometria degli scambiatori di calore per ottenere la massima circolazione di fluido senza incorrere in brusche intrusioni di acqua fredda nei pozzi di produzione. I rischi economici possono essere ulteriormente ammortizzati creando opportunità di vendita del calore residuo. Ciò migliorerebbe notevolmente le prospettive economiche dei progetti e incentiva considerevolmente gli investitori privati a partecipare alle attività legate della geotermia e al suo sviluppo. Un'altra misura per incentivare lo sviluppo del settore geotermico in tutto il territorio svizzero sarebbe l'istituzione di una banca federale dei dati geotermici che gestisca a livello centralizzato i dati sulle fonti e il loro utilizzo, i vincoli aziendali e ambientali, i regolamenti e gli standard, il fabbisogno di elettricità e di calore dell'utenza finale così come le relative infrastrutture di approvvigionamento.

Aspetti legali

L'attuale quadro legislativo e di vigilanza dei singoli Cantoni svizzeri non rappresenta di per sé un ostacolo allo sviluppo della geotermia. A prima vista il trasferimento della competenza giuridica e di vigilanza a un'autorità federale può apparire auspicabile e potrebbe potenzialmente accelerare di molto l'accesso alle risorse geotermiche, ma non si ritiene realizzabile sul piano politico. Esistono leggi cantonali e procedimenti legali che regolano lo sfruttamento del sottosuolo e consentono la fruizione delle fonti geotermiche, sebbene siano raramente pensate per la geotermia.

La concessione emessa dalle autorità cantonali per effettuare prospezioni di fonti geotermiche non implica automaticamente il diritto alla concessione del permesso di sfruttamento delle risorse geotermiche rilevate. Ciò costituisce uno svantaggio per il titolare della concessione di prospezione che abbia investito nelle ricerche ricavandone dati positivi. Allo stesso modo in alcuni Cantoni non è ben chiaro se l'emissione di una concessione o autorizzazione allo sfruttamento debba avvenire solo tramite bando pubblico. Alcuni Cantoni fanno riferimento al cosiddetto “modello di concentrazione” della Confederazione che aspira ad assicurare una certa uniformità alla richiesta di varie concessioni a diversi enti. Ma solo pochissimi Cantoni hanno adottato tale modello, che prevede un'unica autorità cantonale preposta al coordinamento di tutti gli altri enti cantonali competenti ai fini del conferimento unitario delle concessioni, semplificando così la procedura. Per favorire lo sfruttamento del sottosuolo in generale e delle risorse geotermiche in particolare sarebbe inoltre utile includere il sottosuolo nei Piani strutturali e direttori cantonali; questi piani, infatti, costituiscono strumenti fondamentali gestiti dalle autorità cantonali per la pianificazione territoriale della superficie e di aree del sottosuolo in cui dovrebbero essere sfruttate le fonti di energia geotermica. Nel 2014 è stata avviata una serie di iniziative della Confederazione e del Consiglio nazionale allo scopo di creare condizioni giuridiche che accelerino la procedura di concessione. Tuttavia ciò deve essere affiancato da un'accurata valutazione incentrata sui diritti di sovranità cantonale e, ad esempio, sulle conseguenze indesiderate dell'eccessiva emissione di regolamenti in deroga ai Piani direttori. Diversi Cantoni hanno emesso varie disposizioni e regolamenti per la prospezione e lo sfruttamento delle fonti di geotermia di profondità. L'adozione delle pratiche che si rivelano efficaci è un metodo decisivo e poco costoso per l'istituzione di un quadro giuridico ottimale. È vero che la Confederazione non possiede competenze fondamentali per regolamentare la geotermia come fonte di energia, ma è praticamente l'organo predestinato a creare una legislazione “duttile” fornendo consulenza e costituendo una piattaforma federale di sostegno (senza competenze giuridiche) al fine di affiancare attivamente i Cantoni nel varo e nell'esecuzione delle relative misure, ordinanze e direttive.

Opinione pubblica e percezione del rischio

L'accettabilità sociale della geotermia di profondità dipende in buona misura dalla percezione pubblica di quest'ultima. Analizzando i dati raccolti nei focus group all'intero della società, nei socialmedia e dagli articoli di giornale è possibile ricavare determinati argomentazioni ricorrenti o cosiddetti frame. Uno dei frame comprende ad esempio argomentazioni legate alla strategia energetica svizzera: «La geotermia di profondità potrebbe offrire un contributo all'attuazione della strategia energetica svizzera», oppure: «La geotermia di profondità non è un'opzione realistica». Un secondo frame riguarda i rischi: da un lato si sottolineano i rischi e le imponderabilità, dall'altro la percezione di poterli tenere sotto controllo. Un terzo frame concerne invece la tecnologia, che da un lato è considerata utile e promettente, mentre dall'altro è ritenuta problematica e predestinata al fallimento. Infine il quarto frame ruota intorno alla questione dei costi: la geotermia è economicamente sostenibile o richiede esborsi eccessivi? I dati indicano che l'opinione pubblica è soggetta a forti oscillazioni, dovute al fatto che molte persone hanno atteggiamenti decisamente ambivalenti. Le prime fasi di sviluppo della geotermia non hanno concorso a un chiaro posizionamento dell'opinione pubblica, nonostante l'eco pubblica relativamente forte prodotta dai progetti di San Gallo (2013) e Basilea (2006/2007).

Le attività nel sottosuolo vengono spesso associate a idee come l'intromissione nella natura, all'eventualità, pur assai improbabile, di terremoti devastanti o all'impatto visivo degli impianti (per es. le alte impalcature delle torri di trivellazione). Trasmettere la complessità di gestione della “profondità invisibile” richiede competenze teoriche altamente astratte che risultano difficili da veicolare con chiarezza al pubblico dei non esperti.

Grazie alla loro natura molto dinamica e alle modalità con cui vi vengono trattati gli argomenti, i social media e i contribuiti nei canali di comunicazione tradizionali possono fungere da segnali precoci di ribaltamento dell'opinione pubblica. Finora i social media hanno sostanzialmente ignorato la geotermia di profondità (anche dopo il caso di San Gallo). Ogni qualvolta se ne dà notizia, l'opinione pubblica svizzera manifesta un atteggiamento da neutrale a positivo.

L'industria e la scienza occupano ruoli particolari nel discorso pubblico. Al momento l'industria sottolinea, in quanto gruppo di interesse, le potenzialità della geotermia, mentre la scienza ne mette in evidenza i rischi e le incertezze. Entrambi i gruppi trarrebbero maggior vantaggio se comunicassero un punto di vista più equilibrato: l'industria potrebbe far riferimento di propria iniziativa ai rischi e alle incertezze, mentre gli scienziati potrebbero dedicare qualche attenzione anche alle strategie (esistenti o possibili) di riduzione dei rischi.

Integrazione degli aspetti ambientali e economici, dei rischi e della sicurezza di approvvigionamento

Nell'ambito dell'analisi integrativa è stata condotta un'analisi multicriterio delimitata per scopo decisionale (MCDA). Essa fornisce cifre aggregate sulle prestazioni delle varie fonti alternative di energia tenendo conto di criteri ecologici, economici, sociali e di sicurezza di approvvigionamento, incrociati con le preferenze dei diversi gruppi di interesse. Questo tipo di indagine favorisce un processo decisionale responsabile e può fungere da orientamento nei dibattiti pubblici e nei processi partecipativi. La MCDA evidenzia i punti di forza e debolezza relativi delle varie alternative a confronto senza proporre una graduatoria conclusiva delle tecnologie. Essa evidenzia piuttosto la dipendenza della classifica stessa dalle preferenze soggettive dei vari gruppi di interesse. L'analisi ha considerato tutte le principali nuove energie rinnovabili di interesse per la Svizzera (compresa l'energia fotovoltaica, l'energia eolica e il biogas), limitandosi alle sole tecnologie disponibili.

In generale la MCDA condotta nell'ambito di questo studio conferma che i sistemi geotermali in grado di combinare produzione di energia elettrica e termica conseguono risultati nettamente migliori rispetto a quelli di sola produzione di elettricità tramite geotermia. Privilegiando il profilo preferenziale che pondera in modo equilibrato i principi fondamentali della sostenibilità, con particolare attenzione per la tutela del clima, la minimizzazione della tossicità per l'uomo, dello sfruttamento dei metalli e dei rischi (fatta eccezione per la sismicità indotta) e la sicurezza di approvvigionamento, la geotermia è la migliore classificata nel panorama generale. Il profilo preferenziale che pondera in modo equilibrato i principi fondamentali della sostenibilità ma pone l'accento sullo sfruttamento idrico e la sismicità indotta si dimostra al contrario sfavorevole per la geotermia.

Raccomandazioni selezionate

Lo studio comprende un numero relativamente ampio di raccomandazioni rivolte alla politica e alla scienza. Ecco un riassunto delle più importanti:

- Bisognerebbe spostare l'attenzione dei soggetti decisionali e dei gruppi di interesse sul ruolo potenzialmente importante che l'energia geotermica può svolgere in un approvvigionamento energetico sempre più decentralizzato, assicurato da una quota elevata di energie rinnovabili ma disponibili solo a intermittenza. La geotermia è infatti una delle poche "nuove" opzioni rinnovabili utilizzabili nel mercato dell'energia elettrica per la fornitura dell'energia elettrica di base, offrendo un contributo sostanziale in termini di sicurezza dell'approvvigionamento. Il potenziale ruolo della geotermia nel futuro deve quindi essere contestualizzato nel sistema globale di approvvigionamento energetico.

- L'elettricità prodotta da impianti geotermici di profondità presenta, in condizioni operative normali, un bilancio ambientale favorevole. Dal punto di vista ecologico e con particolare attenzione alla tutela del clima, la geotermia potrebbe fornire un contributo interessante al futuro mix energetico svizzero e merita quindi di essere presa seriamente in considerazione.
- Per ampliare il mercato è tuttavia necessario promuovere ulteriormente la produzione di energia geotermica. Le aziende saranno così motivate a intensificare gli sforzi nella ricerca e nello sviluppo indirizzati alla realizzazione dei pozzi geotermici, contribuendo a propria volta alla riduzione dei rischi e dei costi correlati alla produzione di energia geotermica. Oltre alle attuali garanzie contro i rischi e alle rimunerazione a copertura dei costi per l'immissione in rete di energia elettrica, le sovvenzioni potrebbero riguardare l'ulteriore individuazione e caratterizzazione di fonti di calore nonché lo sviluppo di tecnologie e di progetti dimostrativi.
- Data la considerevole insicurezza sulle potenziali riserve geotermiche in Svizzera, è auspicabile l'avvio di un'ampia iniziativa di ricerca orientata ad accertarne i vantaggi d'impiego, associata a un programma di progetti dimostrativi e pilota per permettere la costruzione di un sistema petrotermale che soddisfi i necessari requisiti commerciali.
- Sarebbe un notevole progresso se i siti dotati di potenziale geologico fossero riuniti insieme alla regolamentazione politica, alle esigenze della popolazione (in relazione alla sismicità) e ai mercati del calore in un modello economico implementato in un GIS (*Geographic Information System*). In questo modo potremmo calcolare meglio i costi di produzione dell'elettricità geotermica e individuare le aree a più alto potenziale tenendo conto di tutti i fattori.
- I rischi sismici possono essere valutati e controllati, ma non eliminati. Il grado di successo e di sostenibilità economica della geotermia di profondità dipende fortemente dal livello di rischio sismico che i vari gruppi di interesse sono disposti a sopportare. A tale riguardo la società deve valutare e scegliere il grado di rischio che ritiene accettabile.
- Negli ultimi anni la ricerca e la capacità di prevedere scosse sismiche indotte hanno fatto notevoli progressi grazie a progetti finanziati dalla comunità scientifica e dall'industria. Tali sforzi devono essere portati avanti anche negli anni a venire, con particolare attenzione alla validazione di nuovi strumenti di modellizzazione e di strategie di riduzione del rischio. Progetti dimostrativi e pilota rivestono un ruolo decisivo in questo senso. Inoltre molti dei processi rilevanti per la sismicità indotta sono caratterizzati da invarianza di scala e possono dunque essere studiati anche in piccoli laboratori sotterranei. Per risolvere il problema di creare serbatoi efficienti limitando i rischi sismici è necessario condurre una ricerca multidisciplinare che coinvolga le geoscienze, le discipline tecniche e l'informatica.
- In Svizzera lo sfruttamento del sottosuolo è regolamentato dai Cantoni. Ciò crea alcune difficoltà ai potenziali gestori di impianti geotermici. Un quadro normativo

omogeneo (ad es. un modello di concentrazione) o un centro di competenza federale potrebbero semplificare e accelerare il procedimento.

- Alcuni Cantoni hanno adottato un modello di concentrazione in cui un unico ufficio amministrativo coordina il contenuto delle varie concessioni ai fini del loro conferimento unitario. Nel modello menzionato la decisione di conferire una concessione comporta il rilascio di tutte le autorizzazioni e decisioni degli altri uffici competenti. Questa soluzione risulta essere efficiente e pratica. In genere evadere una richiesta di concessione richiede comunque di affrontare numerose questioni che riguardano anche altre autorizzazioni. L'adozione generalizzata di un simile modello velocizzerebbe le procedure e semplificherebbe la comunicazione con i destinatari delle decisioni.
- Spetta per principio ai Cantoni regolamentare lo sfruttamento del sottosuolo. Vanno regolamentati in particolare: responsabilità, tipi di sfruttamento, espropriazioni forzate, permessi di sfruttamento, procedure, risorse umane e materiali, garanzie, interazioni con altre concessioni, oneri, esecuzione e tutela legale.
- L'intero processo di pianificazione, localizzazione e realizzazione dei progetti di geotermia deve essere seguito con il coinvolgimento della società e di tutti i gruppi di interesse. Detto coinvolgimento va attentamente pianificato, costantemente monitorato e scrupolosamente valutato. La caratterizzazione dei siti in base a criteri sociali (in relazione a particolari necessità e in collaborazione con i comuni) potrebbe completare la caratterizzazione tecnica dei siti in futuri progetti (pilota).
- L'interesse dei media è perlopiù destato da eventi spettacolari adatti a fare notizia, come i terremoti. Ciò potrebbe influenzare l'opinione pubblica nei confronti della geotermia di profondità, focalizzando l'attenzione della gente sugli argomenti a sfavore. I progetti di geotermia di profondità dovrebbero perciò includere da subito la comunicazione e la partecipazione pubblica. La comunicazione dovrebbe essere trasparente e informare con franchezza tanto sulle opportunità quanto sulle difficoltà, inclusi i rischi e le strategie per ridurli. In questo è fondamentale divulgare informazioni in un linguaggio chiaro, comprensibile ed equilibrato.

Acknowledgements

The authors gratefully acknowledge the support of TA-SWISS to conduct this timely project. The study would not have been possible without Dr. Sergio Bellucci's conviction that its topic is important. Also, his contributions to the discussions were highly motivating and useful. Dr. Christina Tobler facilitated our work in many ways by organizing regular meetings, being very responsive, and providing constructive feedback and encouragement in the course of the project. At the beginning of the project we profited from the strong support from Dr. Emiliano Feresin. We also acknowledge the guidance and support in communication and dissemination matters provided by Ms. Christine D'Anna-Huber and Dr. Lucienne Rey.

The project team profited greatly from the interactions with the very broad multi-disciplinary experience of the members of the Project Advisory Borad (PAB), who generously shared their knowledge with us. We are particularly indebted to the Chairman of the SC, Dr. Gunter Siddiqi. He skilfully chaired the meetings and moderated the discussions, provided advice and many comments that helped us to substantially improve the quality of the report.

The authors of Chapter 6.2 would like to give their sincere thanks to Ernest L. Majer from Lawrence Berkeley National Laboratory, US for his contribution to Section 6.2.5.1, Christopher J. Bromley, GSN Science, NZ for his contribution to Section 6.2.5.2, Betina Bendall and Michael Malavazos from the Government of South Australia, AU for their contribution to Section 6.2.5.3, and Sigridur Kristjansdottir, Iceland GeoSurvey (ISOR), IS for her contribution to Section 6.2.5.4.

The authors of Chapter 8 are grateful to Prof. Dr. Ernst Huenges[1] and Prof. Dr. Stefan Wiemer[2] who provided expertise in the video interviews shown in the context of focus groups. We would like to thank all the participants who joined the focus groups, invested their time and were willing to express their opinion. Also, we very much appreciated the support of the local contact persons from Neuchâtel, Sursee, Riehen and Tiefencastel who helped to organize and conduct the focus groups. We are grateful for the valuable support of the student assistants Matthias Hoppe, Lisa Kastl and Leonie Steckermeier.

The project benefited from the support of the Swiss Federal Office of Energy (SFOE). Finally, the study would not have been possible without huge in-kind contributions by its authors and their home organizations.

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1. Introduction

Peter Burgherr, Stefan Hirschberg, Warren Schenler (PSI), Keith Evans (ETHZ)

1.1 Background

1.1.1 Why is a TA-SWISS study on the proposed topic needed?

Switzerland is facing a turn in its energy policy ("Energiewende") where nuclear power plants will be phased out at the end of their safe service lives, where new fossil generation potentially would add CO_2 emissions to an electricity mix that has been largely CO_2 free to date, where more conventional renewable, nearly CO_2-free energy resources are likely to be insufficient, and where it is uncertain that additional efficiency savings will be sufficient to counter increased electricity demand that is linked to economic growth and an increasingly electrified energy sector.

In this context, deep geothermal energy is a potential resource of both heat and electricity generation that is extremely large, nearly CO_2 free, domestically sourced and probably reliable. These advantages, and in particular the enormous potential scale of the resource, give great incentive to answer the questions – how much of this resource is available at what economic cost, what are the environmental and risk-related externalities that must be borne by the public, how do these multiple criteria compare to competing future energy resources, and will the regulatory framework and public acceptance exist to allow geothermal energy to provide a significant contribution?

The current TA-SWISS project is needed to answer these questions in a comprehensive and balanced way, using an interdisciplinary evaluation approach that facilitates comparison with other technologies and that will support stakeholder decision-making. There are no perfect energy solutions, but understanding deep geothermal's strengths and weaknesses will provide a first structured indication for the role it can play in the portfolio of solutions for the Swiss energy future.

Conventional geothermal (hydrothermal) resources require the presence of three principal factors; 1) sufficiently high temperatures in the subsurface, 2) the presence of hot water bearing geologic formations or structures and 3) a sufficiently high transmissivity or of the rock to enable the requisite production and re-injection rates of geothermal brines. The exploitation of such geothermal resources has historically proceeded (as with most resource extraction) from the highest quality and least common resources to lower quality and more common resources. This progression is shown in **Figure 1** below, which schematically shows the progression from dry steam to flash steam to binary cycle plants. In the rare case that dry steam is available from groundwater trapped below an impermeable geological cap layer, it is simply used in a turbine generator and reinjected. Lower quality hydrothermal aquifers may also be tapped, and the geothermal fluid or brine is flashed to steam, separated from the remaining fluid and similarly used in a turbine generator (there may be two separators to supply high and low pressure steam). If the resource quality is even lower, it is then usual to use a binary cycle plant. The hydrothermal fluid is used to boil an organic working fluid at a relatively low temperature, which is then used to drive the turbine generator. The working fluid is condensed and reused, and the geothermal brine is reinjected.

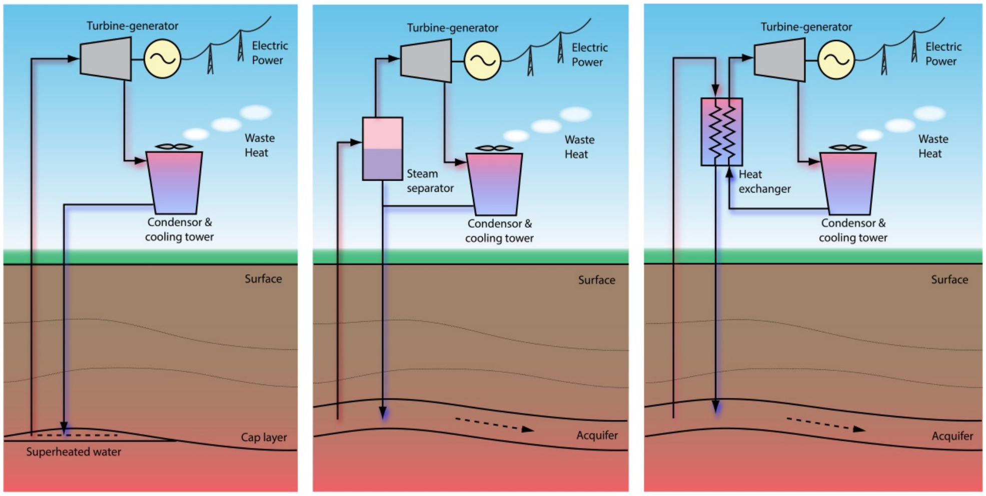

Figure 1: *Dry steam, flash steam and binary cycle hydrothermal plants.*

There is a great incentive to be able to site geothermal generation at locations where a hydrothermal resource is not available (i.e. to use a petrothermal resource). This is the reason that research and development has been actively pursuing Enhanced or Engineered Geothermal Systems (EGS), shown schematically below in **Figure 2**. Cold water is injected into the hot rock that has been fractured to provide a large heat exchange area. Cold water percolates through the engineered subsurface heat exchanger and extracts the heat stored in the solid rock mass. One or more production wells bring the heated water back to the surface. Although an EGS system could drive a flash-steam plant in the right conditions, it is more common to assume that a binary cycle plant will be used, as described above.

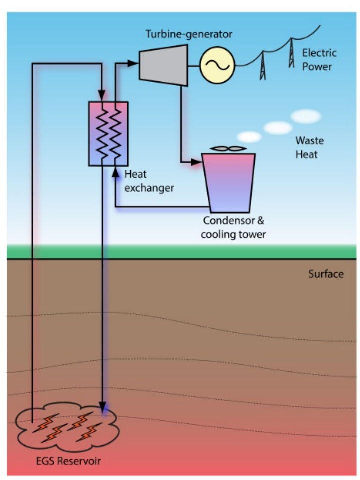

Figure 2: *Enhanced geothermal system binary plant.*

An EGS plant primarily only relies on one site dependent factor (high temperature at depth), and depends on technical and engineering techniques for reservoir stimulation to ensure reservoir size, fluid flow rates and reservoir life. EGS is perceived as a highly attractive option, and is the ultimate goal for the long-term (10−30 years) development of deep Swiss geothermal energy. But owing to operational and technical risks, EGS is not yet ready to be deployed in a competitive manner in the market place. Both hydrothermal and petrothermal resources are discussed in more depth in Chapter 1.5.

1.1.2 Integration of TA-SWISS project in Swiss research landscape

In September 2012, the Swiss Government approved the “Action Plan for Coordinated Energy Research”, with the goal of ensuring the Research and Development (R&D) required for the new Energy Strategy 2050. Among the actions to be financed in the Aktionsplan is the establishment of Swiss Competence Centers for Energy Research (SCCER). The list of SCCER priorities identified by the Swiss Government includes also Supply of Electricity, focusing on deep geothermal energy, Carbon Capture and Sequestration, and hydropower technologies and resources. The SCCER Supply of Electricity is led by ETH Zurich with PSI as one of the core partners, and initiated its activities at the end of 2013.

As part of its mandate, the SCCER Supply of Electricity will issue periodic reports on the availability of resources for electricity production at the global, European and Swiss scales. These evaluations will be upgraded with time to take into account the very rapid technological advances recorded and expected in different sectors of electricity production (e.g. the widespread diffusion of shale-gas extraction and its possible role in gas-fired power generation).

The TA-SWISS report on deep geothermal energy fits very well into this strategy, providing the starting point for future evaluations of the SCCER Supply of Electricity. The consortium of academic partners participating in the current project is at the core of the new SCCER Supply of Electricity, providing the necessary conditions of continuity and long-term prospects, to avoid duplications and contradictions among different activities and reports.

1.1.3 Significance of the topic

Just as the coming gap in electricity generation and the requirement for new capacity will be large, and the size of geothermal resource is great, so a proper technology assessment of geothermal power is both significant and needed. This significance can be appreciated by considering the following areas.

National Significance – Switzerland has for a long time had an electricity mix dominated by hydro and nuclear generation that is almost completely CO_2 free. In addition, Switzerland should reduce its overall CO_2 emissions relative to 1990 by at 80%−95 % by the year 2050 in order to meet the emission allowance set by Intergovernmental Panel on Climate Change (IPCC) (Climate Change 2007: Working Group III: Mitigation of Climate Change[3]), which reinforces the goal of avoiding CO_2 from new fossil generation unless mitigated via CCS. The

[3] See more details in Box 13.7 at
http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch13−ens13−3−3−3.html

size of the Swiss geothermal resource and the lack of CO_2 emissions therefore make geothermal generation very central for reaching this national goal. In addition, since Switzerland has had a tradition of self-sufficiency in electricity generation (at least on a net annual basis), the use of renewable and domestic geothermal resources is also essential for energy security. Many European countries are hoping to meet their future needs with imported power, but "not everyone can import," so a significant domestic resource cannot be discounted.

International Significance – Reductions in greenhouse gas emissions contribute to Switzerland's international commitments. Lower fossil fuel consumption leads to reduction of Switzerland's energy dependence and an increased balance of trade, particularly as imported natural gas is the most likely fuel for new thermal generation and may be subject to supply interruptions. However the international markets can also have significance for Switzerland since geothermal technologies, including drilling R&D, are generally driven by the much larger international oil and gas sector.

Technological Significance – It is not expected that this project will develop new geothermal technologies, but rather that it will highlight technological areas where new development exist or are especially possible/probable or significant in reducing costs or environmental impacts. If Swiss research institutes are active in these areas there may be possible international markets for developed expertise.

Economic Significance – The size of the geothermal resource is very large, but it is also highly variable in the various factors that affect the cost of production. It is therefore important to understand the relative contributions of these different factors, to be able to model the cost of geothermal power production under different conditions, and to combine the cost model with resource estimates to find the amount of energy available at different cost levels. This will allow an estimation of how significant geothermal power as an energy resource may be competing with both fossil and renewable future generation technologies.

Political Significance – Energy policies related to competing future generation technologies, cost of generation, CO_2 emissions, import dependence, etc. are all of significant political interest, and should be decided on a shared basis of factual analysis.

Social Significance – Public acceptance is of key importance for any new energy technology and geothermal power is no exception. The earthquakes triggered by the Basel project during its reservoir fracturing process and the incident during the drilling in St. Gallen dominated the public debate at the time, but overall public perceptions of geothermal power are probably subject to recovery based on its other characteristics. It is therefore important to see how the public views acceptable risk versus the other strengths and weaknesses of geothermal generation.

1.1.4 Prior state of knowledge and in particular aspects considered relevant to TA

Resources – The state of subsurface geothermal-petrophysical knowledge is inadequate, based solely on a scattered number of wells that have been drilled to different depths for a range of purposes, and data that has not been combined in any systematic way or under any common legal and regulatory regime. In general it is easier to interpolate temperature data to obtain thermal gradient information than it is to determine the localized permeability or potential for permeability enhancement (i.e. 'stimulatability') of potential reservoirs that are key to an economically attractive hydrothermal or petrothermal development. While an assumed national distribution of these properties will suffice for estimating a rough cost curve for available generation, it does not provide the specific data for siting individual plants.

Technology – The surface technology for a binary hydrothermal or petrothermal plant is relatively mature, and there is significant historical experience with hydrothermal generation. However for petrothermal plants, there has been limited experience in building prototypes. Underground heat exchangers have been successfully created, but none have so far met the requirements of scale and impedance of a commercial system. Whether such commercially viable subsurface heat exchangers can be routinely engineered remains to be demonstrated, and is one of the key questions.

Environment – Few studies on the life cycle impacts on environment and human health, i.e. life cycle assessment studies of geothermal power generation systems, are published. However, none of them integrates Swiss specific boundary conditions in terms of available heat resources, potential sites, etc., which would be relevant for an assessment in the Swiss context. Other environmental effects (H_2S and other non-condensable gas emissions, brine production, etc.) of existing geothermal steam and hydrothermal plants are basically avoided by reinjection of the geothermal fluid.

Economic – Geothermal cost models exist to estimate the levelized cost of electricity for geothermal generation, based on assumptions about well count, drilling costs, reservoir characteristics, plant cost, etc. (i.e. the United States Department of Energy Geothermal Electricity Technology Evaluation Model (US DOE GETEM) model, and models developed by PSI). Such models must be adapted to Swiss conditions, with assumptions for current and future cost factors.

Social – The positive social impression of geothermal power owes in large part to generally favorable views and attitudes resulting from a widespread diffusion of near-surface geo-thermal technologies, health aspects (spas) and sentimental connotations related to "Mother Earth." On the negative side are the implications of the induced seismicity due to the experience with the Basel and St. Gallen projects. A survey is needed to further extend and quantify this public opinion, but such a survey would also benefit from an educational component to help predict changes in public opinion as the relative strengths and weaknesses of geothermal power become more widely known.

1.1.5 Expected developments in the proposed research area

The need and potential market for geothermal power are expected to persist. It is expected that research and development trends in exploration, drilling, fracturing, etc. will continue to be adapted from the much larger oil and gas production sector. The most important developments would be the demonstration of a functional petrothermal Enhanced Geo-thermal System (EGS) plant with the successful creation of a large fractured heat exchanger at depth, and the possible demonstration of revolutionary drilling technology that would permit significant reductions in drilling costs. Other expected trends include performance improvements in exploration, downhole instrumentation, geotechnical computation and simulation, and incremental cost reductions in many areas.

1.2 Problem description

The present study of deep geothermal energy is aimed at the systematic collection and generation of relevant information about the Swiss geothermal resource and the strengths and weaknesses of the associated geothermal technologies. Ultimately this will allow a comparison with other future energy technologies, and thus provide a perspective on the relative role and scope that each may play in the future Swiss energy system.

1.2.1 Questions to be answered

The TA-SWISS Request for Proposal (RFP) gave a list of questions that the project should answer. The project team believes that in order to best answer these questions it is helpful to restate them with some different emphases, as below

Resource – The RFP asks whether there is sufficient reliable data to estimate the potential for deep geothermal energy, whether there is a sufficient exploitable resource, and whether there is any gap in resource knowledge and if so can it be overcome. The enormous scale of the gross thermal resource in situ means that in one sense it is possible to give an initial and automatic answer that yes, there is a sufficient, exploitable resource. But this leads to two related questions. The first is − What is the range of quality for the geothermal resource, and what are the related costs at which it can be produced? The second is – Is there sufficient information to identify the best locations to produce energy at the most economic costs? (subsequently paying attention to other siting factors). The knowledge gaps are most likely to be relevant in relation to these more specific questions.

Technology – The RFP asks what are the key technology challenges related to geothermal technologies and where is the need and possibility for improvement. As the RFP also notes, drilling costs are the dominant cost component for geothermal power (50–75%). The key technology challenges are therefore related to reducing average drilling costs. This means reducing the number of wells needed (including exploration wells), reducing actual drilling costs, and extending well life (fewer wells over the life of the plant). Fluid production and efficiency improvements also spread well costs over a larger amount of generation.

It is worth noting that the TA-SWISS request for technology assessment of deep geothermal power includes hydrothermal, petrothermal and geothermal heat probe (deep, single borehole heat exchanger) resources. However, it was felt that the greater emphasis in the project should be given to petrothermal development, since this has the greatest potential for power generation. Experiences to date indicate that the hydrothermal resource in Switzerland appears to be much more limited, due to the relative infrequency with which permeable, saturated formations or structures have been found at the depths, of sufficient hot water productivity and where temperatures are high enough to be of interest. The geothermal borehole heat exchanger approach of using a single well to produce high temperature process heat is a relatively lower risk approach as there is no need to develop a fractured heat exchanger. But this also severely limits the scope of the heat production and/or well life. The primary need is for a large scale source of electricity generation, and for this need the focus must be on petrothermal production, with the added benefit that a very large quantity of residual heat is available as a byproduct.

Economy – The RFP asks what are the expected costs of geothermal generation, and how competitive will these be with other competing technologies, as well as how can these costs and risks be reduced? Given a calibrated, Swiss-based cost model for geothermal generation, the first question is readily restated to ask "what is the amount of geothermal generation available at or below a given cost" (i.e. what is the geothermal cost supply curve). Such a cost model also readily gives the cost sensitivity for different cost-related factors (and in particular, the well related factors mentioned above) to quantify the effects on levelized cost of improvement in component costs, as well as the sensitivity of different cost risks.

Environment – The RFP asks "What are the possible environmental and health impacts of deep geothermal energy, including ground and surface water contamination and induced seismicity, can the Life Cycle Assessment (LCA) impact be determined, and how does geothermal energy compare to other renewable resources?" Impacts on the environment and human health from the normal operation of geothermal power generation technologies are addressed by the environmental analysis within this project. Risk related aspects like induced seismicity or potential water contamination due to unintended incidents are dealt with in the society and risk related work packages.

Regulation – The RFP asks whether current regulations (mostly subsurface related) are sufficient for extensive geothermal development, and whether regulation is most appropriate at the cantonal or federal level. These questions seem very appropriate, with perhaps the need to ask whether demonstration of good regulation in one canton as a template for adoption by other cantons may be an acceptable alternative to federal level regulation, and if so what standards could be common across cantons? The question related to an ethical debate on risk seems most appropriate to be included in the social context of the public perception, below.

Society – The RFP asks "what is the perception of geothermal power by the Swiss population, and have the post-Basel fears and anger disappeared?" These questions appear entirely appropriate, possibly with the additional need to ask how the population may feel after learning more about the strengths and weaknesses of geothermal energy, and how they compare to other technologies (and in particular, other renewable technologies).

1.2.2 Goals of the project

Given the discussion of the RFP's questions mentioned above, the following project goals were formulated to answer the restated emphases.

Resource – The goal was to determine whether there is sufficient reliable data on the Swiss geothermal resource to estimate the Swiss geothermal cost supply curve, whether there is sufficient reliable data to target the best Swiss geothermal locations, and whether measures can be implemented to improve the database.

Technology – The goal was to survey the status of current and projected geothermal technologies and to provide the appropriate Swiss costs to the economic work package, with an emphasis on technologies affecting the total average drilling costs that dominate levelized generation cost. Technology performance data should also be supplied to the life cycle analysis work package.

The objective of the work was to provide an overview of the current status of the technology in question (i.e. reservoir engineering), identify shortcomings, and suggest research strategies for overcoming them. The methodological approach taken began by summarizing experiences to date and lessons learned, based on extensive literature reviews. The members of the consortium are all scientific leaders in their respective domains and well connected to the ongoing scientific and technological developments at the national and international levels. In addition to literature reviews, we conducted interviews with selected individuals and organizations outside of our consortium, in order to tap into their specific knowledge and insight into upcoming developments and future trends. Gaps, particularly in regards to industry experience with actual execution of geothermal projects, were filled by consulting the Advisory Committee for the study.

In a second step, we identified the relevant gaps and limitations in the current understanding and addressed the uncertainties that this carries for the technology assessment. We also suggest and prioritize future research and technology development needs for Switzerland.

Economics – The goal was to apply the Swiss-calibrated geothermal cost model using the resource quality data and technology cost data from the first two work packages to the geothermal cost supply curve for Switzerland and the sensitivity of levelized cost to cost components and their risks.

Environment – The goal was to quantify the various direct and indirect life cycle environmental burdens for use in a comparison with other generation technologies, and in particular other "new" renewable resources.

Regulation – The goal was to survey federal and cantonal legal and regulatory framework(s), and if applicable to recommend suitable modifications.

Society – The goal was to determine public opinion on geothermal power, including issues related to general and seismic characteristics, as well as ethical treatment of risk issues in comparison with other generation technologies.

Integration – The goal was to combine the results of the other individual work packages in order to allow comparisons with other electricity supply technologies, to produce recommendations for technological and regulatory development, and to disseminate the results of the analysis to stakeholders and the general public. The comparisons profited from pre-existing indicators established by PSI for other relevant technologies.

1.2.3 What new results and approaches are expected from the project?

The questions and goals discussed above represent a state-of-the-art application of technology assessment as adapted and suited to the specific requirements of the geothermal field. The main original value of the current work is a comprehensive state-of-the-art review, new results of the analysis and the systematic approach to an integrated geothermal evaluation, with comparison with other technologies, and subsequent recommendations and dissemination of results. The scope of the project budget meant that in some areas, the approach was limited to a survey of the available knowledge base, rather than extensive new research (i.e. the status of resource data, technology data and regulation). Such data were combined with the new analysis and data collection in the economic, environmental and social areas.

1.3 Project structure and boundaries

1.3.1 Target audience

While the energy debate is of interest to the general public, particular stakeholders include government officials on the federal and cantonal levels, politicians, electric utilities (also on different levels), regulators, environmental groups, customers and the public. The results and recommendations of the project are aimed to support these stakeholders in comparing the strengths and weaknesses of geothermal and competing technologies, as well as disseminating these results to opinion shapers, including the media.

1.3.2 Prioritization of project elements

The size of the project budget means that not all work packages could be given equal weight, or that some areas had to be based on partner expertise and knowledge surveys rather than original new research. Emphasis has therefore been given to relatively unexplored areas such as Swiss resource assessment, economics, environment, risks, and public acceptance. Surveying geothermal technology developments can be primarily based on existing knowledge. Following the request from TA-SWISS the Swiss regulatory framework was given more attention than originally intended.

1.3.3 Pre-existing or planned connections with other projects dealing with similar questions (national and international contacts)

Project team partners have had multiple research projects with strong relevance to the work packages described within this proposal. There are various and ongoing connections with current Swiss and international geothermal research projects. A strong interaction with the recently established National Competence Center (SCCER) Supply of Electricity was highly desirable (see also Section 1.2). Therefore, the work undertaken in the current project was tightly intertwined with SCCER, and thus fostered the development of a geothermal roadmap. Another strong link was with Geotherm-2 (the successor of Geotherm-1) of the Competence Center Environment and Sustainability (CCES) and Competence Center Energy and Mobility (CCEM) with additional support from the Swiss Federal Office of Energy (SFOE) and the geothermal industry.

1.3.4 Project organization

Because the geothermal assessment in this work required use of different methodologies for the individual work packages, it seemed reasonable to address these as part of the individual work package descriptions. However, the overall framework of the proposed analysis and the relationship between the different work packages is shown below in **Figure 3**. As can be seen, the resource and technology work packages (WP1 and WP2) both provide information to the economic, environmental and risk assessment work in WP3, WP4 and WP5. There is also feedback between the regulatory and public opinion tasks (WP6 and WP7), particularly related to the ethical risk issues involved. Finally, the various tasks provided specific inputs into Work Package 8 for the final, interdisciplinary and comparative assessment, leading to the project conclusions and recommendations, and dissemination to TA-SWISS, stakeholders, and other ongoing geothermal research efforts.

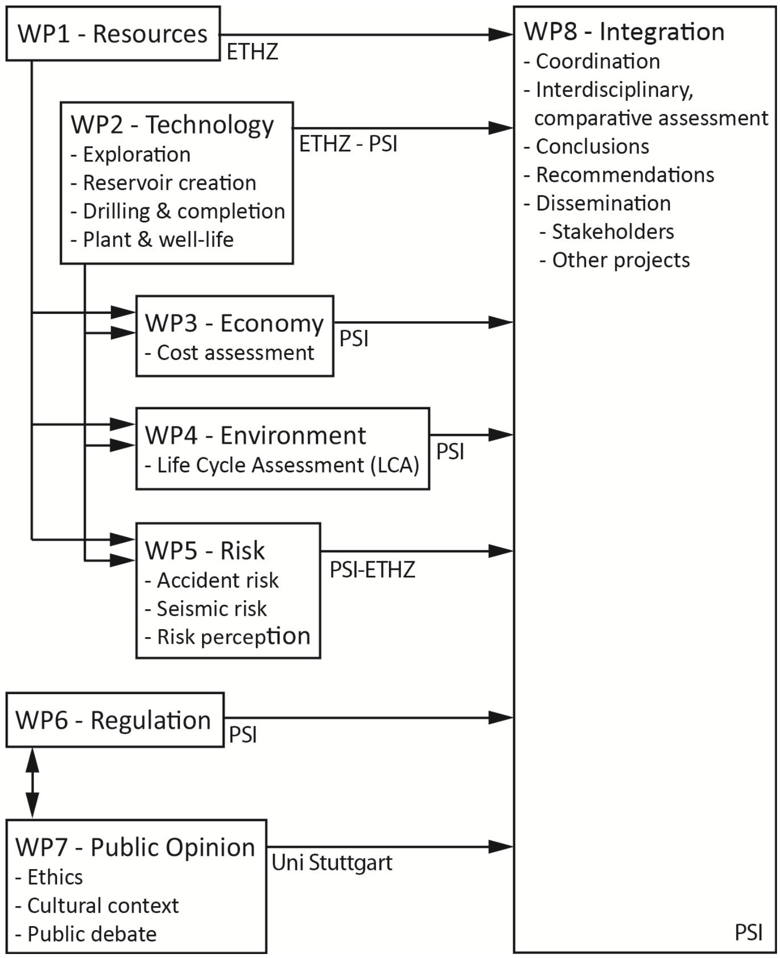

Figure 3: *Flowchart of the analytic framework.*

Chapters 2–9 of this report summarize the work in the various work packages. Before this we shortly summarize the status of geothermal energy globally and in Switzerland.

1.4 Status of geothermal energy

1.4.1 The historical context of geothermal development

Geothermal energy has been used in the form of natural hot springs since prehistoric times, and during recorded history for bathing and heating buildings from China to Rome. Direct heat is still most dominant form of geothermal use, with a wide range of uses from district heating, industrial use, agriculture (greenhouses and drying), aquaculture and heat pumps. The world's oldest example of geothermal district heating dates to the 14th century in Chaudes-Aigues, France, with more modern pioneering examples in Boise, Idaho (1892) and Klamath Falls, Oregon (1900). Geothermal heat pumps are a natural outgrowth, and were developed in the 1940's with the first commercial demonstration in Portland, Oregon in 1946. **Figure 4** below shows the distribution of direct uses of geothermal heat in 2010, for a total use of 438 TJ/yr in 78 countries (Lund *et al.*, 2011, also cited by IGA 2013). Geothermal heat pump capacity installed has grown by about 20% per year over the past two decades, and Switzerland is a leading market for this technology on a per capita basis with compound annual growth rates of about 12% since 2000 (Statistik der geothermischen Nutzung in der Schweiz Ausgabe 2012).

Figure 5 shows the sources of Swiss geothermal heat use, and the dominant share of shallow heat pump boreholes.

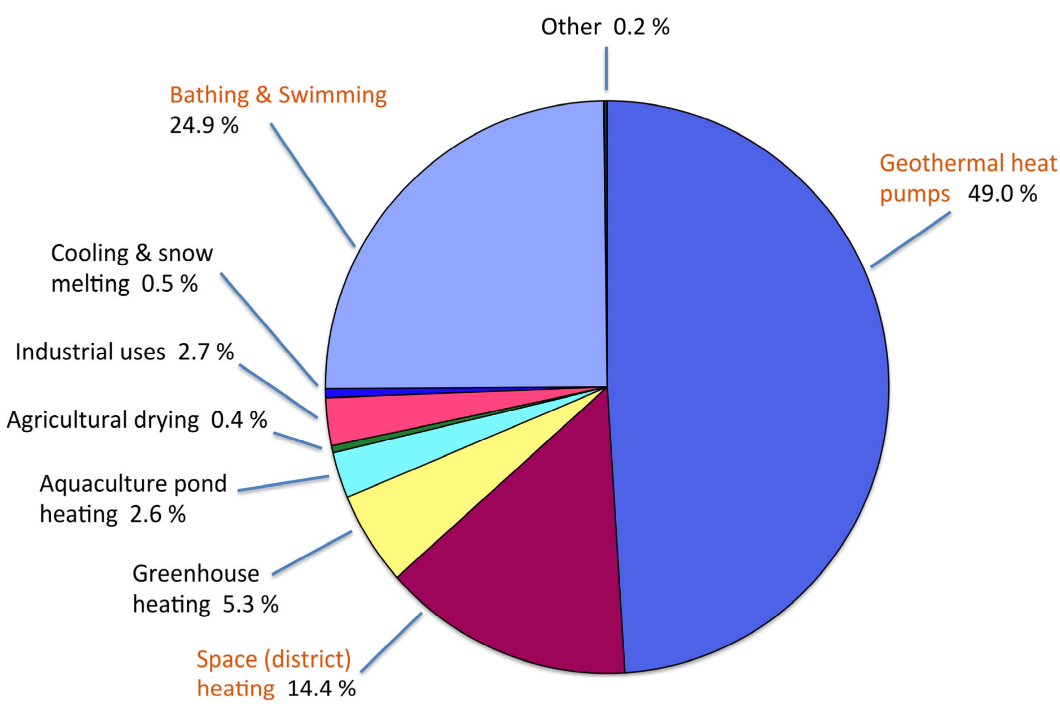

Figure 4: *Direct uses of geothermal heat worldwide in 2010 (Lund et al., WGC 2010).*

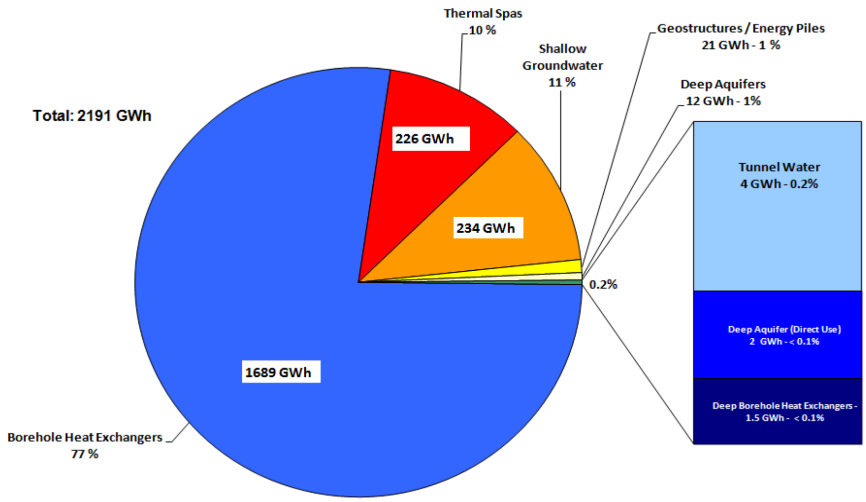

Figure 5: *Direct and indirect uses of geothermal heat in Switzerland 2012 (Source: Statistik der geothermischen Nutzung in der Schweiz Ausgabe 2012)*[4].

This report focuses on the use of geothermal energy for the generation of electricity. Although industrial use of geothermal energy started in Larderello, Italy in 1827 for the production of boric acid, the first demonstration of geothermal generation did not take place until 1904, with the first world's first commercial generation plant following in 1911. Further generation plants were built in New Zealand in 1958 and at the Geysers in California in 1960.

Figure 6: *First demonstration of geothermal generation, Larderello, Italy.*

[4] Statistik der geothermischen Nutzung in der Schweiz Ausgabe 2012: http://www.geothermie.ch/data/dokumente/miscellanusPDF/Publikationen/Geothermiestatistik%20Schweiz%202012.pdf

As noted earlier in this chapter, there has been a natural progression since these early beginnings from the use of the rarest, and highest-quality, resources to the use of lower quality, but more ubiquitous, resources. For geothermal energy, this has meant a progression from dry steam plants, to plants that flash hot geothermal fluid into steam to binary plants that use hot geothermal fluid to boil a secondary working fluid. Further developments have included the Kalina cycle for increased efficiency. Enhanced/Engineered Geothermal Systems are a natural step along this progression, where instead of searching for relatively rare sites where there is a natural geothermal fluid resource, water is instead injected and recovered to drive the generation plant, which can potentially access a much broader resource (Section 1.4.2 below).

In keeping with the resource progression noted above, geothermal plants to date have been primarily located at geological hotspots near the boundaries of major tectonic plates. The dominant example of this has been the exploitation of geothermal resources around the "Pacific Ring of Fire" as shown in **Figure 7** below. The United State is the world's largest geothermal generator, with plants built first at the Geysers, north of San Francisco, and later followed by hydrothermal plants across California, and to a lesser degree also in Oregon and Idaho.

This map also shows other concentrations of geothermal generation in the eastern Pacific, where Indonesia is second in global generation, having just overtaken the Philippines. Other concentrations of geothermal generation include Iceland, parts of Europe from Turkey to Italy where the African plate is moving north into the European plate, and the central rift valley of Africa.

Figure 7: *World map of geothermal plants*[5].

[5] Source: www.map.thinkgeoenergy.com

These concentrations of development show the effects of a coincidence of geothermal resources, technological and financial capabilities, and government policies. While the US is the largest generator of geothermal power, the share of geothermal power is small compared to the overall electricity market. For many other countries geothermal generation has a much higher market share and significance (e.g. Iceland at 29%, El Salvador at 25%, Kenya at 20%, the Philippines at 15%, New Zealand at 14%, and Costa Rica and Papua New Guinea at 12%)

Figure 8 and **Figure 9** below show the growth of geothermal generation worldwide over the last 30-plus years by nation and by world region, respectively. Note that the legend on the right gives the names of the countries and regions in the rank order of their total generation in the final year of 2012.

It is interesting to note that the generation curves are not monotonically increasing, but rather show dips, reflecting the fact that individual wells and even fields do show resource depletion. In the case of the US, decreasing generation was partially due to declining production at the Geysers. This is the world's single largest field, with 1517 MW of total capacity at 22 plants using over 350 wells. Decreasing steam production was addressed by reinjecting treated wastewater from neighboring towns for fluid recharge.

1.4.2 EGS technology

Classical EGS systems seek to extract heat from low-permeability rocks where there is relatively little water in place by constructing a heat exchanger between two or more boreholes in the rock mass. The technology to achieve this was pioneered at the Fenton Hill site in New Mexico, USA by the nearby Los Alamos National Laboratory, who developed two reservoirs that operated from 1974 to 1992 in two separate phases. Such systems were referred to as Hot Dry Rock systems. Subsequently, other terms have been used to emphasize different aspects of specific reservoirs, such as Hot Dry Rock (HDR) and Hot Wet Rock systems. More recently, classical HDR systems have become known as Petrothermal systems, to emphasize the distinction from hydrothermal (conventional geothermal) systems where there is a significant quantity of hot water in-place. Petrothermal systems are also known as EGS systems. However, there is no consensus as to whether 'EGS' denotes Enhanced or Engineered Geothermal Systems. A sensible distinction between the two is to identify Engineered Geothermal Systems as Petrothermal systems, to emphasize the fact that they involve the engineering of the heat exchanger. Enhanced Geothermal Systems are more logically identified with poorly-performing conventional geothermal systems whose productivity has been *enhanced* by applying reservoir stimulation technology. USDOE currently has a major program of supporting Enhanced Geothermal System development on the margins of conventional geothermal fields where the natural reservoirs require stimulation methods to become commercial (see Section 3.2.1.8).

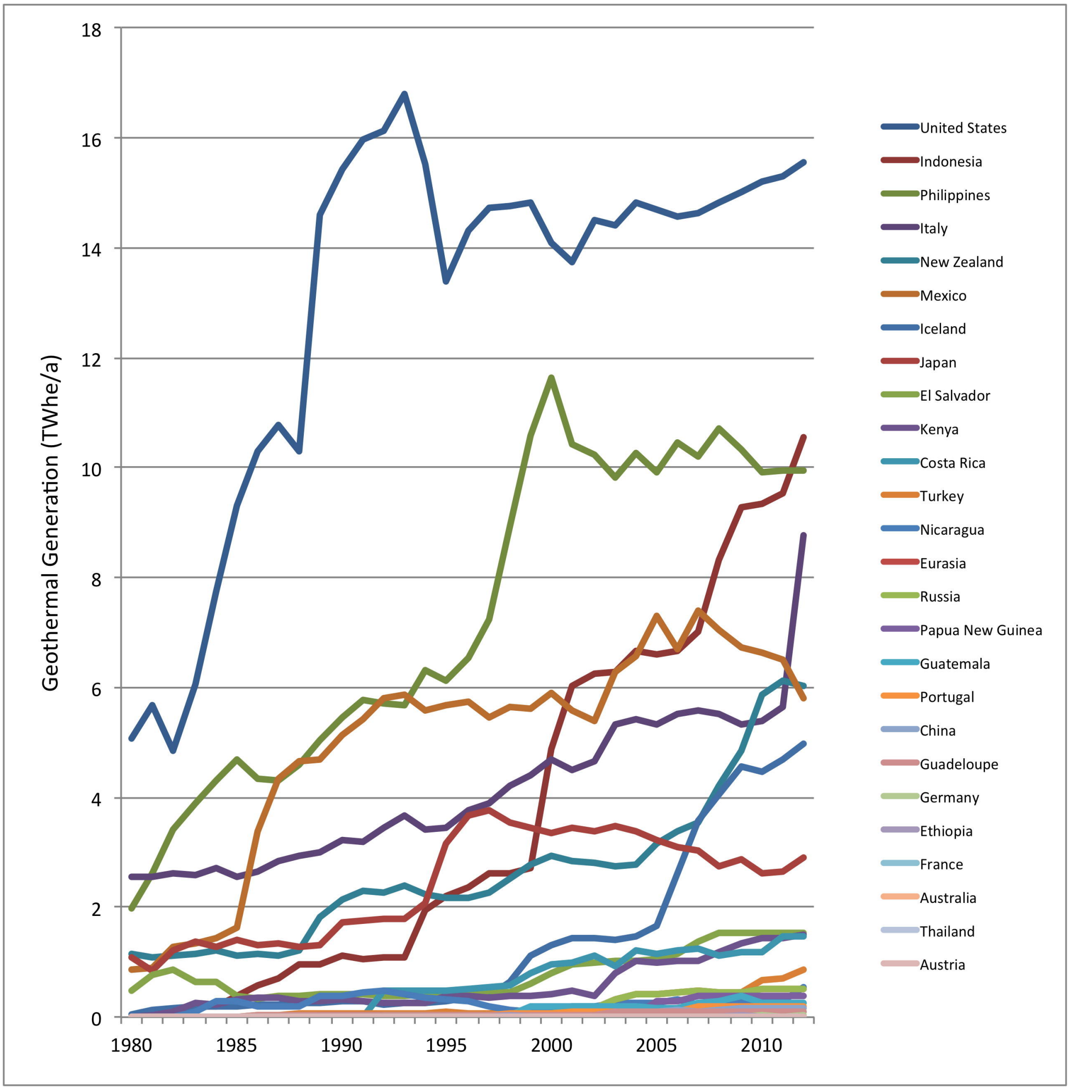

***Figure 8**: Geothermal generation by nation*[6].

[6] Source: US DOE–EIA

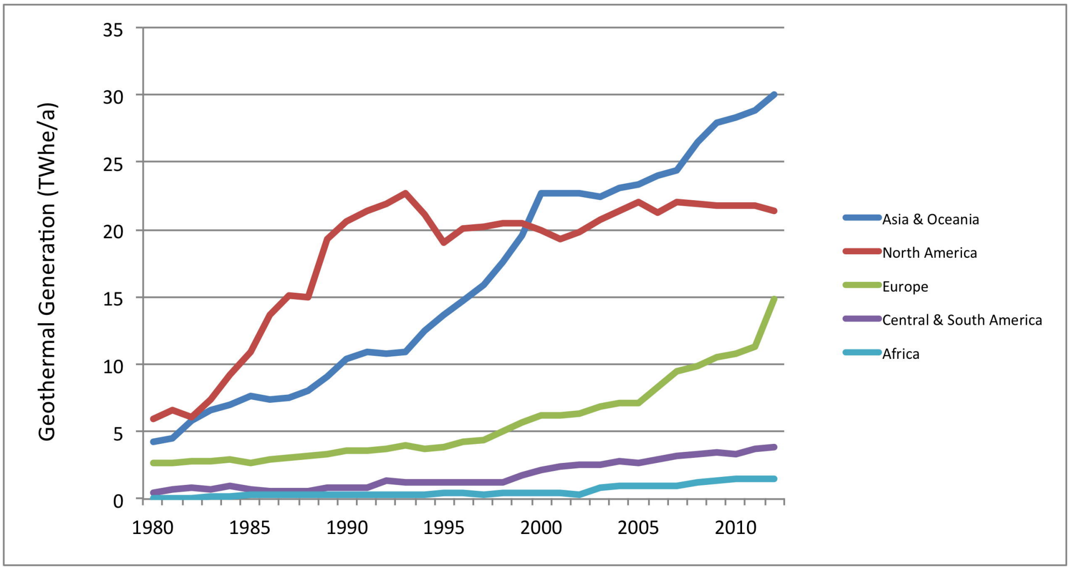

Figure 9: *Geothermal generation by world region (Source: US DOE-EIA).*

There are two active petrothermal sites in Europe. One is at Soultz-sous-Forêts in France, where two reservoirs have been developed in granite at different depths (doublet and triplet). The other is a doublet at Gross Schönebeck in sedimentary rocks of the North German Basin. Both projects are able to produce electricity.

Other current EGS research efforts include planned and ongoing efforts in Cornwall, UK and Portugal. The Australian government has supported HDR research since 2007, with a reported 33 firms involved in EGS.

Table 1 below shows a survey of EGS projects (as of April, 2014), including research and development, thermal and generation projects with a range of technologies and stages of completion. The first page shows current projects with ongoing generation, while the second page shows projects under development, followed by projects that have been concluded or abandoned.

Table 1: *EGS projects past, present and future (Breede et al., 2013).*

Project	Location	Operator	Description	Start date	End date	Rock type	Well depth	Reservoir (fluid) temp.	Stimulation methods	Flow rate (l/s)	Plant type	Capacity (MWe)	Seismic events	Status / comments
Bruchsal	Germany	EnBW, EWB	Commercial	1983		Bunter Sandstone	1,874 to 2,542	123	Unknown	28.5	Kalina	0.55	Microseismic	Ongoing generation - high salt contents (100 g/l); high CO2 concentration
Landau	Germany	BESTEC, Geox	First implementation of EGS technology in Germany; first and only EGS in town in (D)	2003		Granite	3,170 to 3,300	159	No stimulation for producer; hydraulic for injector	70 to 80	ORC	Up to 3.6	Microseismic (≤2.7 M), felt by residents	Ongoing generation
Insheim	Germany	Pfalzwerke geofuture GmbH	New concept, side-leg injection well	2007		Keuper, perm, bunter sandstone, granite	3,600 to 3,800	165	Yes	65 to 85 (planned)	ORC	4.8	M: 2.0 to 2.4 and microseismic	Ongoing generation
Neustadt-Glewe	Germany	WEMAG AG, Stadt Neustadt-Glewe, Geothermie Neubrandenburg GmbH	Commercial, pilot plant for low enthalpy	1984		Sandstone	2,320	99	Unknown	35	ORC	0.21	Unknown	Ongoing generation - high salt content, high gas concentration
Unterhaching	Germany	Geothermie Unterhaching GmbH & Co. KG, Rödl & Partner GbR	First Kalina power plant in Germany	2004		Limestone	3,350 to 3,580	123	Acidizing	150	Kalina	3.36	Unknown	Ongoing generation
Soultz	France	European cooperation project	R&D	1987		Granite	5,093	165	Hydraulic fracturing and acidizing	30	ORC	1.5	Microseismic (M = −2 to 2.9)	Ongoing generation - corrosion due to high salt contents
Bouillante	France (Guadeloupe)	Geothermie Bouillante, CFG-Services, BRGM, ORKUSTOFNUN, COFOR	Commercial	1963, 1996		Volcanic lavas and tuffs	1,000 to 2,500	250 to 260	Thermal cracking	150	Flash	15	Microseismic	Ongoing generation
Altheim	Austria	Municipality of Altheim, Terrawat	Commercial	1989		Limestone	2,165 to 2,306	106	Acidizing, hydraulic stimulation	81.7	ORC	1	Unknown	Ongoing generation - clogging by stone and bentonite mixture
Lardarello	Italy	ENEL Green Power	R&D	1970		Metamorphic rocks	2,500 to 4,000	300 to 350	Hydraulic and thermal stimulation	100	Not known	700	≤3.0 M	Ongoing generation - highly corrosive, total loss of circulation when very high permeability fracture zones are met
Coso	USA	Coso Operating Company	R&D	2002		Diorite, granodiorite,	2,430 to 2,956	≥300	Hydraulic, thermal and chemical	Unknown	Unknown	240	≤2.8 M	Ongoing generation
Desert Peak	USA	Ormat, GeothermEx	R&D	2002		Volcanic and metamorphic rocks	About 1,067	179 to 196	Shear, chemical, hydraulic	100	Unknown	1.7	Microseismic: −0.03 to 1.7	Ongoing generation - wellbore instability due to chemical stimulation
Berlín	El Salvador	Shell International, LaGeo	Developing EGS project in a geothermal field	2001		Volcanic rocks	2,000 to 2,380	183	Hydraulic fracturing and chemical	Unknown	Binary	54	≤4.4 M	Ongoing generation
Cooper Basin	Australia	Geodynamics Ltd.	Largest demonstration project in the world	2003		Granite	4,421	242 to 278	Hydraulic	30	Unknown	1	≤3.7M	Ongoing generation
Hijiori	Japan	Japan's new energy, NEDO	Developing EGS technologies	1985		Granodiorite	1,805 to 1,910	190	Hydraulic fracturing	178	Binary	0.13	Microseismic	Ongoing generation - high water losses, precipitation of anhydrite

Project	Location	Operator	Description	Start date	End date	Rock type	Well depth	Reservoir (fluid) temp.	Stimulation methods	Flow rate (l/s)	Plant type	Capacity (MWe)	Seismic events	Status / comments
Le Mayet	France	Not known	Research	1978		Granite	200 to 800	22	Hydraulic fracturing with and without	5.2			Microseismic, not felt on	Under dev. - little & conflicting information in open domain
Genesys Hannover	Germany)	Federal Ministry of Economics &	Demonstrate single well concepts	2009		Bunter sandstone	3,900	160	Hydraulic fracturing	7 (planned)			Microseismic (1.8 M)	Under dev. - salt deposition has been removed
Groß Schönebeck	Germany)	GFZ, Schmidt + Clemens GmbH + Co. KG	1st *in situ* geothermal laboratory, EGS research	2000		Sandstone and andesitic volcanic rocks	4,309 to 4,400	145	Hydraulic gel proppant and fracturing, thermal, chemical	20			Negligible (max, −1.8 to −1.0M)	Under dev. - Production-injection experiment and data interpretation and modelling finished
Mauerstetten	Germany	Exorka GmbH, GFZ, TUBAF	Research	2011		Limestone	4,545	130	Chemical; hydraulic	Unknown			Unknown	Under dev. - Seismic monitoring system installed, hydraulic stimulation next
St. Gallen	Switzerland	ITAG Tiefbohr GmbH	Commercial: heat and power	2009		Malm, shell limestone	4,450	130 to 150	Chemical and hydraulic				3.5 M	Under dev. - production test interrupted by pump failure & resulting seismic
Newberry	USA	AltaRock Energy, Davenport Newberry	Demonstration for EGS stimulation/ research	2010		Volcanic rocks	3,066	315	Hydroshearing, multi-zone isolation	Unknown			Microseismic	Under dev. -stimulation started successfully
Northwest Geysers	USA	Calpine Corporation	Demonstration/ research	In 1980s		Metasedimentary rocks (greywacke)	3,396	About 400	Thermal fracturing	9.7			Microseismic (0.9 to 2.87 M)	Under dev. - stimulation stage (5 MW of potential production)
Paralana	Australia	Petratherm, Beach Energy	Commercial power development	2005		Metasediments, granite	4,003	171	Hydraulic	Up to 6			Microseismic ≤2.6 M	Under dev. - drilling of Paralana 3, submit funding application
Falkenberg	Germany		Investigation of hydraulic fracturing, shallow depth	1977	1986	Granite	500	13.5	Hydraulic fracturing	0.2 to 7 (test)			Microseismic	Concluded experimental project
Genesys Horstberg	Germany		Testing new single well concepts at old gas well	2003	2007	Sedimentary	3,800	150 (115)	Hydraulic fracturing	10 to 20			No measured event	Concluded experimental project
Fjällbacka	Sweden		Experimental project	1984	1995	Granite	70 to 500	16	Hydraulic fracturing and acidizing	0.9 to 1.8			Microseismic	Concluded experimental project
Rosemanowes	UK		Experimental project	1977	1992	Granite	2,000 to 2,600	79 to 100 (54.2 to 80)	Hydraulic fracturing, viscous gel, proppants	4 to 25			Max. magnitude, 3.1	Concluded experimental project
Fenton Hill	USA		First EGS in the world 1974	1974	1993	Crystalline rock	2,932 to 4,390	200 to 327 (180 to 192)	Hydraulic fracturing	10.6 to 18.5			Microseismic	Concluded experimental project
Ogachi	Japan		Test run EGS project in shallow depth	1989	2002	Granodiorite	400 to 1100	60 to 228 (160)	Multiple wells with multiple fracture zones; hydraulic	6.7 to 20			Few microseismic	Concluded experimental project
Bad Urach	Germany	Forschungs- Kollegium Physik des Erdkörpers	EGS pilot by one borehole only	1977, 2006	1981, 2008	Gneiss	3,334 to 4,445		Hydraulic fracturing				Microseismicity	Abandoned - bore rods torn off in borehole
Basel	Switzerland	Geopower Basel	Planning to develop EGS project	1996	2009	Granite	5,000		Hydraulic fracturing				Frequent earthquakes (including 3.4 M)	Abandoned - induced seismicity exceeded acceptable levels
The Southeast Geysers	USA	AltaRock Energy	Redrill a well for EGS demonstration project	2008	2009	Greywacke	1,341		Multiple fracture zones in wells				Induced seismicity risk	Abandoned - wellbore collapse and induced seismicity risk

DiPippo (2013) also gives a broad overview of previous and current EGS projects worldwide.

1.4.3 Geothermal projects around Switzerland

Figure 10 shows the location of deep geothermal projects currently operating in Switzerland. All 9 of these projects are producing heat without any generation of electricity. The hydrothermal heat production project in St. Gallen was cancelled in May 2014, due to low fluid production test results and the discovery of natural gas during drilling[7]. The EGS project in Basel was abandoned in December 2009 after a full review of the seismicity induced by well stimulation from December 2006 to January 2007. **Table 2** also shows the total number of geothermal plants, and their thermal power and heat production for Switzerland in comparison with several other European countries.

Figure 10: *Currently operating deep geothermal systems in Switzerland. (Source: Swiss Geothermal Association)[8].*

Table 2: *Number, power and production of geothermal plants in service – European country comparison.*

Country	Plants in Service: Total	Electricity only	Heat only	Electricity & heat	Capacity and Production: Power (elec.) (MWe)	Generation (MWhe)	Power (heat) (MWt)	Heat (MWht)
Switzerland	9	0	9	0	0	0	8,4	10.300
Germany	21	1	16	4	11,9	54.600	197	>= 232'000
France	45	3[1]	42	0	16,5	95.000	>= 273.7	1.234.600
Italy	46	39	7	0	882,5	5.654.000	152,2	n.a.
Austria	9	0	6	3	1,4	3.800	50,3	167.300
Netherlands	8	0	8	0	0	0	41,4	199.700

n.a. = not available
[1] 2 on Guadeloupe

[7] http://www.geothermie.stadt.sg.ch/aktuell/uebersicht.html

[8] http://www.geothermie.ch/index.php?p=deep_geothermal_projects

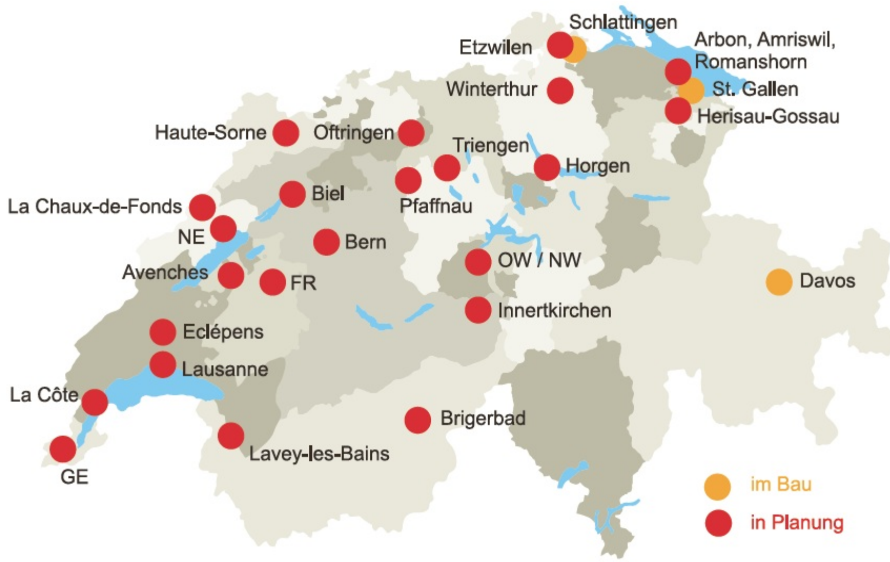

Figure 11: *Deep geothermal systems currently under construction or being planned in Switzerland (Source: Swiss Geothermal Association)*[9].

In addition to the 9 geothermal plants currently in operation, another 3 are currently under construction (2 for heat and 1 for electricity) and another 23 plants are in planning (9 concretely). The location of these plants is shown in **Figure 11** above. The total number and thermal power of these plants are also given in **Table 3** and **Table 4** below in comparison with some other European countries.

Table 3: *Number and power of geothermal plants under construction – European country comparison.*

Country	Plants under Construction[1] Total	Electricity only	Heat only	Electricity & heat	Not known	Capacity Power (elec.) (MWe)	Power (heat) (MWt)	Not known
Switzerland	3	0	2	1		2.5-5	17-20	
Germany	18	3	6	6	3	79,9	2	
France	1	1	0	0		25	2	
Italy	5	5	0	0		40,8	2	
Austria	0	0	0	0		0	25	
Netherlands						0	2	

[1] Info by plant frequently missing
[2] Included with "Plants being planned"

[9] http://www.geothermie.ch/index.php?p=deep_geothermal_projects

Table 4: *Number and power of geothermal plants being planned – European country comparison.*

Country	Plants being planned[1], Plants in planning[2]	Electricity only	Heat only	Electricity & heat	Not known	Capacity Power (elec.) (MWe)	Power (heat) (MWt)	Not known
Switzerland	23[1]	1	1	21		n.a.	n.a.	
Germany	63	5[2]	6[3]	18	35	67,7	57,6	
France	38	0	27	0	11[4]	n.a.	249,98	
Italy	26	14[5]	12	0	10	96	123	
Austria	2	0	1	1		85		
Netherlands	3	0	3	0		0	40,5	

n.a.= not available

[1] 9 in concrete planning

[2] 1x no info for electricity

[3] 1x no info for heat

[4] EGS without info for electricity, heat

[5] ENEL: 120 exploration permits issued

The current situation in Germany was further reviewed, since geological conditions in some areas can be similar to those in northern Switzerland. The German Association for geothermal power (”Bundesverband Geothermie GtV”) provides updated lists of existing shallow and deep geothermal power plants[10] (GtV, 2013). As of October 2013, 25 running plants with a total installed capacity of 223 MW thermal and 23 MW electrical were listed. Of these, three were geothermal probes and the remaining plants were of the hydrothermal type. The highest installed capacities are mentioned for Oberhaching-Laufzorn with heat production of 40 MW_t (a 4 MW binary plant is currently under construction) and Kirchstockach as well as Dürrnhaar with electricity production only at 5.5 MW_e each. The maximum well depth is 3445 m. The following tables are taken without adaptation from (GtV, 2013) and show details of the 25 running plants as well as the 13 projects in the construction phase. A further 43 projects are in the planning phase, out of which 4 are EGS plants and all the remaining plants are of the hydrothermal type. Many of the plants are planned for cogeneration of heat and electricity. Wells of more than 6000 m depth are planned. **Figure 12** shows the location of many of these projects that are in the Munich region.

[10] http://www.geothermie.de/wissenswelt/geothermie/in–deutschland.html

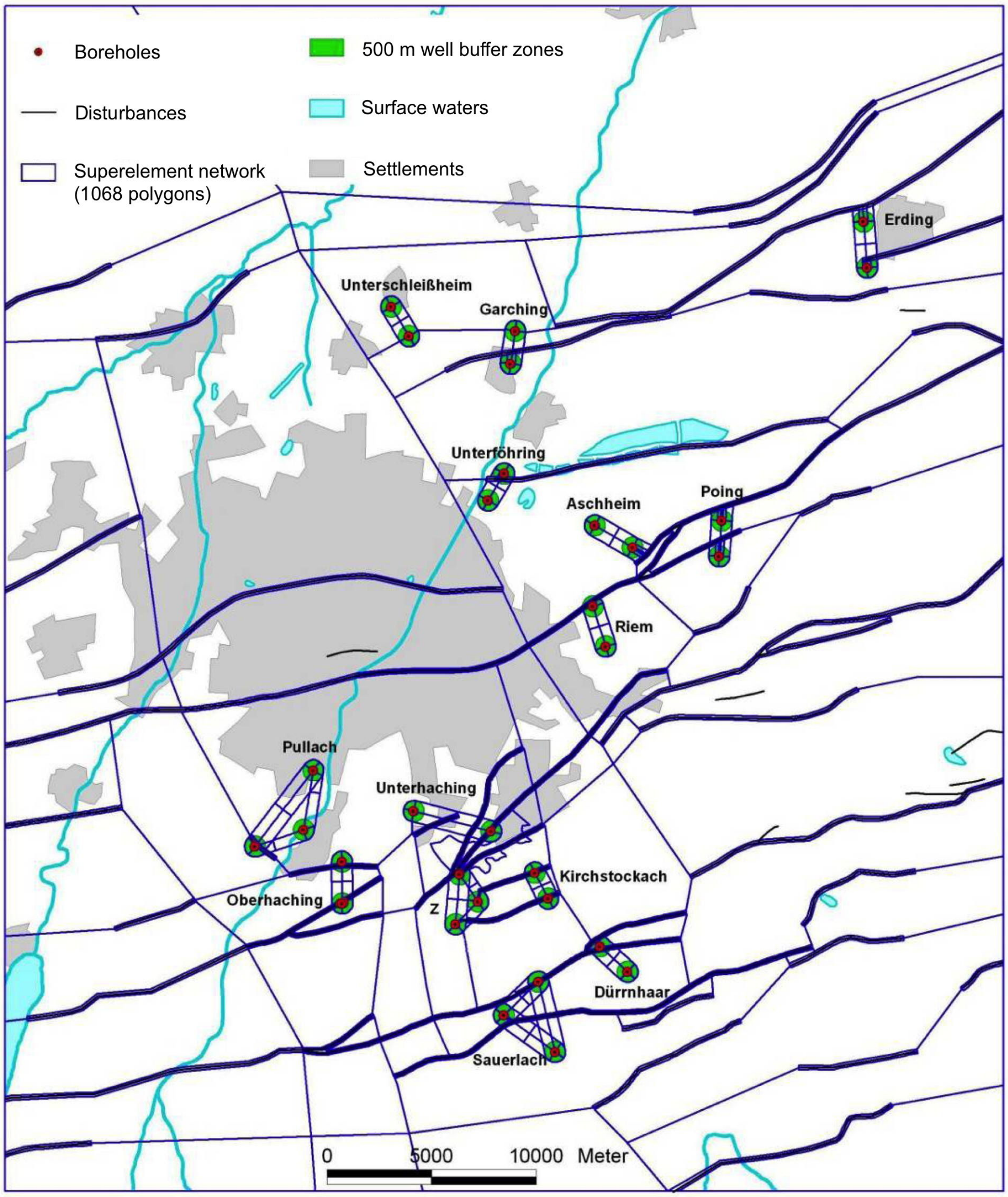

Figure 12: *German geothermal projects in the region of Munich.*

Table 5: *Deep geothermal projects in Germany – running plants and projected plants as to November 2013. GtV (2013).*

	Status	Name	Bundesland	Art der Nutzung	MW_{therm}	MW_{el}	max. Temperatur in °C	Teufe in m	Förderrate (l/s)	Jahr d. Inbetrieb-nahme
1	26 Projekte in Betrieb	Arnsberg	Nordrhein-Westfalen	Sonde	0,35	0	55	2.835	5,6	2012
2		Aschheim, Feldkirchen, Kirchheim	Bayern	Hydrogeothermie	19	0	85	2.630	75	2009
3		Bruchsal	Baden Württemberg	Hydrogeothermie	5,5	0,55	120	2.542	24	2009
4		Dürrnhaar	Bayern	Hydrogeothermie	0	7	141	3.926	130	2013
5		Erding	Bayern	Hydrogeothermie	9,7	0	65	2.200	55	1998/2008
6		Garching	Bayern	Hydrogeothermie	6	0	74	2.100	100	2010
7		Grünwald	Bayern	Hydrogeothermie	5,3	4**	130	4.083	140	2011
8		Heubach/Groß-Umstadt	Hessen	Sonde	0,09	0	38	800	0	2012
9		Insheim	Rheinland-Pfalz	Hydrogeothermie	0	4,8	165	3300	85	2012
10		Kirchstockach	Bayern	Hydrogeothermie	0	7	139	3.882	130	2013
11		Landau	Rheinland-Pfalz	Hydrogeothermie	5	3,6	160	3.340	70	2007
12		München-Riem	Bayern	Hydrogeothermie	10	0	93	2.746	75	2004
13		Neubrandenburg	Mecklenburg Vorpommern	Hydrogeothermie	3,8	0	53	1.267	28	1987
14		Neuruppin	Brandenburg	Hydrogeothermie	2,1	0	64	1.700	13,9	2007
15		Neustadt Glewe	Mecklenburg Vorpommern	Hydrogeothermie	7	0	99	2.320	35	1994
16		Oberhaching-Laufzorn	Bayern	Hydrogeothermie	40	0	130	3.300	138	2011
17		Poing	Bayern	Hydrogeothermie	7	0	76	3.000	100	2011
18		Prenzlau	Brandenburg	Sonde	0,15	0	108	2.790	k.A.	1994
19		Pullach	Bayern	Hydrogeothermie	15	0	107	3445	105	2005/2012
20		Simbach/Braunau	Bayern	Hydrogeothermie	8	0	80	1.942	80	2001
21		Straubing	Bayern	Hydrogeothermie	4,1	0	36	800	45	1999
22		Unterföhring	Bayern	Hydrogeothermie	9	0	87	2.512	85	2009
23		Unterhaching	Bayern	Hydrogeothermie	38	3,36	122	3.350	150	2007
24		Unterschleißheim	Bayern	Hydrogeothermie	28,36	0	79	1.960	100	2003
25		Waldkraiburg*	Bayern	Hydrogeothermie	13,5	k.A.	108	2.650	65	2012
26		Waren	Mecklenburg Vorpommern	Hydrogeothermie	1,3	0	63	1.566	17	1984
		SUMME			238,25	26,31				
		*Leistung bei Vollendung des Wärmenetzes								
		**Kraftwerk in Bau								
1	13 Projekte in Bau	Aachen, Super C	Nordrhein-Westfalen	Sonde	0,45	0	85	2.500	0	k.A.
2		Altdorf (BY)	Bayern	Hydrogeothermie	k.A.	k.A.	65	611	90	41548
3		Brühl	Baden Württemberg	Hydrogeothermie	ca. 40	>6	155	3.320	>100	2015
4		Geretsried/Wolfratshausen	Bayern	Hydrogeothermie	40	5	145	5.200	100	2015
5		Groß Schönebeck	Brandenburg	EGS	k.A.	k.A.	150	4.400	k.A.	k.A.
6		Hannover	Niedersachsen	EGS	2	0	170	3.901	8	nicht absehbar
7		Ismaning	Bayern	Hydrogeothermie	7	0	77	1.906	85	2013
8		Kirchweidach	Bayern	Hydrogeothermie	5	6,6	128	3.500	130	2015
9		Mauerstetten	Bayern	EGS	k.A.	5	130	4.000	k.A.	k.A.
10		München-Freiham	Bayern	Hydrogeothermie	20	0	90	2.700	100	2014
11		Sauerlach	Bayern	Hydrogeothermie	4	5	140	4.480	110	2013
12		Taufkirchen/Oberhaching	Bayern	Hydrogeothermie	40	5	133	3.800	120	2014
13		Traunreut	Bayern	Hydrogeothermie	12	4	118	ef (2.Bohrung)	130	2014

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2 WP1: Resources

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Cooling down 1 km³ of granitic rock by 10 °C would release heat energy of 5000 GWh. The energy stored in the hot rocks a few kilometers beneath our feet is enormous. Temperatures at depths of 4 or 5 km are above 120 °C and high enough in principal to allow electricity production in a geothermal plant. This heat, however, cannot be used easily and directly since heat transfer within rocks is very slow by human standards. To increase efficiency of heat transfer, water is the medium of choice for heat extraction and heat transport – for nature and industry. In a closed loop geothermal system, cool water reaches hot rock at depth via dedicated injection wells. After extracting heat by direct contact with the rock – in a so-called heat exchanger – the hot water is lifted back to the surface with the aid of pumps.

One of the key issues of deep geothermal energy exploitation is the use of a technology that can efficiently extract the heat energy from the hot rock formations. Different kinds of systems are applied (**Figure 13**) depending on the depth and geologic structure of the geothermal resource. In a few areas, structures related to deep aquifers with a natural flow of hot water can be found (hydrothermal systems). In most regions, however, rocks below a few kilometers' depth are normally of relative low porosity, thus prohibiting the flow of water to allow efficient heat exchange. To enhance efficiency of water flow and heat extraction, rocks of the reservoir volume must be fractured by high-pressure fluid injection, creating a local fracture network (petrothermal systems or enhanced geothermal systems). A third possibility is the use of deep borehole heat exchangers for heat extraction, with a closed fluid loop.

In this section of the report, we primarily address the exploitation of geothermal energy in hydro- and petrothermal systems (with the main emphasis on the latter) at depths greater than 4 km and temperatures above 120 °C. Electric power production is possible for temperatures above 100 °C, and with future technology developments even likely for lower temperatures. Conversion rates from thermal to electric power are low, on the order of 10%, depending on temperature of the produced water. Economic power production needs at least 120 °C. In binary systems the production fluid is kept under pressure and does not transform into steam even for temperatures well above 120 °C. We will also address the possibility of heat extraction for direct heating at depths of 2−3 km (60−70 °C) as an alternative to shallow heat pump systems (**Figure 13**).

Currently, in Switzerland no electric energy is produced from geothermal sources. Countries with high geothermal (electric) power production, such as the world-leader USA, Italy (region of Tuscany), or Iceland are fortunate to have volcanic regions where high temperatures and flow rates can be achieved at very shallow depths. This is not the case for countries like Switzerland or Germany, which currently are comparatively small players but with quite some activities ongoing targeting the non-volcanic hot deep rocks (see Section 1.4 for more details).

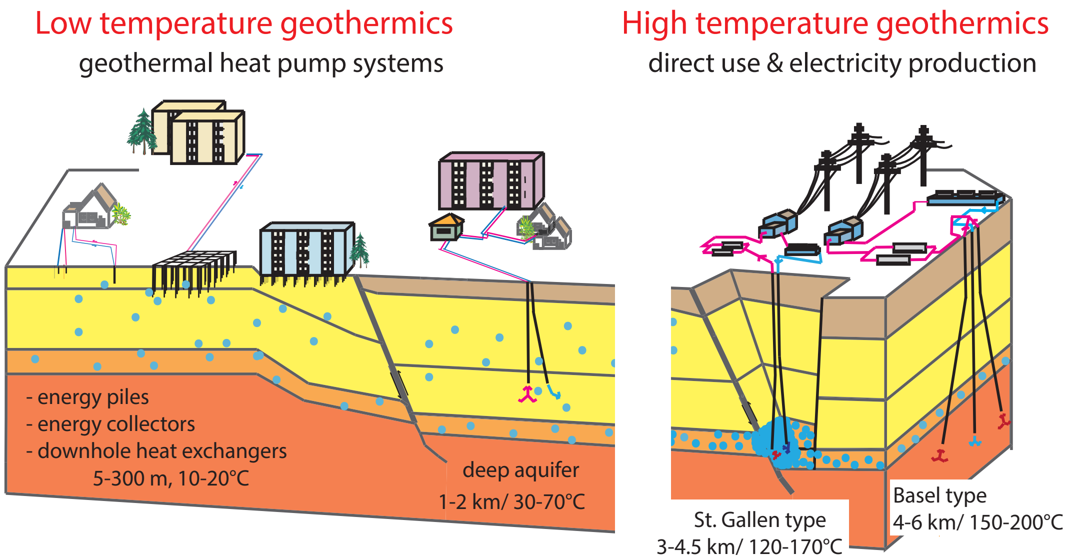

Figure 13: *Different types of systems using geothermal energy. At present, low temperature geothermal systems in combination with heat pumps for all heating of buildings are widely used in Switzerland. High temperature geothermal systems for electricity production, however, are still only in planning state.*

2.1 Geothermal as sustainable and renewable energy

Beneath any place on the surface of the earth, rock temperature increases with depth due to the natural geothermal gradient. The Earth consists of a hot core (temperatures above 5000 °C) surrounded by a viscous fluid called mantle overlain by a 100 km thick solid layer called the lithosphere that includes as its top part the crust. Due to low outside temperature, a continuous heat flow has existed from the hotter inner part of the earth through the earth's surface for more than 4000 million years and it will likely continue to do so for a similar period to come. While heat transport in a viscous fluid like the earth's mantle is dominated by convection, thus providing the motor for plate tectonics, within the solid lithosphere and crust the dominant mode of heat transport is conduction. The conductive lithosphere provides a very effective insulation of the earth's hot interior from the cool outside. This is expressed by the relatively high geothermal gradient of – on average – 30 °C/km in the top crustal layers typical for young continental areas like Switzerland, corresponding to a natural heat flow density of about 70 kW/km^2 (**Figure 14**). The heat released annually through the surface of Switzerland by natural surface heat flow amounts to 24'000 GWh, approximately one third of the annual energy consumption for heating purposes in Switzerland (**Figure 15**).

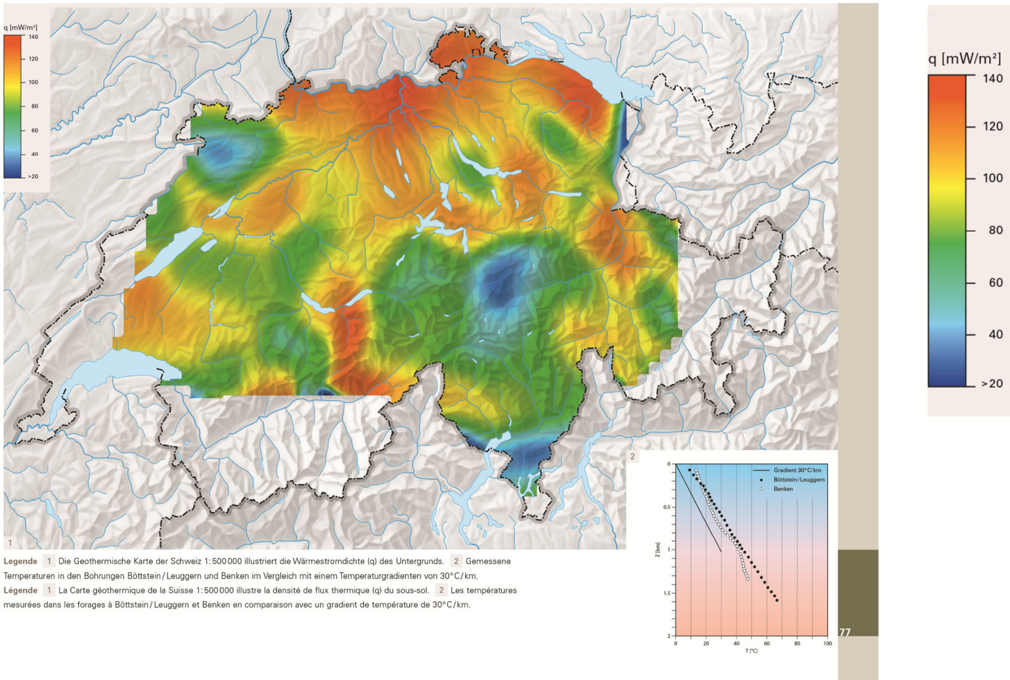

***Figure 14**: Surface heat flow map of Switzerland (swisstopo, 2013).*

With the earth's interior remaining hot for many million years to come, geothermal energy may well be seen as a renewable source of energy. In principle, it is available at all locations within Switzerland and independent of season. This makes geothermal energy different from other resources like, i.e., wind energy that is preferably obtained in particular locations or like solar energy that has a strong daily and seasonal component. While global geothermal energy will not be exhausted within a multitude of human time spans (**Figure 16**), local subsurface rock volumes used as geothermal reservoirs may eventually be cooled down to a degree that will make them ineffective for further heat extraction. Of course, heat extracted from the hot rocks of a geothermal reservoir will always be replaced from below, but temperature recovers slowly since heat conduction is a relatively slow process. Eventually, the reservoir is cooled down so that economic production of thermal energy is not possible any more in this particular location. Hence, while the geothermal energy in Switzerland in principle is a renewable resource, specific geothermal energy facilities and reservoirs intrinsically have limited time spans of a few to several decades.

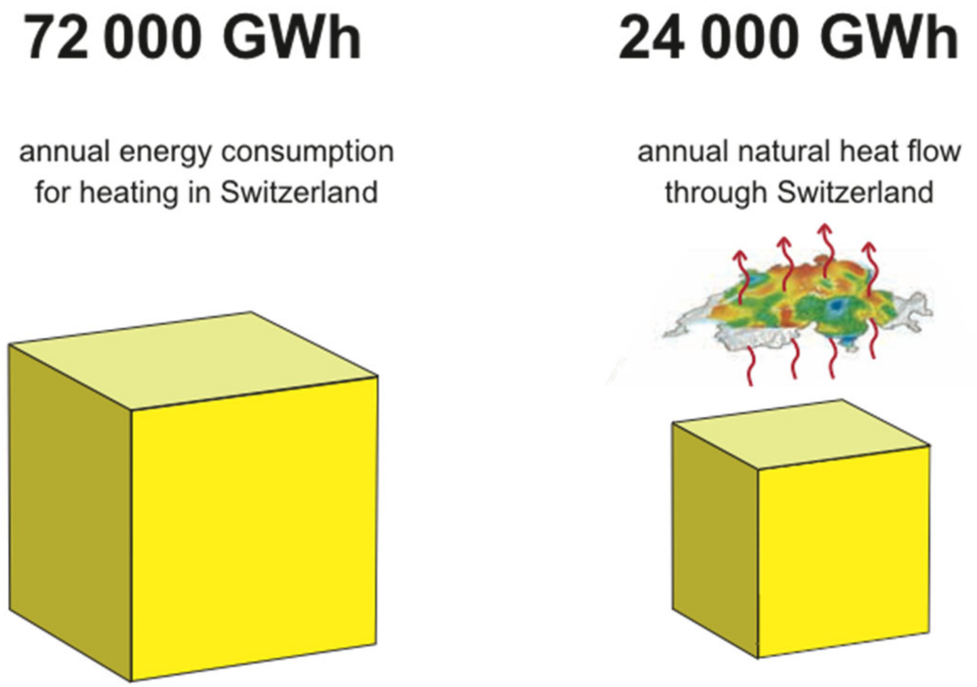

Figure 15: *Annual natural heat flow from Earth's interior through surface of Switzerland amounts to about 1/3 of the annual energy consumption for heating (2013). Note that this heat flow is renewable, continuous and available everywhere though laterally variable in strength.*

2.1.1 What is a geothermal resource?

Following the Australian Geothermal Reporting Code (2010), geothermal resources are defined as "*a geothermal play which exists in such a form, quality and quantity that there are reasonable prospects for eventual economic extraction. … The location, quantity, temperature, geological characteristics and extent of a geothermal resource are known, estimated or interpreted from specific geological evidence and knowledge.*" It also states that the term geothermal play "*is used as an informal qualitative descriptor for an accumulation of heat energy within the Earth's crust. It can apply to heat contained in rock/ or fluid. It has no connotations as to permeability or the recoverability of the energy*."

Most existing regional and local studies carried out in Switzerland employ the above perspective. They identify certain geologic structures that may have, in theory, the "potential" to be used for geothermal exploitation. Then, a volumetric approach is used to estimate the "geothermal productivity" from a temperature model combined with assumptions on reservoir permeability. Any predictions of recovery factors, defining the fraction of heat stored in the rock that can be extracted relative to a base temperature, are speculative or even arbitrary. Estimates reported as "geothermal potential" or "geothermal productivity" that are based on such volumetric calculations naturally are very large (**Figure 16**) and must be understood as speculative extrapolations without any quantitative relation to realistic productivity estimates. For more relevant estimates of geothermal resources, extensive geophysical exploration is a prerequisite to obtain detailed subsurface information. Precise knowledge about the temperature field and geometries of geological formations and their physical parameters at depth are of great importance. Furthermore, reservoir evolution and heat extraction simulation methods reflecting the different types of geothermal system must be applied for more realistic estimates of productivity rates.

Since at present no high-temperature geothermal system in Switzerland is exploited for electrical power production, we apply the world-wide state of knowledge to estimate such geothermal resources in Switzerland. With 8 km depth, the range accessible with current drilling technology goes beyond the needs of geothermal electrical power plants. When discussing resources, we must distinguish between different types of geothermal systems (hydrothermal, petrothermal, or geothermal heating of buildings), different geological units and even tectonic setting. For example, crystalline rocks have in situ poor conditions for strong fluid circulation, so local fracture networks must be stimulated by engineering activities through the well. Natural flow of water in considerable amounts occurs along fault systems in the Mesozoic rock layers of the Swiss Alpine Foreland, whereas the water-saturated Swiss Molasse Basin would show best conditions for the use of borehole heat exchangers.

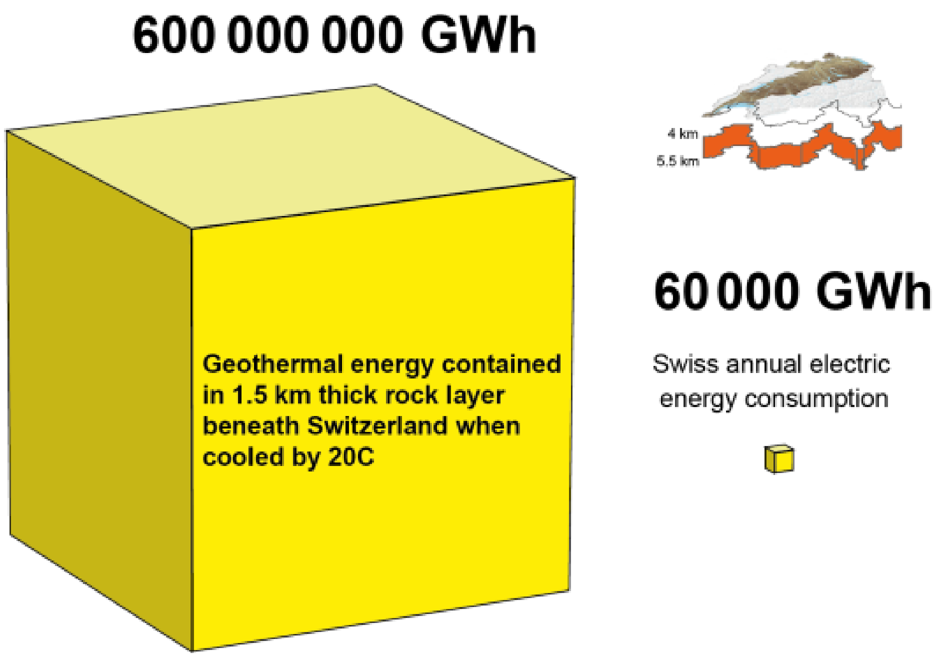

Figure 16: *An immense amount of geothermal energy is potentially available in Switzerland's subsurface. Even if it were not replenished quickly by natural heat flow from below, the energy contained in the layer of rock between 4 km and 5.5 km depth (originally about 150 °C hot) when cooled by only 20 °C would be equivalent to 10'000 years of the current Swiss annual electricity consumption (Bundesamt für Energie, 2013). Presently, however, we are unable to make use of this geothermal energy for electric power production and the technical advances necessary to exploit even a small fraction of it in the future represent great challenges (see text).*

2.1.2 From resources to reserves

In principle, geothermal **resources** may be seen as unlimited, since thermal energy is available at high quantity, and the heat energy produced is sustained by the continuous heat flow. Geothermal **reserves**, however, are defined as "*that portion of an indicated or measured geothermal resource which is deemed to be economically recoverable after the consideration of both the geothermal resource parameters and modifying factors*" (2010). To prove a geothermal reserve, it must be drilled and tested to establish if temperature and flow rates are sufficient, and predictions of the reservoir lifetime must also be made.

Modifying factors, in this sense, are all limitations which directly affect the likelihood of commercial delivery. Some of these limitations are discussed in other work packages of this report, i.e. social acceptance, legal matters, or economics. Some limitations related to technology and economic viability exist today and pose an obstacle for the exploitation of geothermal reservoirs for electric energy. Hence, one could quickly conclude that geothermal reserves in Switzerland are very small. Without careful analysis of the limitations, however, such a conclusion would be premature.

The main limitations for the estimates of geothermal reserves owe to technology. Stimulation techniques to produce large and efficient heat exchangers at depth are underdeveloped at this stage. An additional limiting factor that has recently come into focus is seismic risk, since enhancing permeabilities for an operating deep geothermal system inevitably increases local seismic hazard of felt and potentially destructive earthquakes to some degree. Both deep geothermal projects in Switzerland were confronted with induced seismicity. In the Basel petrothermal project, seismic events occurring during high pressure stimulation were felt by the community and resulted in a complete stop of the project. In St. Gallen with the hydrothermal exploitation concept, significant seismicity (M3.4) also occurred, though the project was recently terminated due to much too low permeability and natural production of hot water. Obviously, induced seismicity remains a key factor for any future high-temperature geothermal project in Switzerland and must be taken into account when estimating geothermal reserves in Switzerland.

2.2 Types of geothermal systems

Deep geothermal systems extract and utilize the heat contained in the rocks in different ways. The key parameter in all geothermal heat exchange systems at depth is how quickly how much energy for how many years might be extracted from the rock volume. For electric power generation in petrothermal and hydrothermal systems, heat extraction at depth is achieved by "open" water circulation: these systems consist of at least two wells, one for production of hot water and one for re-injection of cooled water. Within the geothermal reservoir at depth the cool injected water diffusively flows from the injection well tip or open section through the hot rock toward the production well where the hot water is collected and pumped to the surface. Hydrothermal systems (St. Gallen type) make use of natural high rock permeabilities usually combined with fault systems while in petrothermal systems (Basel type) permeability must first be significantly enhanced locally to facilitate sufficient water circulation between injection and production wells.

For economic and commercial reasons, hydrothermal and petrothermal systems for electric power production are usually combined with usage of hot water for heating purposes and this was also planned for the geothermal systems in Basel and in St. Gallen. Presently, in Switzerland geothermal energy is only used for heating purpose, mostly with shallow ground source heat pump systems for space heating (2.3 TWh in 2012, (Antics *et al.*, 2013)). The heat pumps necessary with all low temperature geothermal systems, though, consume a significant amount of electric power. The produced thermal energy of direct heating plants using deep geothermal energy was only 10 GWh in 2012. Obviously, with efficient borehole heat exchangers operating as closed systems in depths of about 2 km within the water-saturated Molasse sediments one could envision a significantly increased geothermal contribution to the energy needed for heating in Switzerland but without additional electric power needed for heat pumps. For this reason, in our study we also analyze the potential of high-temperature (> 60°C) geothermal heating systems (in the geothermal energy terminology, so called direct-use systems), without the need of heat pumps.

2.2.1 Hydrothermal systems

Deep hydrothermal systems aim to exploit hot water from natural aquifers at depths of 3−5 km (**Figure 17**). Potential target formations are the Mesozoic rock layers of the Swiss Alpine Foreland that have a relatively high natural permeability in connection with systems of extensive fracture zones, that in general are related to specific geologic structures in the basement (i.e., Permo-carboniferous troughs). It is common practice to further increase rock permeability by acid stimulation that dissolves minerals and may open fluid path ways.

The produced hydrothermal fluids in general are re-injected into the aquifer in order to prevent a pressure decline over time, and to dispose of the highly mineralized fluids. If the produced water is hot enough, the generation of electric power is possible, as it was planned in the St. Gallen hydrothermal project. Prognosis and estimates of permeability and achievable flow rates of a system, however, are highly speculative and only drilling into the reservoir and hydraulic tests will eventually decide if the requirements for production are met. In St. Gallen, hydraulic tests yielded only 5 l/s instead of the expected 50 l/s that would have been necessary for economic production. Similarly, the Zurich/Triemli project did not show sufficient flow rates from the potential aquifer rock layers. The well was drilled in 2010 down to the crystalline basement at 2700 m depth, and is now used as a deep borehole heat exchanger.

In Germany, a number of hydrothermal projects are producing thermal and electrical energy. One of them is the geothermal plant in Unterhaching near Munich in the Bavarian Molasse Basin. It has similar geologic settings as the St. Gallen system. In Unterhaching, hot water with a temperature of 133 °C is produced from a 3850 m deep well (Malm aquifer), at a flow rate of 150 l/s [11]. The geothermal plant has an installed capacity of 3.3 MW, and produced 8 GWh of electric power in 2012.

Hydrothermal reservoirs are largely open systems, where paths of fluid flow are not well known and may reach over large distances. Over the reservoir lifetime, great volumes of water are extracted and re-injected at another location. There is the risk of changes in water

[11] http://www.geothermie−unterhaching.de

levels or hydraulic pressure, and there is also an increased seismic risk during and after operation.

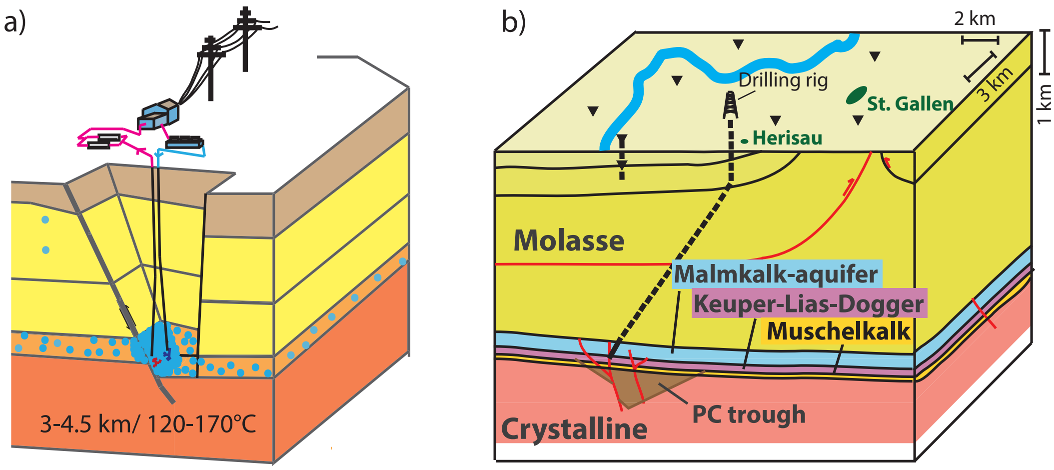

Figure 17: *Hydrothermal system "St. Gallen Type" for electric power production. a) General situation with production and re-injection wells reaching a natural aquifer system at depth of several km with temperatures between 120 °C and 170 °C. b) Situation in St. Gallen showing the exploration well drilled into a local fault system within the Malm limestone aquifer. The planned hydrothermal system in St. Gallen is similar in design and setting to the geothermal plant in Unterhaching (Bavaria) that produced 8 GWh of electric power in 2012.*

2.2.2 Petrothermal systems

Petrothermal systems (**Figure 18**) aim to extract heat from a stimulated reservoir system, mainly in crystalline basement rocks at 4–5 km depth with expected temperatures of about 150 °C. Such systems are primarily intended for electric power generation. In general, granitic rocks are of low permeability and, hence, do not naturally allow a significant fluid circulation. Sometimes, the terminology "hot dry rock" is used for such systems. This is not entirely correct, because rocks are never dry but almost impermeable. To enhance permeability and to create a reservoir that acts as a subsurface heat exchanger, the rock volume must be stimulated by hydraulic fracturing (engineered or enhanced geothermal system, EGS, see Chapter 3 WP2). Fluid is injected under high pressure into the hole in order to create and open fractures in the rock that eventually will allow the water to circulate and heat up efficiently when in contact with the hot rock surface. Compared to hydrothermal systems, petrothermal systems form a relatively local fluid flow cycle from injection well through the fracture system to the production well. The flow rates are controlled by pressure applied for injection and production.

Hydraulic reservoir stimulation is accompanied by induced seismicity. At the Basel Deep Heat Mining project, several seismic events with magnitudes M>3 occurred during and after the high-pressure reservoir stimulation phase (Haring *et al.*, 2008). They were felt by the community and resulted in a complete stop of the project. Pressures necessary for operating a petrothermal system, however, are much lower than for hydraulic stimulation and water circulation remains local. Therefore, estimated seismic risk is lower during operation than during the enhancement period.

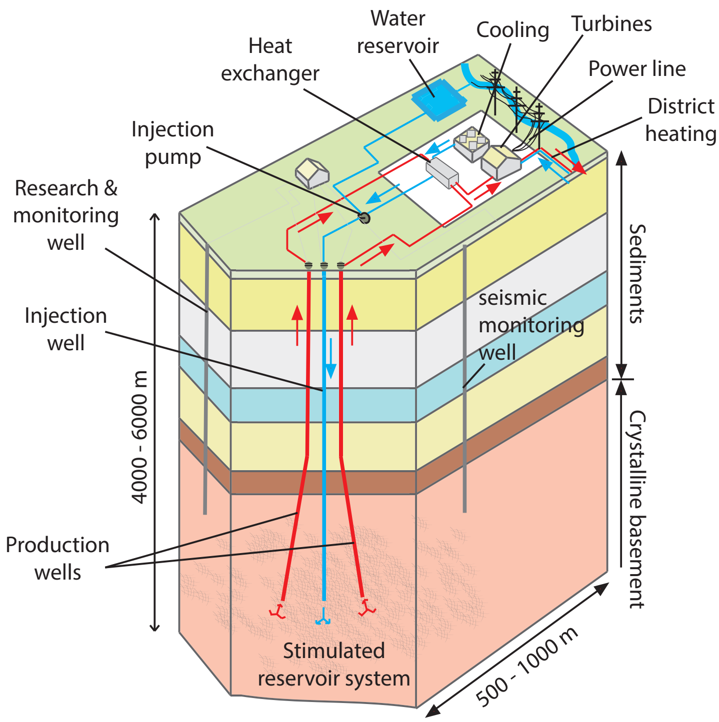

Figure 18: *Petrothermal system "Basel Type" for electric power production.*

There is little experience with petrothermal systems worldwide. An example of an operating site is Soultz-sous-Forêts, France, where the target lies within a pre-existing, relatively high permeable fault system.

2.2.3 Geothermal heating systems

In principal, geothermal heating systems that work without additional heat pumps operate similarly to shallow heating systems but at higher temperature. For direct heating purposes, temperatures above 70 °C are necessary, corresponding to well depths of 2–3 km. Standard closed circuit borehole heat exchangers for heating purposes employ fluid circulation systems within each well by double tubing. The fluid is injected into the outer tube and is extracted from the inner tube. Heat exchange between rock and fluid is achieved through the outer walls of the well casing. In order to achieve production temperatures of up to 50 °C at significant flow rates, however, efficiency of heat exchange must be increased, possibly by simply increasing the contact area either with wider bore holes or with a series of wells. No significant seismic risk is currently known to be associated with this kind of geothermal usage.

The heat extraction eventually cools down the rock volume locally, in the direct vicinity of the well and long-term performance of the system depends on natural heat transport from the surrounding rock volume toward the well. Efficient natural heat transport in subsurface rock is explicitly associated with the abundant presence of water that is able to flow even at a very slow rate. Such conditions are possible and even likely in much of the Tertiary sediments in the Swiss Molasse Basin.

In Switzerland, some borehole heat exchangers were installed in wells drilled for hydrothermal projects that did not show economic flow rates (i.e. Weggis, Zurich/Triemli, and maybe St. Gallen), but no such well exists that was planned as a deep borehole heat exchanger from the beginning. At Triemli, the borehole heat exchanger reaches a depth of 2371 m.

2.3 Reservoir prospecting methodologies – state of the art

A geothermal resource analysis requires knowledge of the thermal and hydraulic three-dimensional (3D) situation at depth that may be acquired by local application of a series of exploration methodologies specifically designed to provide targeted information (**Figure 19**). A regional 3D structural model is the basis for further derivation of hydraulic and temperature models. They are related through thermal and hydraulic rock properties, respectively. Borehole measurements give direct access to petrophysical properties at depth though only for a specific location. Most information about the subsurface is inferred from geophysical measurements made at the surface. Different geophysical imaging methods exist, like seismic or electro-magnetic surveys. They are explained in WP2. Rock properties are measured on rock samples in the laboratory for appropriate temperature and pressure conditions, or in well logs directly. A very important geophysical parameter for geothermal systems – the temperature field at depth –, however, may not be measured directly. Rather, the temperature field at depth must be calculated taking into account surface heat flux (**Figure 14**), structural and hydraulic situation, and the thermal parameters. Thus, numerical modeling plays an important role, taking into account the physical laws of heat transport, as well as defined boundary conditions and borehole temperature profiles.

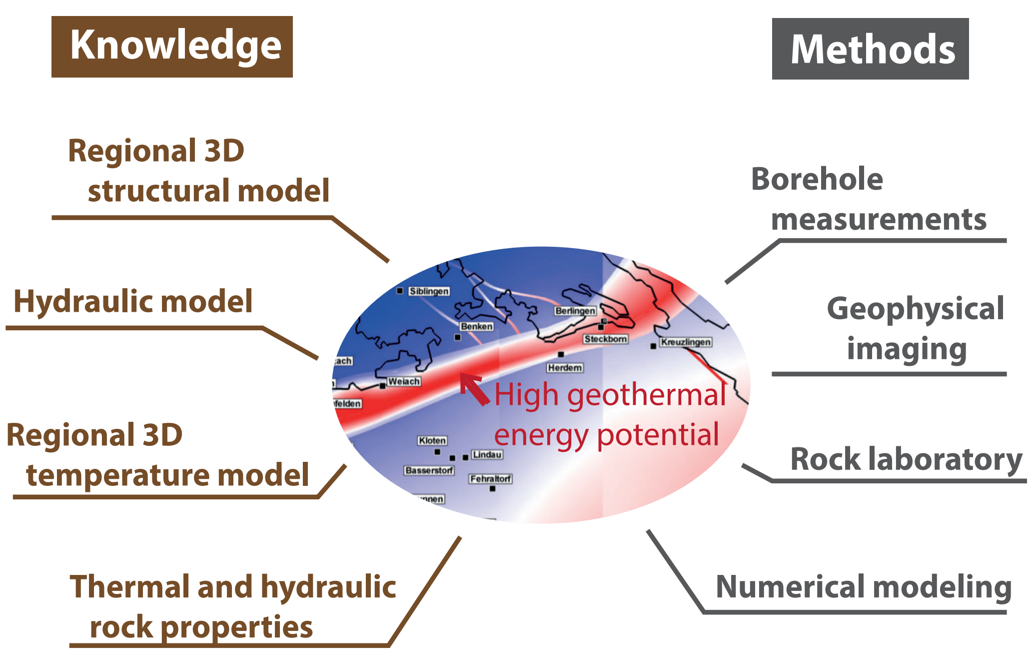

Figure 19: *Knowledge and methods for geothermal resource analysis in addition to excellent regional geologic information (modified from Kohl* et al*. 2005).*

2.3.1 Structural and hydraulic information

Structural models are built on information about lithological units and stratigraphy, which is collected from geologic profiles, outcrops of geologic formations, or borehole core samples. The models importantly constrain the kinematics of the subsurface, which when coupled with appropriate constitutive models yield important insights into the dynamics – especially from a mechanical point of view – of a geothermal reservoir. Also, information about fault systems must be included, that can be derived from seismic imaging surveys. Structural models on different levels help in resource estimation and in well planning (**Figure 20**). **Figure 20a** shows the numerical model of the geologic structure of a 40 km by 60 km region in northern Switzerland, down to 10 km depth (Signorelli and Kohl, 2006). The crystalline basement consists of weathered and probably fractured rock on top that outcrop towards North-East. Below the covering layer of younger sedimentary rocks, there is a Permo-carboniferous (PC) trough within the basement rocks. This structural model was used for further temperature modeling. **Figure 20b** shows a cross section through the St. Gallen geologic model with the exploration well GT-1 indicated. The target of the drilling was the Malmkalk aquiferous layer and a fault zone, reaching down to a PC-trough.

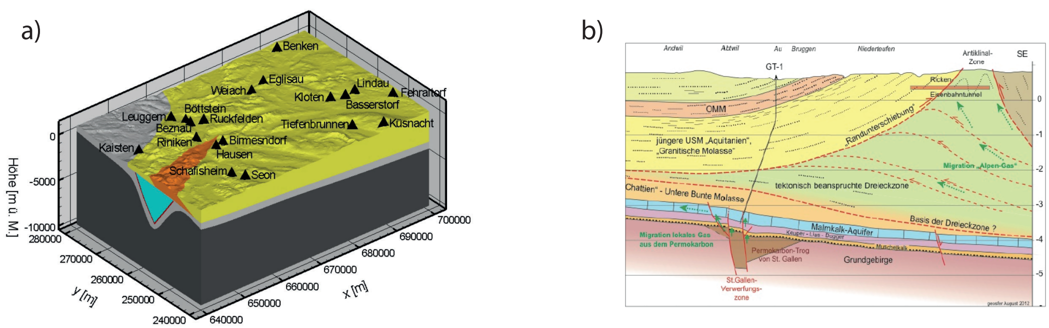

Figure 20: *Geologic subsurface models. a) Numerical model of the geologic structures for a region in Northern Switzerland. Blue color indicates a Permo-Carboniferous trough (Signorelli and Kohl, 2006). b) Geologic model of the St. Gallen region showing the drilling into the fault zone (from: Stadt St. Gallen).*

The most important geophysical technique for mapping complex layer and fault structures is the high-resolution reflection seismic imaging. It is a very advanced tool that in combination with drill holes plays a key role in oil and gas exploration. Seismic waves originating from an artificial source at the surface are reflected at layer boundaries and other structures with significant impedance contrast at depth. The waves are recorded by a number of geophones arranged in a 2D or 3D geometry at the surface. **Figure 21** shows an example of a seismic profile and the structure inferred from the observed reflections and constrained by borehole data where available. In the Swiss Alpine foreland, numerous seismic surveys were carried out for hydrocarbon exploration. Also, many data sets were collected by National Cooperative for the Disposal of Radioactive Waste (NAGRA) searching for potential locations of deep radioactive waste repositories.

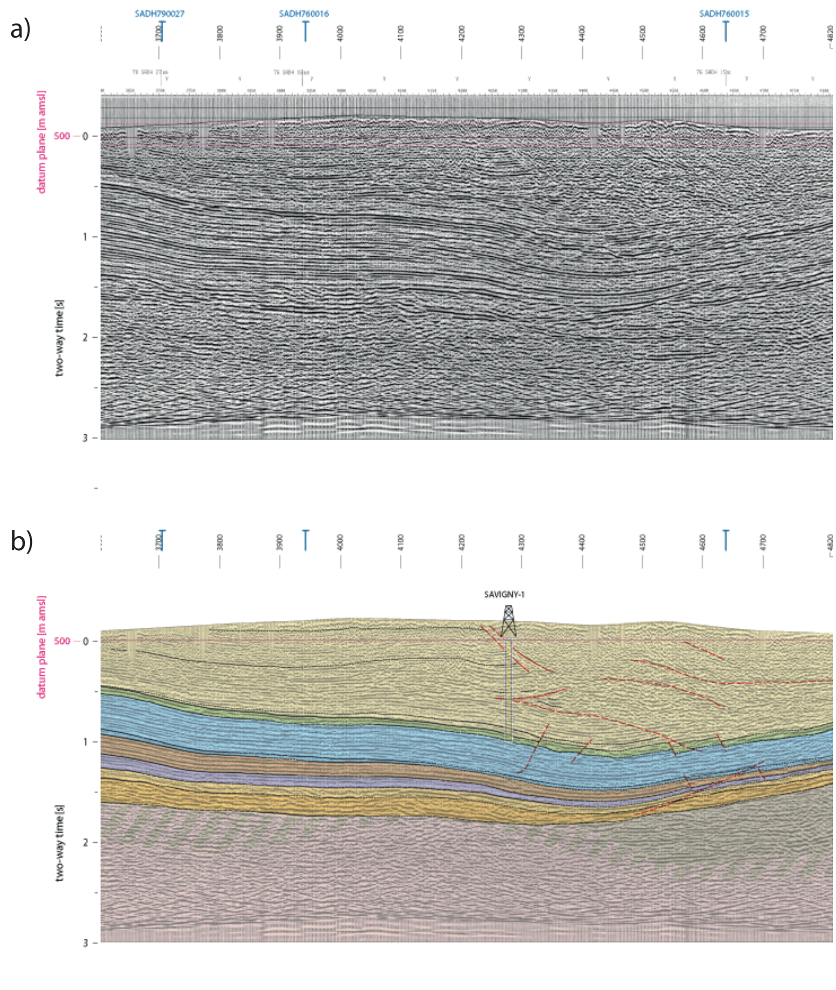

Figure 21: *Seismic interpretation of example reflection profile in Swiss Molasse Basin (Sommaruga et al., 2012). a) Profile of reflection seismic data and b) seismic interpretation showing individual sedimentary layers in different colors.*

For the Seismic Atlas of the Swiss Molasse Basin (Sommaruga *et al.*, 2012), more than 1200 km of selected reflection seismic profile data and, additionally, all available borehole data were analyzed and interpreted in the light of geologic information. The result is a regional structural model down to several kilometers depth. Geometry and thickness of the sedimentary layers covering the basement are shown in 15 transects and many maps of the interpreted horizons, i.e. base Mesozoic, top Dogger, or base Tertiary covering the Molasse Basin (**Figure 22**). The two sections in **Figure 22c** (extract from Transect 3 located in western Switzerland) and **Figure 22d** (extract from Transect 11, representative for the eastern Molasse Basin) well document the systematic difference in structure across the Mittelland. In the west, the layers of the Mesozoic sediments are much thicker and at shallower depth than in the east. Conversely, thickness of the Tertiary Molasse sediments is much increased in the eastern part of the basin. Common to all of Swiss northern Alpine foreland is a significant increase in depth of the granitic basement from northwest (NW) to southeast (SE) towards the Alps. In the eastern Molasse Basin, potential aquifer Mesozoic layers can be found at depths greater than 4 km (T > 120 °C) as, i.e., in St. Gallen.

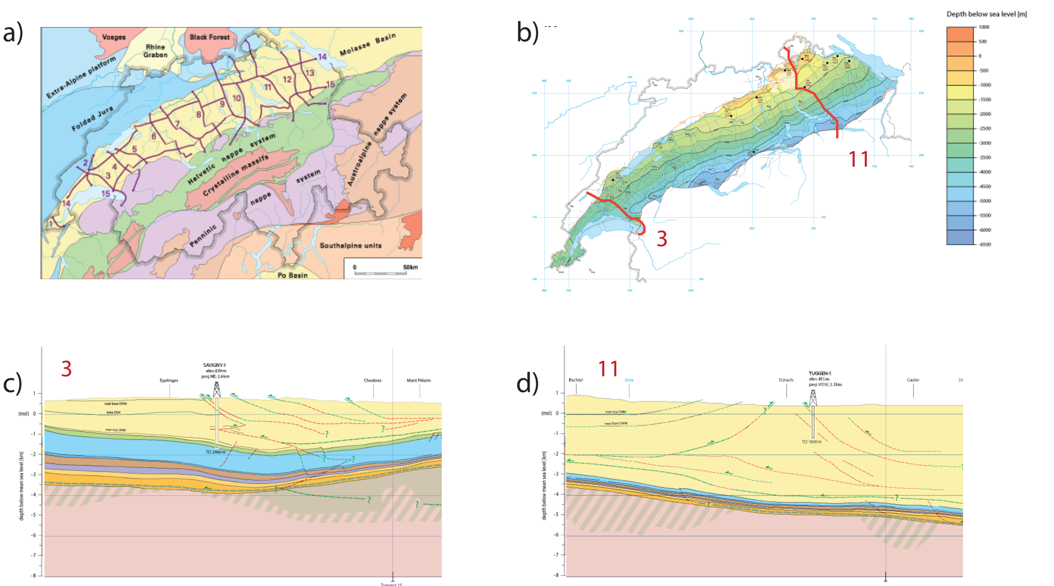

Figure 22: *a) Tectonic overview and location of the 15 profiles of the Seismic Atlas of the Swiss Molasse Basin. b) Depth map of base Mesozoic. The two red lines show the location of the profiles shown in c) and d). Cross sections representative for c) Western and d) Eastern Switzerland showing a systematic difference in structure (Sommaruga et al., 2012).*

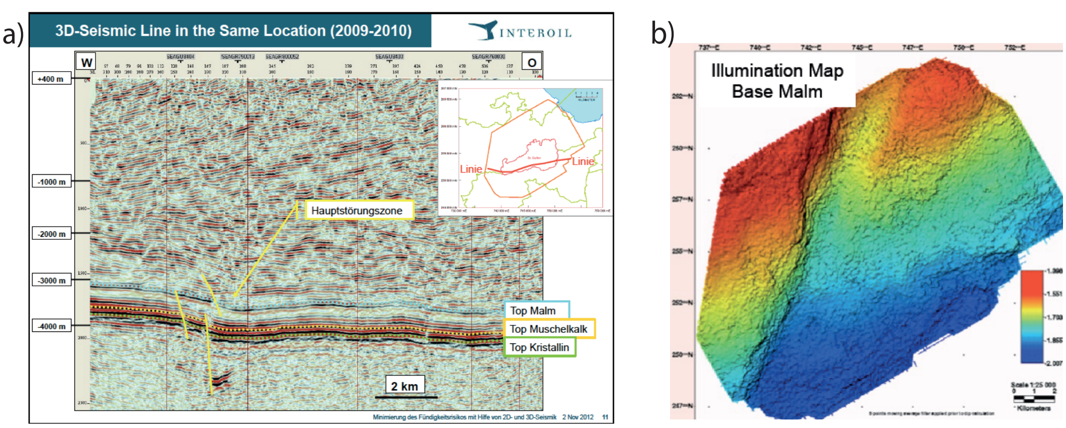

Figure 23: *Results of the 3D seismic survey of the St. Gallen geothermal site. a) 3D seismic cross section with main horizons and main faults indicated. Location of the line as well as the survey area are shown in the inset. b) 3D map of the fault structure (Interoil AG).*

The Seismic Atlas provides important information about the regional subsurface structure of the densely populated Swiss Mittelland for assessing its geothermal potential. Additionally, 3D seismic surveys must be carried out at selected sites in order to better resolve relevant local structure and fault systems. **Figure 23** shows results from a 3D seismic survey obtained for the St. Gallen geothermal site. A cross section along a profile through the future hydrothermal resource region in the Mesozoic layers reveals the target fault structure (**Figure 23a**) that is documented in map view of the base Malm interface as part of a regional fault system of up to 30 km length (**Figure 23b**).

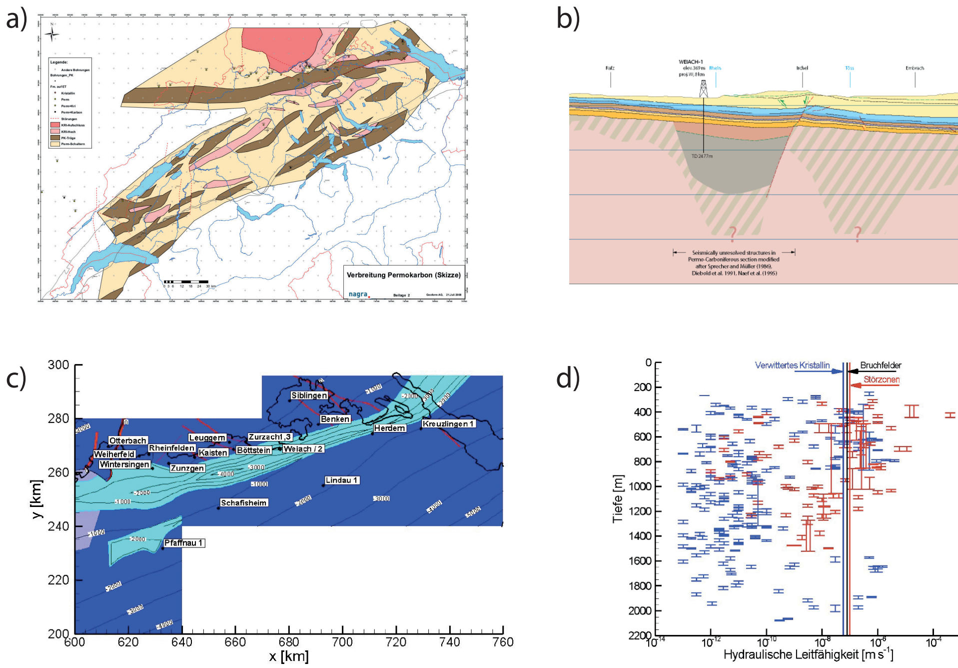

Figure 24: *a) Distribution of Permo-Carboniferous troughs (brown) (Nagra, 2008). b) Cross section showing the Weiach-trough that was drilled by the Weiach-1 well. Northern part of transect 11 of the Seismic Atlas of the Swiss Molasse Basin (Sommaruga et al., 2012). c) Hydrogeologic map of the top crystalline showing higher hydraulic conductivities beneath the Permo-Carboniferous troughs (cyan). Location and names of wells reaching the crystalline are also shown (Signorelli and Kohl, 2006). d) Hydraulic conductivities of the crystalline from borehole measurements in North-Eastern Switzerland. Higher hydraulic conductivities are observed in fault zones (Thumann) compared to the undisturbed weathered crystallines (blue) (Signorelli and Kohl, 2006).*

Permo-carboniferous troughs (PC troughs) are graben structures that exist within the crystalline basement and are filled with sediments (**Figure 24**). It is assumed that there are fractured rocks and deep reaching fault systems at the trough boundaries. A somewhat speculative map of the spatial distribution of PC troughs in Northern Alpine foreland is shown in **Figure 24a** (Nagra, 2008). There is a large uncertainty about these structures. To better resolve these structures in crystalline rocks, high-resolution 3D seismic imaging (see, i.e., **Figure 23b**) would be needed and it must be verified by deep well information (i.e. Weiach-1 well, **Figure 24b**). PC troughs are likely to exhibit increased fluid circulation and thus higher conductivities relative to the crystalline basement rocks (**Figure 24c**). Therefore, precise knowledge of these structures has a direct influence on the reliability of hydraulic models. Hydraulic conductivity may significantly vary over short distances, as, i.e., observed in various borehole measurements in the upper, weathered part of the crystalline basement

(**Figure 24d**). Hydraulic conductivity strongly increases in the presence of extensive fractures and fault systems as, i.e., the one targeted in the St. Gallen project. In the Swiss Molasse basin, there is also a chance of natural gas entering a well driven into such fault systems. The gas that entered the well in St. Gallen likely originated from the PC trough below the Mesozoic aquifer layer, migrating upwards along existing faults (**Figure 20b**).

Information about hydraulic conductivity, as well as other hydrogeological data from deep wells can be found in the BDF-Geotherm web database of geothermal fluids in Switzerland (Sonney and Vuataz, 2008).

2.3.2 3D subsurface temperature field

The distribution of temperature at depth is an important parameter when estimating geothermal resources. In Switzerland, the average geothermal gradient at which temperature increases with depth is 30 °C/km. There exist, however, significant local deviations from average gradient depending on geology and water circulating at depth. The surface heat flow map of Switzerland (Medici and Rybach, 1995) documents the heat flow density through earth's surface (**Figure 25**). It is mainly derived from borehole temperature logs and thermal conductivity of the rock. The data basis for the heat flow map was 150 data points within Switzerland, and additional points in the neighboring countries, with a quite uneven spacing. No data were available for the Valais and eastern Alps. Also, corrections must be applied to the measured heat flow, i.e. correction for topography or the effect of the last ice age, when earth's surface was colder. In Switzerland, heat flow density varies between 40 and 130 MW/m^2. This is, of course, much less than in volcanic areas (e.g. Iceland), but still significantly higher than for Northern European countries. The annual heat flow amounts to more than 1000 MWh/km^2 in areas with a high heat flux.

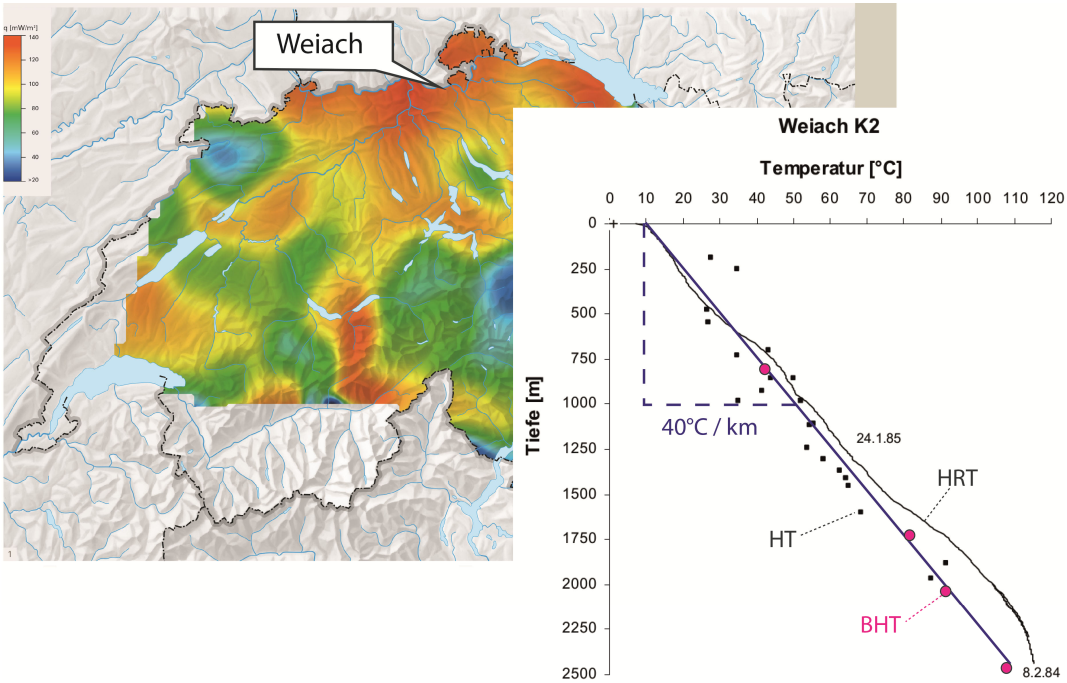

Figure 25: *Surface heat flow map of Switzerland (swisstopo, 2013; Medici and Rybach, 1995) and borehole temperature data of the Weiach well (Schärli and Kohl, 2002). Different methods were used: high resolution temperature (HRT) logging, bottom hole temperature (BHT), and temperature measurements during hydraulic testing (HT). Measured data can be approximated by a geothermal gradient of 40 °C/km.*

Surface heat flow values may not be linearly converted to temperature at depth, but a relatively high heat flow density in an area is a clear indicator for a geothermal gradient above the average and, hence, higher temperatures at shallow depth. Temperatures observed in the Weiach-well, which is located in an area with high heat flow density in northern Switzerland, can be approximated by a geothermal gradient of 40 °C/km (**Figure 25**). Routinely observed borehole temperature measurements provide the main information for temperature at depth but they often exhibit large uncertainties, depending on how they were obtained. Furthermore, there might be systematic differences between measured temperature of the drill mud and the in-situ temperature of the surrounding rock formation. Measured temperatures must be corrected for thermal disturbances due to the drilling process and due to the influence of local water circulation. The most reliable − though most costly − method is to measure the bottom hole temperature (BHT) where circulation of the drilling fluid has been stopped for a while to approach the actual temperature of the surrounding rock.

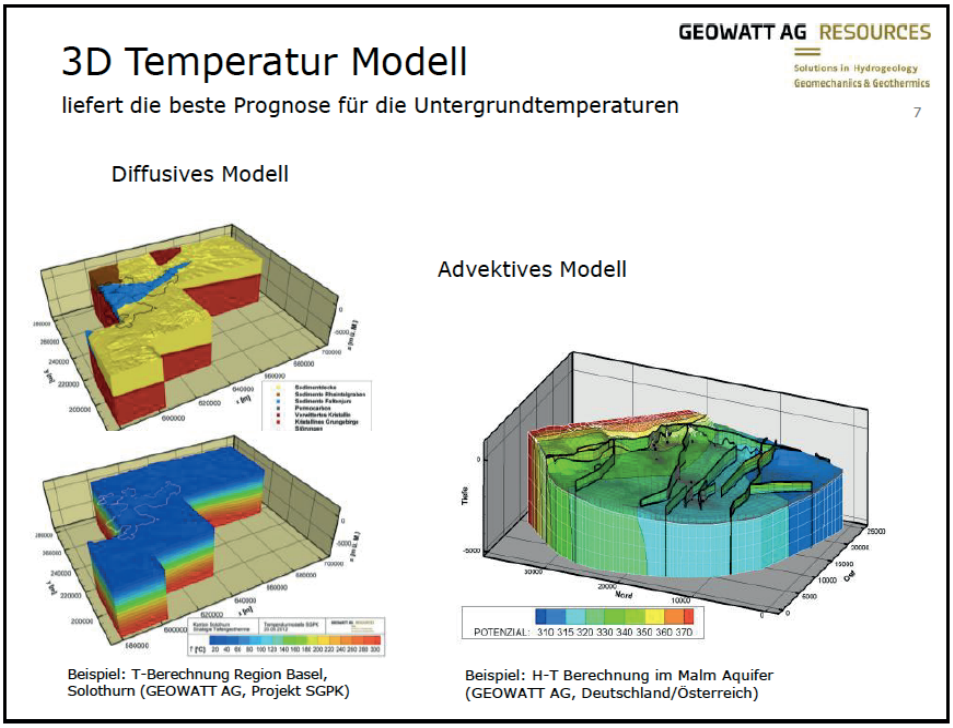

Figure 26: *Numerical modeling is used to achieve a regional 3D temperature model. Diffusive as well as advective processes of heat transport must be considered (Geowatt AG, 2013).*

Knowledge of the surface heat flow is essential for estimating the subsurface temperature field. Heat transport in rocks is either conductive or convective. Heat conduction is a slow, diffusive process from high to low temperatures. It depends on thermal rock properties (thermal conductivity, heat capacity, density) that can be examined with rock samples in the laboratory. Rock properties for numerous rock samples from all around Switzerland are available in databases (Schärli and Kohl, 2002; Leu *et al.*, 2006; Zappone and Bruijn, 2012). Convection of fluids is driven by density and pressure variations. Fluids can collect and transport heat very efficiently when moving through porous rocks and fracture networks. Convection most significantly contributes to the subsurface temperature distribution. Upwelling hot fluids that go upwards along deep reaching fault systems can cause local high-temperature anomalies, as for example in the Upper Rhine Graben. Numerical modeling of the three-dimensional temperature field must account for diffusive and convective heat transport (**Figure 26**). Convective heat transport by moving fluids is relevant for hydro-thermal systems (St. Gallen-type). Models must be based on reliable structural and hydraulic models, and must be constrained by borehole temperature profiles.

The currently available heat flow map is the version of 1995 (Medici and Rybach, 1995) when only a few deep bore holes were available and the map (**Figure 25**) is obviously insufficient for the purpose of assessing the geothermal resources in Switzerland. In northern Switzerland there exists a reasonable number of borehole temperature measurements (**Figure 27a**) including, in particular, temperature observations from deeper than 1000 m depth that are most useful to constrain deep 3D temperature models. An updated temperature model was provided by Geowatt AG for the Swiss Molasse basin, including all recent temperature data acquired and resulting in a new 70 °C temperature map with better spatial accuracy (**Figure 27**).

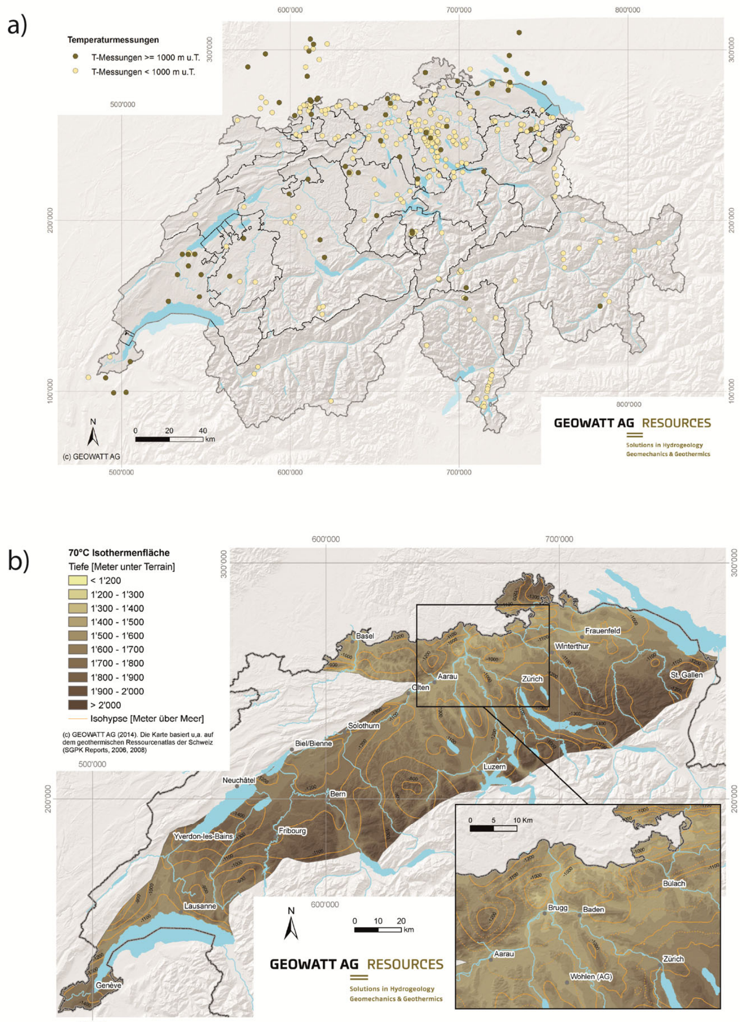

Figure 27: *Updated 3D temperature model for Molasse basin and northern Switzerland. a) Locations of borehole temperature measurements in Switzerland. Black dots indicate data from depths greater than 1000 m. b) Map of the 70 °C isotherm. Area in northern Switzerland with a relatively high heat flow density is zoomed (Geowatt AG, 2014).*

2.3.3 Geothermal potential

The geothermal potential depends on the physically available thermal energy at depth, given by temperature and thermal rock properties and on our capabilities to extract energy at depth and transport it to the surface. Since the agent for heat transport is a fluid, the simplest parameter for estimating the geothermal potential is the flow rate at which a sustainable production of the hot fluid is possible. In many studies, a formula from Gringarten (Gringarten, 1978) is used to estimate flow rates in hydrothermal systems. Even with good hydraulic data about the transmissivity of the aquifer, preferably from borehole measurements, there still remain high uncertainties, because transmissivity values may strongly vary laterally within the same aquifer formation. With the estimated flow rate *Q*, the thermal power or productivity of a geothermal site (P_{th}) is calculated according to Signorelli and Kohl, 2006, as

$$P_{th} = \rho\ c_P\ Q\ \Delta T,$$

assuming a temperature difference ΔT between produced and re-injected water. ρ and c_P are the density and specific heat capacity of the transport fluid (water).

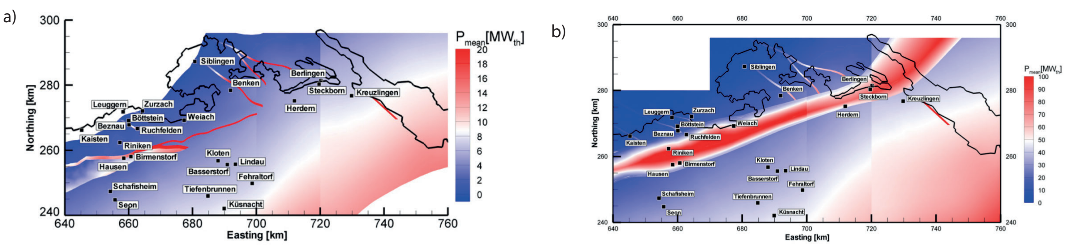

Figure 28: *a) Estimated mean geothermal productivity of the Upper Muschelkalk. b) Calculated thermal productivity for doublets in the topmost 500 m of the crystalline rocks (Kohl et al., 2005).*

Such estimates of the geothermal potential were made for regions in northern and western Switzerland (Signorelli and Kohl, 2006; Kohl *et al.*, 2005; Baujard *et al.*, 2007). Individual aquifers were considered, in particular, those in the fractured uppermost 500 m of the crystalline basement, in the Upper Muschelkalk, and the Upper Marine Molasse. Unsurprisingly, the estimated geothermal potential follows the temperature model to a very large degree. The Upper Muschelkalk is exposed at the surface in the NW of the study region and descends to 4.5 km depth in the south-east with temperatures reaching up to 200 °C in the deepest part (**Figure 28**). The depth of the crystalline varies from near-surface in the NW to more than 4 km in the SE. It is intersected by a southwest-northeast (SW-NE) striking PC-through which has much higher values in transmissivity and in temperature than the surrounding rocks, leading to significantly higher geothermal potential (**Figure 28b**).

2.4 Resource analysis

For high-temperature geothermal energy usage in Switzerland, along the definitions by the Australian Geothermal Reporting Code Committee, 2010, presently insignificant resources and zero reserves are implied. These definitions, however, are strictly operation-oriented and do only in a general sense apply to the current situation in Switzerland where no geo-hermal electric power plant exists but chances and demands for technology and research development need to be explored. Geothermal resources are defined as the recoverable part of the locally available subsurface thermal energy (2010). The key parameter in such estimation is the “recoverable part” and we have reason to believe that technological advances in heat exchangers at depth are possible and they would dramatically increase the recoverable fraction. Therefore, in the following we primarily address the potentially available high-temperature geothermal resources in Switzerland rather than reserves.

2.4.1 Geothermal resources for electric power plants

Natural geothermal resources in the depth range from 4 km to 5.5 km (target temperature range of 120 °C to 180 °C) are very large and for most parts sustained by continuous replenishment (**Figure 15** and **Figure 16**) though locally they will be depleted after approximately 30 years of operation. At present, there exist two types of geothermal systems for non-volcanic regions that allow the production of electric power, hydrothermal (St. Gallen type, **Figure 17**, currently operational in Unterhaching, Bavaria) and petrothermal (Basel type, **Figure 18**, currently operational in Soultz, Rhinegraben).

Based on past experience (Triemli–Zurich, St. Gallen), natural hydrothermal systems of sufficient temperature and flow rates are only rarely if at all available and difficult to find in Switzerland. Furthermore, experience in St. Gallen documents induced seismicity of up to M3.5 as possible if not likely during exploration and construction period for hydrothermal systems targeting fault systems in the Mesozoic basement in Switzerland. This increase in seismic risk during the construction and stimulation period might eventually become manageable with an appropriate Advanced Traffic Light and Assessment System for Induced Seismicity (ATLASIS) procedure (see WP5, Section 6.2) Considering an operation period of 30 years for a system like the one proposed for St. Gallen with 50 l/s flow rate, this would amount to approximately 1 km^3 of water re-injected into the “aquifer”, i.e. fracture zone, that to the best of our knowledge must be understood as part of a seismically active fault system with a historically documented potential of up to M5 earthquakes. Hence, the increase in seismic risk due to long-term operation of a hydrothermal electric power plant is significantly larger than the one resulting from stimulation and construction and it might well be judged as too large in the densely populated Swiss Mittelland. In the light of the above mentioned limitations and consequences that may not be overcome by technical developments, **we do not expect a significant contribution from hydrothermal systems to geothermal electric power production** in Switzerland in the future.

Petrothermal systems (Basel Type) demand artificially created heat exchanging systems at depth. During such a stimulation process microseismic activity is inevitable and seismic activity that can be felt by the local population is always possible (**Figure 29**). Obviously, in future projects we must account for this seismic risk and we must develop stimulation procedures that result in satisfactory reservoir creation while mitigating this risk, i.e., by an appropriate ATLASIS system (see WP5, Section 6.2). Due to the locally restricted fluid flow at depth and the relatively small volume of water circulating, seismic risk during long term operation may be assumed to be lower for petrothermal than for hydrothermal plants. Furthermore, one might envision reducing seismic risk somewhat by favorably locating petrothermal systems in upper crustal blocks with limited or possibly even reduced tectonic stress than otherwise present in the northern Alpine foreland as a result of ongoing Alpine orogenic processes. In the granitic basement of Switzerland north of the Alps there exist a number of regional fault systems, some of which are known to have been seismically active in the recent past. These fault systems might actually reduce the risk for larger earthquakes induced by petrothermal plants if the latter are located within crustal blocks surrounded by but distant from such more regional fault systems.

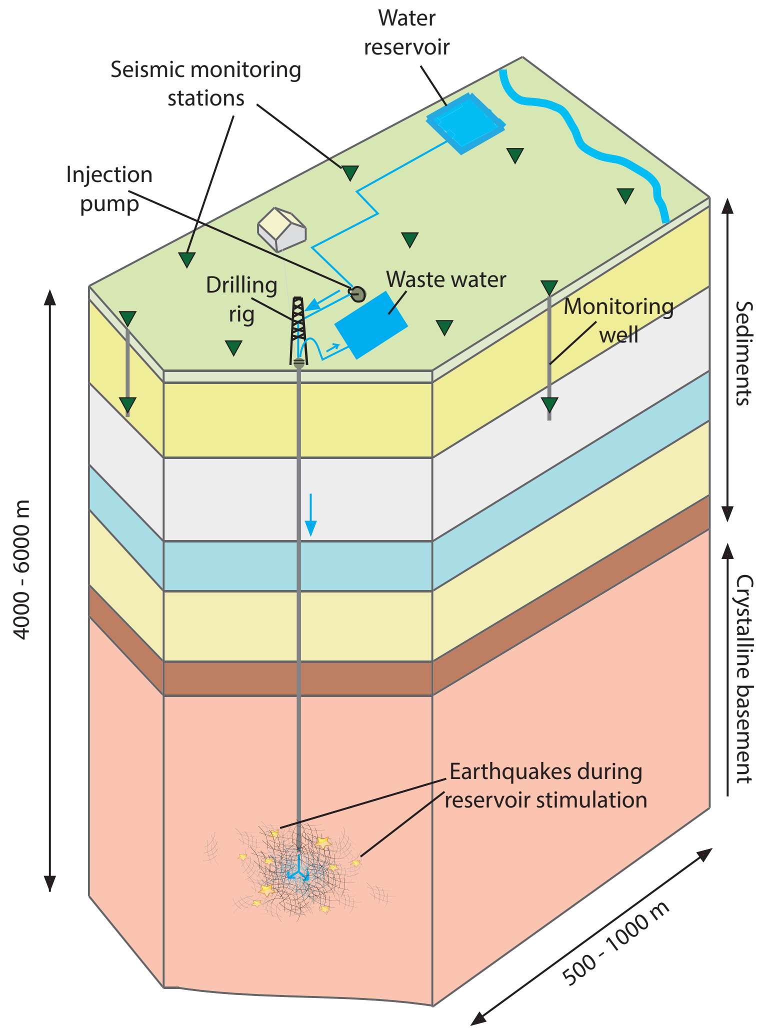

Figure 29: *Situation during stimulation work for a petrothermal system (Basel type, see* ***Figure 18****). The process is similar to that known as "fracking" and the creation of a volume with enhanced permeability in the hot and otherwise almost impermeable rock is intimately linked with micro-earthquake activity.*

Presently, our technical capabilities are far from constructing petrothermal heat exchangers with efficiencies high enough to produce 10–50 MW of electric power for a sufficient period of time. Therefore, major technical advances are needed to create a sustainable heat exchanger in the deeper underground with acceptable seismic risk. As much as they constitute a challenge, such technical advances are certainly not a priori impossible. Based on the assumption that within several years' time efficient petrothermal systems in non-volcanic regions might become technically feasible, we may estimate the geothermal resources for electric power production in Switzerland.

With the exception of the deepest part of the Molasse basin the type of rock 4 km to 5 km beneath the surface in Switzerland is similarly favorable for petrothermal systems both inside and outside the Alps, while induced seismic hazard inside the Alps might be somewhat larger if correlated with the natural seismicity observed at shallow depth. More important, however, is the significantly larger uncertainty of the most important existing and seismically active fault systems in the Alps, while beneath the foreland some of those faults are well known and we have an established methodology, high-resolution 3D seismics, to reliably map the granitic basement at that depth range. A conservative estimate for the geothermal resources might take into account 40% of the area of Switzerland (outside the Alps) and 1% recovery of the subsurface geothermal energy contained in the 1.5 km (between 4 km and 5.5 km depth, cooling by 20 °C) at depth, thus, totaling 0.4% of the subsurface energy documented in **Figure 16** or 40 times the current annual electricity consumption in Switzerland. Whatever the estimates, however, such calculation remains speculative and only **documents a significant potential for petrothermal electricity power plants if challenging technical advances in construction of heat exchangers are made**.

2.4.2 Geothermal resources for direct-use heating purposes

Though the project originally exclusively targeted electricity generation by geothermal energy, we propose as a secondary focus the assessment of geothermal resources for direct heating purposes. In principal, high-temperature geothermal heating systems operate similarly to shallow heating systems but at temperatures above 70 °C, corresponding to well depths of 2−3 km. Such high temperatures would allow direct heating without the use of electrical heat pumps. Considering that currently nearly all geothermal energy usage in Switzerland relies on additional electric energy consumption for heat pumps to reach sufficiently high-temperature production fluids, high-temperature geothermics for heating purposes could also contribute to reducing traditional electricity consumption thus allowing its use for other applications.

Standard borehole heat exchangers for heating purposes that employ closed fluid circulation systems within a well by double tubing work very well but at present are of limited efficiency. Technical development for more efficient closed-circuit borehole heat exchangers is needed. Efficient natural heat transport in subsurface rock is explicitly associated with the presence of abundant water that is able to flow though the rock at a very slow rate. Such conditions are possible and even likely in much of the Tertiary sediments in the Swiss Molasse Basin. Induced seismic risk even for open-circulation geothermal systems at this depth in the Molasse sediments seems to be minor compared with Basel and St. Gallen type systems. We therefore propose to consider the approximately 40 km wide region along the northern Alpine front from the Lake of Geneva to the Bodensee with a thickness of the Tertiary sediments of more than 2.5 km as a geothermal resource area where we could make use of the annual heat flow (**Figure 15**) as a sustainable energy source for direct heating purposes.

2.4.3 Necessary information for national resource planning

For a more elaborate and reliable estimation of geothermal resources for electric power generation, additional and updated information are crucially requested. This information includes:

- A new and updated surface heat flow map of Switzerland
- A regional temperature model of the Swiss Molasse Basin for the 70 °C depth environment

- A regional temperature model of Switzerland for depths from 120 °C to 170 °C
- A reliable map of major fault systems in the granitic basement in the northern Alpine foreland
- A seismic risk assessment for petrothermal plants in the granitic basement in relation to regional fault systems and tectonic loading by Alpine orogeny
- An improved traffic light seismic monitoring system during the reservoir enhancing procedure for petrothermal systems
- Developing quantitative modeling of long-term heat extraction and reservoir behavior for resource and reservoir assessment rather than oversimplified calculations such as current estimates (Signorelli and Kohl, 2006; Kohl *et al.*, 2005; Baujard *et al.*, 2007). This will allow creation of a sustainable heat exchanger in the underground with acceptable seismic risk and with increased efficiency.
- Improved efficiency in closed circuit, deep borehole heat exchangers.

2.5 Conclusions and recommendations

A **geothermal resource** is the estimated recoverable thermal energy with respect to a predefined base temperature and specific geothermal exploration systems. The estimate is based on geological and geophysical information. With current underground knowledge, estimates about the geothermal resources in Switzerland can only be made at a very rough level. High uncertainties remain in key parameters such as temperature, permeability, and volumes. Direct measurements are needed.

Geothermal reserves are derived from the resources by applying limitation factors (technological, economic, social, legal etc.). The main limitation is seen in the technology. Stimulation techniques to produce large and efficient heat exchangers at depth are underdeveloped at this stage. Also, seismic risk is an important limitation factor. The current knowledge about resources in Switzerland is too vague and the current level of efficiency of a deep geothermal heat exchanger is too low to allow reliable reserve estimates.

Geothermal energy may well be seen as a **renewable energy source**. Even when envisioning production by future optimal geothermal systems, the extracted heat is small compared to the energy content of the earth. However, local depletion of a reservoir volume over a few to several decades is possible and even likely for petrothermal systems. In such cases, the reservoir may not be recharged by the natural heat flow within an economically reasonable time frame.

There is a very limited geologic setting suitable for **hydrothermal systems producing electric power** in Switzerland. We do not expect a substantial contribution from hydrothermal systems to future geothermal electric power production in Switzerland.

Petrothermal technology for electric power production is seen as applicable in a wider range of tectonic environments. However, it must first be demonstrated that EGS technology is a viable option in order to complete a meaningful assessment of deep geothermal resources.

We propose the **use of geothermal energy for direct heating** purposes. High temperatures accessible from about 2 km to 2.5 km in depth would allow direct heating without the use of electrical heat pumps. Technical development of more efficient closed circuit deep borehole heat exchangers is needed. Induced seismic risk even for open-circulation geothermal systems at this depth in Molasse sediments seems to be minor compared with Basel and St. Gallen type systems. Exploitation of closed-circulation heat exchange systems, however, should be highest on the list for further technical developments.

We have identified a number of **activities and information required** for an improved nation-nal resource assessment. The new-to-be-invented sustainable heat exchangers need to have acceptable seismic risk and increased efficiency. In parallel, quantitative modeling of long term heat extraction and reservoir behavior will contribute to understanding and developing the EGS technology.

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3 WP2: Technology

3.1 Exploration

3.1.1 Geophysical methods to explore deep geothermal reservoirs

Stefan Wiemer, Anne Obermann, Eduard Kissling (ETHZ)

For the successful exploitation of deep geothermal resources it is important to have a precise idea of the 3D geometry of the resource and to monitor the evolution of the reservoir with time. Exploration should ideally be able to identify suitable areas for future deep geothermal projects. For hydrothermal projects, potential fluid flow paths along aquifers with higher permeability must be identified, for example within fracture zones, and the permeability anisotropy estimated. The temperature and extent of the resource should be estimated and ideally critically pre-stressed faults avoided. For petrothermal resources, the challenges are somewhat different: here the temperature field, characterization of the existing fracture network and avoiding critically pre-stressed faults are the main targets, whereas fluid content and pre-existing permeability are less relevant.

Accurate geophysical prospecting is a prerequisite for every site investigation, especially for hydrothermal targets that seek to maximize their chances of success. There is a variety of different geophysical techniques available for assessing subsurface conditions, each with its own strengths and limitations, and cost-benefit ratio. Most geophysical methods do not directly measure the parameters that characterize a geothermal system (i.e. temperature gradient, porosity, permeability, salinity, chemical content of the fluid, pressure in the reservoir, state of stress) but measure contrasts in material properties or closely linked parameters (i.e. electrical resistivity, thermal conductivity, streaming potential, seismic velocity and attenuation, magnetic susceptibility, density).

Major geophysical methods in the context of non-seismic geothermal exploration are: gravity, magnetic and magneto telluric (MT) methods (Knútur Árnason *et al.*; 2010; Blakely *et al.*, 2007) to delineate gross structures and deeper parts of the system. Seismic methods (Casini *et al.*, 2010) are used to determine the elastic properties and the 3D geometries of the reservoir with much higher spatial resolution. Controlled source electromagnetic (EM), geoelectric and ground penetrating radar methods (Savin *et al.*, 2001) help to image the electrically anomalous upper part of the reservoir and provide information about the physical conditions at depth (permeability, temperature, etc.) that cannot be inferred with seismic surveys and that are essential for the reservoir characterization. All of these active field electrical/seismic methods can also be operated within drill holes for in-hole logging (Batini and Nicolich, 1985), as well as surface-to-borehole and borehole-to-borehole methods (Gritto *et al.*, 2003). The self-potential method has been used to monitor changes in fluid flow through the reservoir (Yasukawa, 2000) whereas micro-earthquake and acoustic emissions have been studied to capture and characterize fracturing in the geothermal system (Julian *et al.*, 1996; De Siena *et al.*, 2010).

The choice of the appropriate technique or more likely combination of tools is always based on the target structure and the physical conditions of the site. It is worthwhile to note that current geophysical prospecting techniques have clear limitations:

- It is generally not possible to accurate forecast the permeability at depth, because permeability is determined at the micro-scale. Even extensive and expensive high-resolution 3D seismic surveys, such as the ones conducted in the case of St. Gallen at costs exceeding CHF 5 million are only able to identify potentially promising target regions. The actual permeability can only be estimated through drilling into the target, and as in the case of St. Gallen may also turn out to be disappointing.
- While major fault zones, such as the St. Gallen fault zones, can be imaged within sedimentary layers with increasing detail, it is currently not possible to image the pre-existing stresses that may or may not exist on these fault zones.
- The imaging capability within the basement is poor, inferior to sediments. As a consequence, petrothermal projects will find it difficult to forecast reliably the distribution of fractures in the target region, nor will they be able to rule out that medium to large-scale fault zones are nearby.
- The process of fracture generation and fluid flow during stimulation is difficult to observe and to monitor from surface-based geophysical techniques. Micro-seismicity evolution often remains the most useful evidence for modelling fluid flow and fluid rock interaction.

While some of these limitations may be overcome through additional research and development, in the future, it is unlikely that the geophysical methods will improve so much that the principal barriers, imaging stresses and local permeability, will be fully eliminated. In the following we briefly describe each of the major geophysical methods with emphasis on applications and limitations in geothermal exploration. We discuss as well passive seismic methods that can be used for monitoring purposes.

3.1.1.1 Seismic methods

Seismic methods can be roughly divided into two broad categories based on differences in the sources:

Active seismic methods for exploration purposes

The method of choice for deep exploration is 3D reflection seismic surveying. This method uses artificial sources (explosions, weight drop, vibroseis) to create seismic waves and allows imaging of interfaces and reflectivity patterns that are needed to determine the 3D geometry of the reservoir.

Passive seismic methods for monitoring purposes

A distinction is made between passive seismic methods that use the natural and/or induced seismic activity to delineate active faults and permeable zones, and ambient noise methods. Ambient noise methods make use of the continuous tiny vibrations of the Earth's surface. They can be used to monitor mechanical and structural changes before and after reservoir stimulation or production.

3.1.1.1.1 *Active seismic: 2D/3D reflection seismic*

Method

In active seismic methods artificial impact sources such as explosives or vibroseis are used to generate seismic waves. These waves are then scattered at interfaces and sensed by receivers deployed along a line-array (2D seismic), or in a 2D geometry (3D seismic). The data is digitized and recorded. Based on their propagation mechanism seismic waves are primarily grouped into direct, reflected, refracted, and surface waves. Depending on the type of waves used, the seismic survey is referred to as: refraction survey, reflection survey or surface wave survey. For deep geothermal exploitation purposes with reservoirs in a depth range of 3 km to 8 km, the main method of choice is reflection seismic.

Reflection seismic relies on waves that are reflected from the interfaces between materials with a significant contrast in elastic properties (density, seismic velocity). After the data acquisition, the data are processed. The final product from this survey is a section that depicts a detailed image of the subsurface below the surveyed line. As geological structures that host geothermal systems generally show a high degree of complexity of geological structures that vary laterally, 3D surveys are often required. Both data acquisition with vibroseis or explosives, and the data processing are expensive.

Application to geothermal exploration

The main target addressed by seismic surveys is to image the 3D geometry of the reservoir and to infer the elastic properties and attenuation. Interfaces and reflectivity patterns must be imaged with high resolution (tens of meters) so that presumably permeable structures can be identified, such as fracture zones (associated with fault zones), karstic sinkholes, and alignments of fractures and joints that are controlling water flow in naturally fractured reservoirs. This is a big challenge, especially as the determination of the velocities is often complicated. Combinations with borehole measurements (vertical seismic profiling) are advised as they yield better constraints on the velocities and hence depth resolution of the measurements.

Despite the capability of reflection seismic surveys to resolve structural details of a reservoir even at depth, the history of seismic measurements for geothermal exploration is short. The main reason is, without much doubt, the costs of these surveys that make them difficult to fund for tight-budgeted geothermal projects, especially in regions where the complex geology requires 3D arrays. Novel seismic techniques are currently subject to many R&D activities in hydrocarbon exploration. Substantial improvements of the spatial resolution at greater depths are expected to be achieved with seismic full waveform inversion methods (Virieux and Operto, 2009). It is expected that they will be also extremely useful for characterizing geothermal systems.

Some examples of reflection surveys aiming to explore fractured reservoirs are: Unterhaching, Germany (Lüschen *et al.*, 2014), the Larderello-Travale area in Tuscany (Casini *et al.*, 2010), New Zealand (Lamarche, 1992), Japan (Matsushima *et al.*, 2003) and the USA (Majer, 2003).

In **Figure 30** a 3D data cube that is the result of a vibroseis survey in Unterhaching, Germany (Lüschen *et al.*, 2014) is shown. The seismic surveys reveal the geometry of the target layer (Malm).

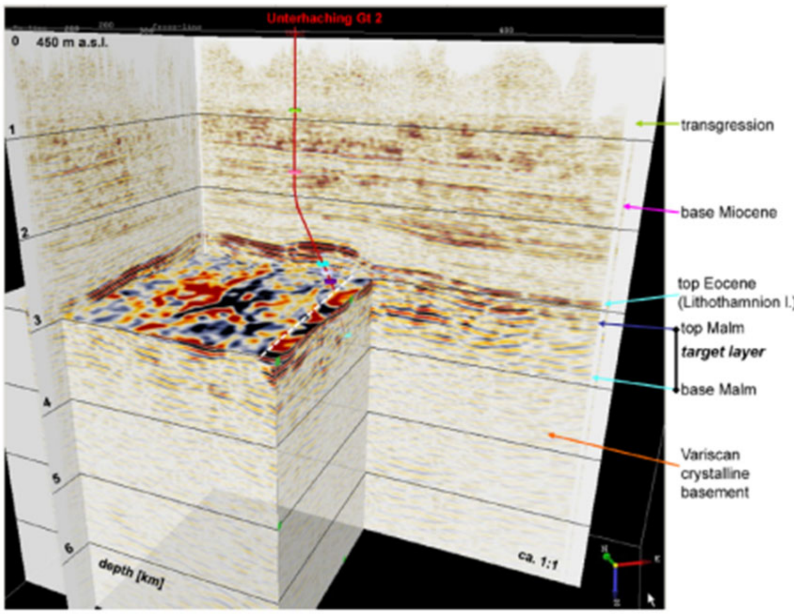

Figure 30: *Panoramic view of a 3D data cube (3D FD depth migration) that was the result of a 3D vibroseis survey in Unterhaching (Lüschen et al., 2014). Main lithological markers from the well are shown on the right. The 45° fault, intersected by the well, is marked by a white dashed line on the depth slice. The target layer (Malm) can be clearly distinguished.*

3.1.1.1.2 Passive seismic methods for monitoring purposes

Passive monitoring of seismicity

Many geothermal areas show an increased level of micro-seismicity (<M2). Locating these micro-earthquakes can reveal active faults and highly fractured areas that are expected to show a high permeability (**Figure 31**). To use passive seismic as an effective exploration tool, a relatively large number of events needs to be recorded. For this purpose at least 5 stations of highly sensitive seismograph units are deployed in the area of interest. Over a period of 1−2 months during stimulation, one can expect to record hundreds of events of magnitude -1 to -2. The challenge remains to accurately determine the location of these micro-earthquakes. Additional information from micro-earthquake locations includes the

determination of Poisson's ratio (ratio of P/S wave velocity). The extensive fracturing of a liquid-filled rock causes Poisson's ratio to be higher than normal as the S-wave velocity is reduced significantly. This ratio is hence indicative of fracturing, and the direction of first motions and fault plane directions.

In **Figure 31** a cross-section of the depth distribution of micro-seismicity of the Olkaria volcanic field in Kenya is shown (Simiyu, 2010). The distribution of seismicity suggests a relatively high elevation of the brittle/ductile boundary below the caldera, indicating high temperatures and shallow depth to the heat source.

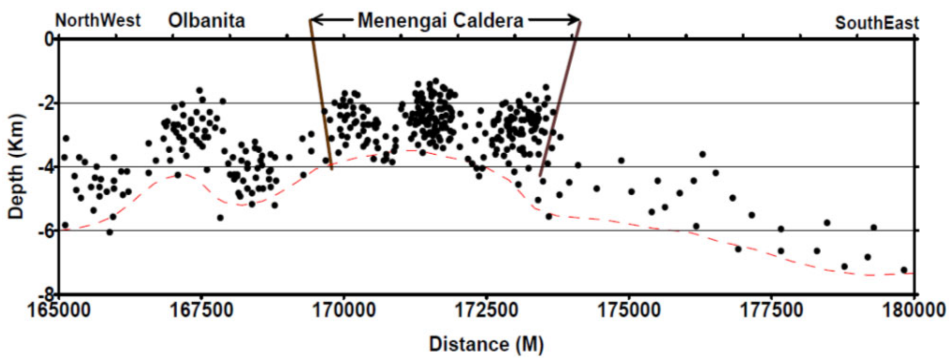

Figure 31: *NW-SE section of seismic events with depth distribution across the Olbanita and Menengai Caldera in Kenia (Simiyu, 2010).*

Ambient seismic noise monitoring

Ambient noise methods are based on the continuous recording at different stations of tiny vibrations of the Earth's surface induced by sea motion and atmospheric changes. It has been shown that (Shapiro and Campillo, 2004) the cross-correlation of these continuous records between different stations converges towards a Green's function that yields all the characteristics of the impulse response function of an active seismic experiment. The ambient noise methods generally make use of multiply scattered coda waves. These coda waves sample the subsurface very densely and are very sensitive to small mechanical or structural changes in the medium that can be recorded in the form of phase shifts or de-correlation in the coda. This technique yields the possibility of constant monitoring of the elastic properties in the medium.

The application of ambient noise methods to geothermal exploration sites is in its infancy. (Hillers, 2014, in preparation) explored the applicability of noise-based monitoring and imaging techniques in the context of the 2006 Basel geothermal project. They observed a significant perturbation of medium properties associated with the reservoir stimulation that can be imaged at the surface. The depth sensitivity of the analyzed wave field indicates resolution of perturbation in the shallow parts of the sedimentary layer above the stimulated deep volume located in the crystalline base layer. The deformation pattern is similar to InSAR (Interferometric Synthetic Aperture Radar)/satellite observations associated with CO_2 sequestration experiments, and indicates the transfer of deformation beyond scales associated with the instantaneously stimulated volume. The detection and localization of delayed induced shallow aseismic transient deformation indicates that monitoring the evolution of reservoir properties using the ambient seismic field provides observables that complement information obtained with standard micro-seismic approaches.

Figure 32 shows an example of a deformation pattern at shallow depth obtained from Basel ambient noise data. High values of the scattering cross section σ indicate a significant perturbation of the scattering properties in the medium. The green cross indicates the position of the injection well and the pink crosses the stations used for the analysis.

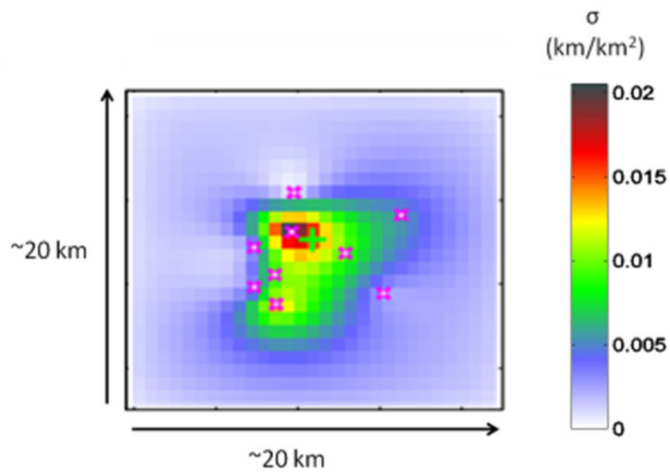

Figure 32: *Deformation pattern at shallow depth associated with the water injection (green cross) at the geothermal site in Basel (Hillers, 2014, in prep). High values of the scattering cross section σ indicate a significant perturbation of the scattering properties in the medium.*

3.1.1.2 Eletromagnetic and electric methods

After delineating the geothermal resource and determining its 3D geometry with reflection seismic surveys, electromagnetic methods are the principal geophysical methods to determine the hydraulic properties of the reservoir (temperature, permeability). The parameter measured is the voltage that reveals the electrical conductivity. Knowing the conductivity, it is possible to establish sensible estimates of porosity and/or permeability of the system, which are important reservoir parameters. An increase in temperature, water content and/or the amount of dissolved solids increases the conductivity by large amounts. Geothermal reservoirs can show an increase by an order of magnitude compared with surrounding rocks at normal temperature.

Among many different types of measurements and configurations, the most important types for deep geothermal exploitation are magnetotelluric and self-potential measurements.

3.1.1.2.1 Magnetotelluric method (MT)

Method

Magnetotellurics (MT) is an electromagnetic exploration technique that investigates the distribution of electric conductivity (a good indicator of thermal anomalies) in the subsurface. The energy for MT is the natural (primary) electromagnetic field. When these variable fields reach the Earth's surface, part of it is reflected back, whereas the remaining part induces electrical currents in the conductive earth. These electric currents (also known as telluric currents) induce in turn a secondary magnetic field. By simultaneously measuring the time variations of the magnetic field and the induced electric field at the surface the electrical properties (i.e. electrical conductivity) of the underlying material can be determined from the relationship between the components of the measured electric and magnetic field variations. The depth penetration of the electromagnetic wave is frequency dependent (lower frequencies reach deeper levels). MT investigations are typically in the range of 500 m to 10’000 m depth. Greater depth penetration requires measuring very low frequencies, which in turn requires longer recording times to obtain satisfactory data quality.

Horizontal resolution of MT mainly depends on the distance between sounding locations; closer sounding locations increase the horizontal resolution.

Application to geothermal exploration

Interesting for geothermal exploitation is that the MT measurements allow the detection of resistivity anomalies associated with faults and the presence of cap rock. A significant decrease in electrical resistivity can be produced by a zone with high fracture density and/or high temperatures.

Dozens of MT geothermal exploration surveys have been made since the early 1980s all over the world (Knútur Árnason *et al.*, 2010; Geiermann and Schill, 2010).

A limitation of the method is however its sensitivity to cultural noise (power lines etc.). When deep structures are analyzed, the measurements probe each time a large volume of rocks, reducing the resolution significantly. To interpret the findings precise prior knowledge of the 3D geometry is necessary (3D reflection seismic).

In **Figure 33**, a 2D interpreted MT-inversion from Soultz-sous-Forêts (Geiermann and Schill, 2010) is shown. Superimposed are the major faults of a 3D geological model. The red line marked (1) gives the approximate upper limit of a conducting clay-rich structure at a depth of approximately 200m. The layering is disturbed by a conductive anomaly (Box-3). Its center with average resistivity of 3 Ohm-meter extends over the Buntsandstein formation into the granitic basement.

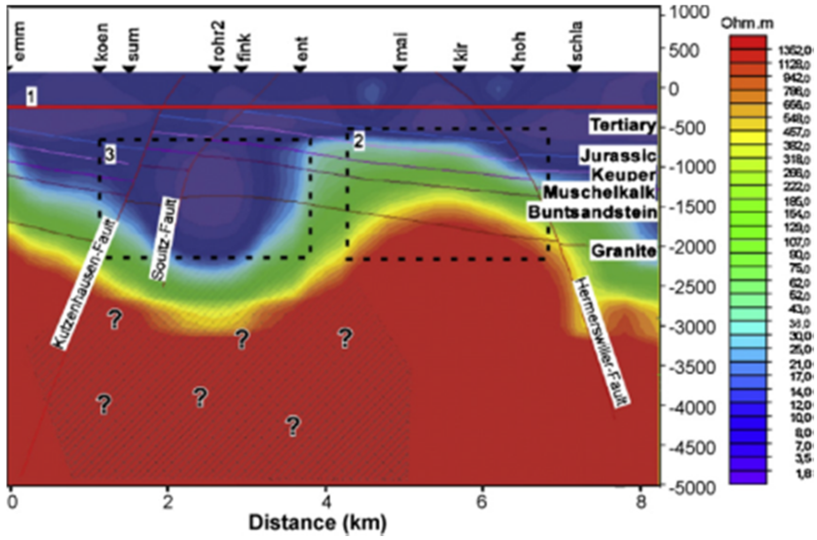

***Figure 33:** 2D interpreted MT-inversion from Soultz-sous-Forêt (Geiermann and Schill, 2010). Superimposed are the major faults of a 3D geological model. The red line marked (1) gives the approximate upper limit of a conducting clay-rich structure at a depth of approximately 200m. The layering is disturbed by a conductive anomaly (Box-3). Its center with average resistivity of 3 Ohm-meter extends over the Buntsandstein formation into the granitic basement. It coincides partly with the Soultz- and Kutzenhausen-Fault.*

3.1.1.2.2 Self-Potential measurements (SP)

Method

Since the 1800s the self-potential (spontaneous polarization or SP) method has been used for mineral exploration. The method measures naturally occurring voltage differences at the surface. These natural voltages have a variety of causes, including ion rich fluid transportation and streaming potentials (Corwin and Hoover, 1979), which occur when waters are forced to move through a fine pore structures, stripping ions from the walls of the pores. To carry out an SP survey, non-polarizing potential electrodes are separated by a distance of tens of meters to several kilometers and placed in contact with the ground; the electric potential difference is measured. The method is simple and inexpensive.

Application to geothermal exploration

Since the 1970s SP surveys have often been used in the exploration for high-temperature geothermal resources (Yasukawa, 2000; Alm *et al*., 2012), where variations of as much as several volts can be observed, but only to a limited extent for low to intermediate temperature systems. SP surveys can delineate concealed geothermal systems when thermal fluids rise close to the surface. SP surveys are often used to refine areas of interest for more progressive exploration methods such as reflection seismic and MT.

In **Figure 34** a self-potential survey of a hot mineral area in the US is shown (Alm *et al*., 2012). The gross dimension of the anomaly can be outlined.

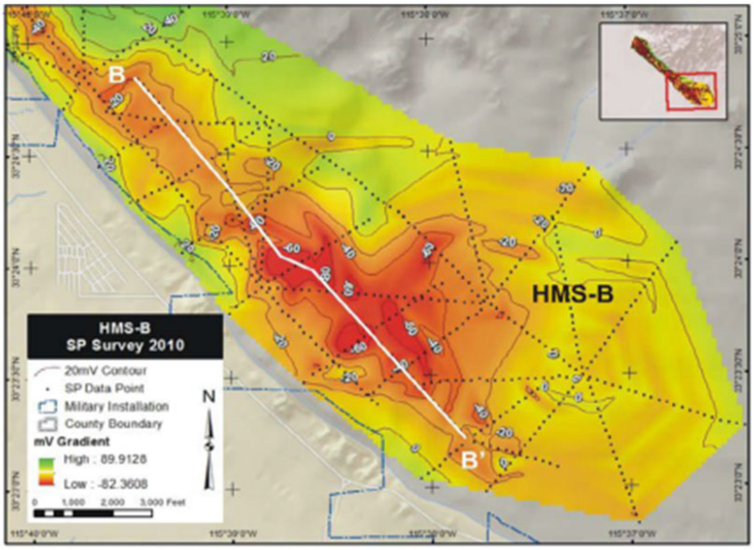

Figure 34: *Self potential survey of the hot mineral spa exploration area, Arizona, USA. The anomaly (marked BB') can be roughly outlined (Alm et al., 2012).*

3.1.1.3 Potential field methods

Gravity and magnetic exploration also referred to "potential field" surveys. They are relatively inexpensive, non-invasive and can quickly cover large areas of ground. The interpretation of the results, however, is problematic and highly ambiguous. These methods can help identify areas that might be of interest for a more detailed investigation with seismic or electrical methods.

3.1.1.3.1 Magnetics

Method

With magnetic surveys spatial changes in the strength of the magnetic field can be mapped. In most cases, the magnetization is controlled by the presence of varying amounts of magnetite and related minerals in the rocks. Magnetic surveys are often performed as regular measurements along parallel profiles separated by tens or hundreds of meters. If a larger scale is desired, aeromagnetic surveys can be used. Ground magnetic measurements provide more detailed information on the sub-surface structures than aeromagnetic data, but aeromagnetic data cover larger areas.

Applications to geothermal exploration

In a geothermal environment the magnetic susceptibility decreases due to the high temperatures. When temperatures reach the Curie point (575 °C for magnetite) ferromagnetic minerals lose most of their magnetization and strong positive anomalies can be detected. The magnetic methods aim at mapping these magnetic anomalies that can be caused by structures such as dykes, faults, lava flows etc. with relatively high concentrations of magnetite. Difficulties when dealing with observed magnetic fields are that the specific character of the anomaly depends in a complicated way on the size and shape of the magnetic bodies.

Figure 35 shows a map of magnetic anomalies in a high temperature field in Iceland (Árnason, 2007). The main geothermal activity correlates with low magnetic intensity.

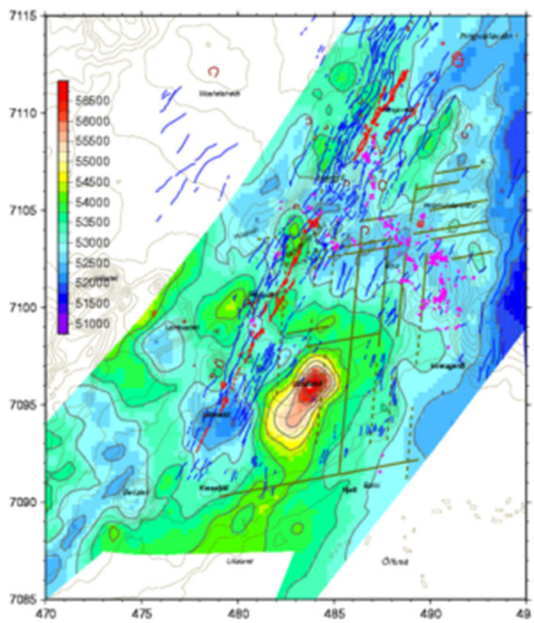

Figure 35: *Magnetic map of a high temperature area in Iceland. The main geothermal activity correlates with low magnetic intensity (Árnason, 2007).*

3.1.1.3.2 Gravimetry

Method

Gravity surveys are used to detect lateral density variations. Density contrasts lead to different gravitational forces that can be measured. The density of rocks depends mainly on the rock composition and its porosity, but partial saturation may also influence the values. To perform a gravity survey, the difference in gravity between a base station (where the absolute value is known) and a field station is measured. Several corrections (latitude, elevation, topography, Bouguer) need to be applied before the measurements can be interpreted.

Application to geothermal exploration

In geothermal areas gravity surveys are mainly performed to monitor subsidence due to fluid extraction. They can also be used in sedimentary areas to map the basement depth variations. In volcanic areas, where geothermal activity is often linked with cooling magma or hot rock beneath, correlations between gravity highs with centers of volcanism, intensive faulting and geothermal activity have been shown.

The gravity method is limited due to the ambiguity that an infinite number of density distributions fits a given gravity field. Additional information is often needed before a solid interpretation can be made, i.e. thicknesses of formations etc. The strength of the gravity method is to assess an excess or deficit of mass.

In **Figure 36**, gravity changes due to the production of a geothermal reservoir in Iceland are shown (Eysteinsson, 2000).

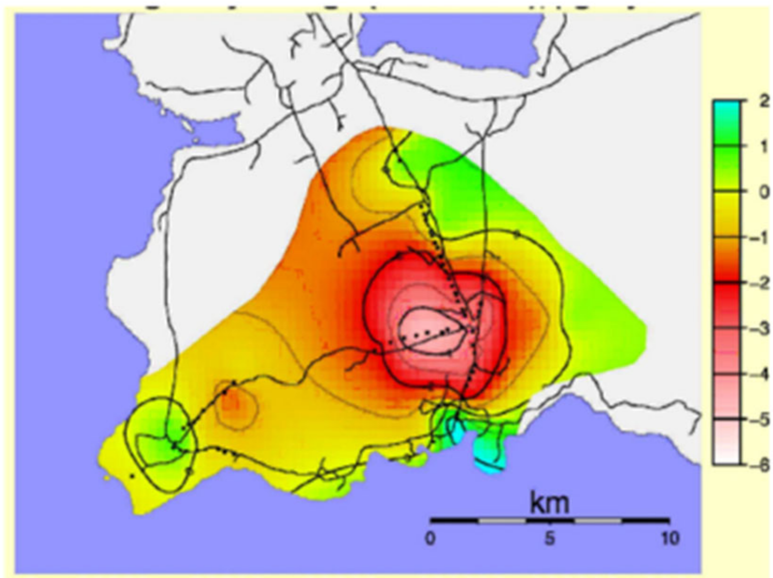

Figure 36: *Gravity measurements showing the mean gravity change (microgal/year) from 1975 to 1999 due to production in the Svartsengi geothermal reservoir (Eysteinsson, 2000).*

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3.1.2 Methods for characterizing deep geothermal reservoirs from borehole measurements

Benoît Valley and Keith Evans (ETHZ)

When a deep geothermal resource is identified using the various techniques described in Section 3.1.1, the only way to confirm the potential of the resource and to determine the detailed characteristics needed for designing the creation of the reservoir and planning its subsequent exploitation is to drill an exploration borehole into the identified target. Numerous borehole-based techniques are then available to characterize some properties of the reservoir at a level of detail that is inaccessible to the resolution of surface based techniques. This section consists of three parts. The first part (Section 3.1.2.1) lists and briefly describes the various types of borehole-based measurements that can be made in the borehole pursuant to the objectives. The second part (Section 3.1.2.2), describes how the measurements are used to derive the characteristics of interest (i.e. the geological model of the reservoir and the stresses prevailing in it). A concluding part (Section 3.1.2.3) lists identified gaps and research needs.

The technologies available to characterize rock masses in deep boreholes are primarily developed for the oil and gas industry. The typical geological environment in which these techniques are developed is a sedimentary basin and thus can differ significantly from the target environment of a deep geothermal reservoir. The available experience in characterizing deep crystalline basement rocks from borehole logs is comparatively limited. Standard log analyses and interpretation techniques available to the oil and gas industry may not be directly applicable to fractured crystalline reservoirs, and the objectives of the logging campaign may be different.

3.1.2.1 Borehole based measurement techniques

The design of the exploration borehole will vary according to the investment strategy of the project owner. In some projects, the exploration borehole can be drilled with a diameter and completion scheme that will not allow its future use as a production or injection borehole. In this case, the only purpose of the borehole is for reservoir characterization and later for reservoir monitoring. For example, an accelerometer string can be installed in such borehole in order to monitor the micro-seismicity occurring during the reservoir stimulation and exploitation, which can significantly increase the quality of the seismic data that can be gathered compared to array based on surface or shallow borehole solely. Additionally, for economic reasons, it can be decided to drill an exploration borehole to a depth that is shallower than the reservoir. This raises the question as to whether rock mass parameters (i.e. stress state, fracturation, seismic response to injection) can be extrapolated to the planned reservoir depth. However, it is often the case that the first borehole drilled is designed to be turned into a production or injection well after the completion of the exploration phase. Such a borehole will obviously reach the target depth of the reservoir. In this case however the reservoir stimulation is likely to be performed very shortly after drilling completion with the drill rig on site, which imposes time and economic pressures to complete the exploration data collection as soon as possible and only limited data analyses can be performed prior to the initiation of the reservoir development phase.

Most deep boreholes are destructively drilled, rather than core-drilled, so that samples of the rock are recovered in the form of cuttings rather than cores. Cuttings can be examined with a stereo-microscope in order to identify the mineralogical content. They can also be prepared in thin section for analysis under polarized light, or in powder form for x-ray diffraction analyses, both of which yield further information on mineralogy. However, it is usually difficult or impossible to accurately describe the texture or the fabric of the rock. Delays for the cuttings to reach the surface in the circulating drilling mud, mixing, and potentially different rise times for different mineralogical species lead to uncertainty in the mineralogical depth profile from cuttings. If mud circulation is lost, for example, when crossing permeable fault zones, no cuttings will be recovered. The size and shape of the cuttings can vary significantly depending on the drill bit and drilling parameters used, and these impact the type of analysis that can be carried out on the cuttings. Polycrystalline diamond compact (PDC) bits are commonly used because they improve drilling efficiency, but they tend to generate very fine cuttings that are more difficult to analyze. Numerous rock mechanical parameters such as strength and elastic modulus cannot be directly determined based on cutting samples.

Qualitative or semi-quantitative characterization of the rock and rock mass can be gained by interpreting drilling parameters. Weight on bit (WOB), rate of penetration (ROP), revolution per minute (RPM), torque and drill bit wearing records can be useful in evaluating characteristics of the rock mass (Mostofi *et al.*, 2011). Records of mud losses and returning mud composition can be indicative of inflow or outflow and thus highlight permeable structure in the rock mass (Hettkamp *et al.*, 2004). More recently, measurement while drilling (MWD) techniques have been developed in order to measure relevant parameters at the drill bit and transmit the data to the surface through mud-pulse telemetry. Initially, this technique was developed to provide a near real-time measure of downhole drilling trajectory and thus allow the steering of the bottom-hole assembly (directional drilling). Nowadays, the technique has been developed to record a variety of downhole parameters and is referred as logging while drilling (LWD) (Hansen and White, 1991).

Petrophysical characterization of a reservoir is improved if a core sample is taken. One possibility is to acquire whole cores using a coring bottom assembly, which can deliver cores of 10 to 20 m in length and 5 to 15 cm in diameter depending on hole size. Obtaining a core from a deep borehole can be a relatively risky operation. An alternative technique is to acquire sidewall cores using a wireline tool. In crystalline rock, such cores can be acquired using a rotary sidewall drilling tool, which can take up to 75 sidewall cores in a single run. Typical sidewall core sizes are 2.5 cm in diameter and 5 cm in length (Schlumberger Oilfield Glossary). The availability of a core allows a more reliable mineralogical analysis to be performed that includes possible texture and fabric determination. It also allows the determination of other petrophysical parameters such as porosity, micro-fracture characteristics (i.e. differential strain analysis), strength, elastic stiffness and sonic velocity. One problem with core samples recovered from deep boreholes is that they are likely to host a micro-crack population arising from the relaxation of the in-situ stresses and the cooling of the sample. This must be considered when determining physical properties of the rock. In addition, typically only a short length of core is obtained compared to total drilled length. Thus, the question arises as to whether the core section is representative of the reservoir at large. Fracture and fault zones are usually of primary importance for geothermal development, yet acquiring core from these zones is the most challenging.

Regardless of whether core samples are taken, wireline logging data are central to reservoir characterization. Logging data are acquired by running logging sondes up the well to obtain profiles of a variety of parameters. The sondes are usually attached together to form a logging string so that all data can be acquired in a single logging run. Logging does not require the presence of a drilling rig on-site. Practically all deep holes will be logged to some degree since parameters like temperature and hole volume are required for completion activities such as casing cementation. The logs that are considered essential for deep geothermal reservoir characterization are temperature logs, caliper logs, borehole wall imaging logs (acoustic or/and electrical), and sonic logs (various configurations are possible). Additional logs considered desirable include spectral-gamma logs, resistivity logs and neutron logs. During injection or production tests, flow logs (spinner) can be run in order to identify the main flowing zones in the well. A list of these logs is provided in with some indication of their usage and limitation. More details in extracting some key reservoir characteristics from these logging data are given in Section 3.1.2.2.

Practically, the acquisition of geophysical logs in deep geothermal boreholes can be complicated by the high temperature encountered. The limiting factor is the exposure of electronic components of the logging tool to high temperatures. Vacuum flasks can be used in order to insulate critical electronic components from the hot environment, thereby extending the operating time. Modern sondes used in the oil and gas service industry that utilize high-temperature electronics can operate up to 170 °C without vacuum flasks. Most companies offer a limited range of 'extreme environment' sondes that can operate up to temperatures of 250 °C, but only for a limited time. Flasked tools run in memory mode on wire-line or electric cable are available for temperatures up to 350−400 ^{o}C as long as the time at temperature does not exceed tool-specific criteria (usually sufficiently long to acquire the desired logs). Electric cables tend to be the “weak link”. The standard practice in geothermal is to avoid the high cost of the extreme environment sondes by cooling the well before logging through circulation. The logs are almost always acquired immediately after the well is drilled and before the casing is run into the hole. Thus a drill-rig is available to conduct the circulation.

Active seismic methods using clamped downhole sensor arrays have promise for imaging fracture zone and fault structures within the reservoir away from the boreholes, but have not been extensively used in projects to date. Vertical Seismic Profiling (VSP) surveys were conducted at the Soultz-sous-Forêts site with some success (Place *et al.*, 2011), but the processing and interpretation of these data is still on-going.

The productivity characteristics of a well prior to or after stimulation can be evaluated by conducting production or injection tests at pressures less than required for stimulation. Measurement of downhole pressure is important since the evolution of the borehole temperature profile during a test produces large changes in the weight of the fluid column in the well. Thus, the wellhead pressure history is usually significantly different from the downhole history, and it is difficult to recover the latter from the former in the detail needed for well test analysis. Hydraulic test procedures are described in Section 3.1.2.2.5. Prior to stimulation, flow rates during hydro tests are often too low to identify permeable fractures from spinner logs, and so some other techniques must be used. Stoneley wave reflectivity logs were found to be useful indicators of permeable zones in the Soultz 3.0−3.5 km reservoir. Temperature logs run immediately after a cold water injection have also proven useful (Schellschmidt and Schulz, 1991).

Dedicated, high-pressure hydraulic tests on small borehole intervals are also used to estimate minimum principal stress magnitude, as described in Section 3.1.2.2.4.

Table 6: *Summary of reservoir characterization methods.*

Method	Application	Limitation and other comments	References
Cuttings record	- mineralogy - petrology - alteration	- imprecise depth - mixing and selective rise - no fabric and texture information	Dezayes *et al*.(2003)
Drilling parameters	- qualitative rock mass properties - permeable structures (mud losses)	- very indirect and interpretative for rock mass properties - critical to disentangle operational effects from effects related to the rock mass response	Mostofi *et al*. (2011)
Whole cores and sidewall cores	- mineralogy - petrology - alteration - texture and fabric - rock mechanic testing	- limited length can induce sampling biases - sampling at large depth can induce core damage that can bias mechanical testing	Schlumberger Oilfield Glossary
Wireline logs			
Temperature logs	- temperature gradient - downhole temperature - indication of flowing fractures	- history of drilling and circulation are required to correct logs run during the warm-up phase following drilling	Schellschmidt and Schulz (1991) Evans *et al.* (2005)
Density logs	- density - vertical stress through weight of overburden integration - dynamic elastic properties (combined with sonic log)	- log can be affected by poor contact of the probe with the borehole wall due to mud cake or rugosity	Valley (2007)
Caliper logs	- borehole breakouts for stress characterisation - cementation	- requires 4 arms or more and an even number of arms to be useful for breakouts identification	Plumb and Hickman (1985)
Ultrasonic borehole imager logs	- wellbore failure identification for stress characterisation - natural fracture characterization - cementation (Schlumberger USIT tool)		Luthi (2001)
Micro-resistivity borehole imager logs	- stress induced fractures for stress characterisation - natural fracturing		

Method	Application	Limitation and other comments	References
Sonic logs	- identification of fracture zones - velocity model for microseismic monitoring - dynamic elastic properties (combined with density log)		Valley *et al.*(2011)
	- permeable fractures from Stoneley wave reflection	Stoneley wave reflection also results from hole irregularity	Evans *et al.*(2005)
Spectral gamma logs	- lithology and alteration		Dezayes *et al.*(2003)
Resistivity logs (laterolog)	- lithology and porosity		
Azimuthal resistivity imager	- lithology and porosity, and also gives an 360° image of the deep resistivity structure of natural fractures. Useful for distinguishing natural and induced fractures.		Henriksen (2001)
Neutron logs	- porosity (hydrogen content)		
Spinner (flow) logs	- identify reservoir outlet/inlet zones during injection or production tests	- resolution is limited and typically only the dominant flow zones are identified	
Surface-to-borehole and cross-hole seismic methods	- geological model and structure identification		Place *et al.*(2011)
Hydraulic tests	- measure well injectivity and productivity indices and their dependence on pressure/flow rate (i.e. resolve the presence of turbulent flow of fracture dilation effects) - identify main flowing zones (combined with flow logs) - estimate S_{hmin}		Kohl *et al.*(1997)

3.1.2.2 Determination of reservoir characteristics

Developing a reservoir model, also referred in the oil and gas industry as a 3D earth model, is central to reservoir characterization (Prieto, 1999; Plumb *et al*., 2000; Lelièvre *et al*., 2012). It consists of establishing the structural framework of the reservoir (lithological boundaries, faults and the discontinuities), as well as characterizing a variety of properties and their variability in space. Current approaches consist in integrating all characteristics on a common platform, a 3D earth model. This includes not only what is often referred to as the geological model (i.e. the definition of lithologies and their boundaries and the discontinuity characteristics), but also the stress, temperature and pore pressure fields, together with numerous physical characteristics and their variability in space (i.e. density, the presence and type of alteration, seismic velocity, deformation modulus and strength characteristics). Although, ideally, one would like to develop a three-dimensional understanding of the organization of structure and discontinuities within the reservoir and the variability of reservoir characteristics, data are typically available from only one or two boreholes. Thus, detailed characterization is limited to the rock volume immediately around the borehole, the degree of uncertainty generally increasing with distance from the well. The determination of the geological model thus relies upon upscaling information derived from the borehole to the reservoir-scale, and remains challenging.

The determination of some reservoir characteristics requires the integration and combination of more than one single measurement method or data set. Generally, the most robust characterization will result from combining independent evidence from multiple sources. The following sections describe the methods that can be used to determine key reservoir characteristics. For the development of deep geothermal reservoirs the fracturing and stress state are of primary importance.

3.1.2.2.1 Temperature gradient and bottom hole temperature

The determination of temperature and temperature gradients are essential for the confirmation of the characteristics of the expected geothermal resources. Such measurements are relatively straightforward provided temperature logs are available. Following standard logging-industry practice, temperature logs should be acquired logging downwards, and the temperature sonde should be lowermost in the 'sonde string' in order to avoid corruption of the natural fluid temperature profile from perturbations due to the passage of the sondes. Additionally, for obtaining measurements representative of the natural in-situ conditions, temperature logs run within weeks of the end of drilling circulation may require correction for the possibly continuing process of warming of the well. Typically, some weeks to a couple of months are required for the well temperature to equilibrate with the natural formation temperature. Since the correction for on-going temperature recovery invariably contains uncertainties, it is sensible to run a temperature log two months or so after drilling completion.

3.1.2.2.2 Petrophysical properties

We group in this section a series of properties of the intact rock including rock type, mineralogy, fabric, alteration, density and rock mechanical characteristics. The description of rock mineralogy, rock type, fabric and alteration is straightforward when whole cores are available. However, since this is rarely the case in deep drilling projects, lithologic description usually relies on cuttings analysis. This significantly reduces the resolution with which the lithological changes can be identified, and precludes the analysis of the rock fabric. It is usually possible to reliably determine the main lithological changes from cuttings analyses. However, the nature of variations within a lithology can be difficult to resolve. Importantly, the occurrence of alteration in relatively narrow zones such as faults or fracture zones, which are of particular interest for geothermal reservoir since they are commonly associated with past and possibly current fluid circulations (Evans *et al.*, 2005a), are difficult to identify within the cuttings record. The analyses of drilling parameters, such as rate of penetration (ROP), and torque, mud logging for gas and fluid losses, and particularly wireline logs, can help in identifying these zones. Various wireline logs can be used to refine the lithological variations. If lithological variations induce changes in the borehole wall roughness, ultrasonic reflectivity images of the borehole wall can capture these variations. Electric and neutron logs are sensitive to the presence of porosity and/or clay minerals associated with alteration products of crystalline rocks. Alteration zones can also be associated with density variations that can be measured with a density (gamma-gamma) log. However, all these approaches to characterize lithological variations are indirect and core samples (spot cores or sidewall cores) are invaluable to “calibrate” the procedure of interpretation of wireline logs to the local site conditions.

Cores are also required to measure mechanical properties of the rock. Rock strength and static elastic properties can only be measured on cores. However, measurement on cores can be flawed due to microcrack damage induced by drilling, and the stress relaxation occurring when the core is removed from confinement. Interpretation of drilling parameters (ROP, etc.) can give qualitative information on the mechanical properties of the rock. Dynamic elastic properties can be determined in-situ by combining the results from a density log and a sonic log. The seismic velocities (compressional and shear wave velocity) can also be measured from sonic logs that provide valuable inputs for the migration of seismic reflection data and for the localization of induced seismicity (velocity model).

3.1.2.2.3 Natural fracturing

In deep crystalline rock masses, the bulk rock permeability is dominated by flow in fractures, while the matrix (the rock blocks bounded by the fractures) can be considered as effectively impervious, although it can provide significant leak-off to storage. Gaining an understanding of the characteristics of the fracture network is thus required to assess fluid flows in a deep geothermal reservoir.

Describing adequately the characteristics of a fracture network is a critical but invariably challenging task. Typically some elements of the fracture network of the geological model can be captured deterministically if they cut the borehole. These elements are essentially limited to fracture zones and faults since only they will have any significant extension away from the borehole. However, the vast quantity of fractures and fracture zones that do not intersect the boreholes must be described statistically. Based on this statistical description, stochastic realizations, often referred as discrete fracture networks (DFN), can be generated.

In most cases, the information to characterize natural fracturing is obtained from borehole wall image logs. In deep boreholes, two imaging techniques are commonly used: ultrasonic imaging and microresistivity imaging. In ultrasonic imaging, ultrasonic reflectivity contrasts of the borehole wall are measured with a beam of ultrasound that has a spot size of the order of a cm in diameter. Natural fractures produce rugosity at the borehole wall that results in low reflectivity values and thus their traces can be identified. In addition, the ultrasonic time-of-flight in the borehole fluid is measured, which allows determining in detail the geometry of the borehole. Microresistivity imaging captures fine changes of resistivity of the borehole wall with an array of button electrodes that produces images with high resolution (a few millimeters).

Both techniques allow the identification of fractures at the borehole wall and the determination of their position and orientation. Fracture traces can be classified using various characteristics (trace continuity, deviation from the expected trace shape for planar features, etc.). Statistical processing of the data allows families of fractures that have a similar orientation and thus similar genesis to be identified, and also the distribution of fracture spacing within each family to be estimated. These parameters are needed (along with others) to generate stochastic discrete fracture network (DFN) realizations of the geological model (Tezuka and Watanabe, 2000). Biases are introduced by the line-sampling of the true fracture distribution by the borehole(s). Fracture length (or persistency) and fracture connectivity − parameters that are of great importance for assessing fluid flow in the rock mass − cannot be determined from borehole wall images.

Discontinuities occur at all scales, from microcracks at the grain scale of the rock up to the macroscopic discontinuities of fractures (single, quasi-planar structures of length of up to a few tens of meters), fracture zones (narrow zone of linked fracture with lengths up to several hundred meters), and faults (large-scale structures that have a well-developed gouge core) (Valley, 2007). Available evidence suggests that discontinuities with lengths upward of 100 m have a dominant influence on the rock mass response to hydraulic stimulation. The location where such zones cut the wellbore can be determined from geophysical logs, but the dip and extent of the structures are difficult to determine. VSP surveys offer some prospect of imaging such fracture zones or faults within 100 m of the wellbore. These techniques are routinely used in the oil and gas industry for improving knowledge of lithological structure, but there is little experience in using it to resolve quasi-planar structures such as faults and fracture zones (Place *et al*., 2011). Monitoring and locating microseismic events induced on structures within the reservoir during stimulation injections can also be used to illuminate key structures in the reservoir. The utility of the method for structural mapping depends upon the sensor array used to monitor the microseismic events. The inclusion of one or more downhole instruments in the array is essential to resolve structural details on scales of 50 m or less, using advanced relocation techniques such as multiplet analyses (Evans *et al.*, 2005b; Moriya *et al.*, 2003). Small-scale fractures generally cannot be individually imaged if they do not cut a borehole. However, the presence of a dominant fracture family in a rock mass may give rise to a velocity anisotropy in the rock that can be identified by seismic methods (Gaucher *et al.*, 1998).

3.1.2.2.4 State of stress

The in-situ stress state is a fundamental quantity for geomechanical analyses and has a first order effect on the permeability of fractured rock masses, and the stability of fractures and faults. It is thus an important factor in determining the stimulation response of the rock mass to fluid injection and the attendant induced seismicity. Stress in the earth crust arises primarily due to the effect of gravity and tectonics. Stress is a tensor quantity and, rigorously, 6 independent parameters at any point in space are needed to fully characterize the stress state. In practice, the assumption that one principal stress is vertical and has a magnitude, Sv, equal to the overburden reduces the stress characterization to determining the magnitude of the maximum and minimum principal horizontal stresses, S_{hmax} and S_{hmin} respectively, and the orientation of either S_{hmax} or S_{hmin}. Based upon experience, it is also found that the magnitudes of S_{hmax} and S_{hmin} follow linear trends with depth (at least within relatively homogenous domains). The relative magnitudes of Sv, S_{hmin} and S_{hmax} define the stress regime. If Sv is the highest, intermediate or lowest, the stress regimes are respectively normal faulting, strike-slip faulting and thrust faulting. The in-situ fluid pressure − referred also as in-situ pore pressure (Pp) − is required to determine the effective stresses, i.e. the stress quantity (note that depending on the process analyzed, there are different effective stress laws that must be considered) ultimately required for geomechanical analyses and thus its determination will also be discussed below.

The in-situ Pp can be determined by observing the piezometric level in wells when perturbations induced by drilling or hydraulic injection have dissipated. The normal situation, referred to as 'hydrostatic', is when the piezometric level coincides with the ground surface. However, if impervious layers are present above the reservoir, the pore pressure distribution can be complex and overpressure or underpressure can be present.

The vertical stress (Sv) can be estimated by integrating the weight of the overburden. For this, a complete profile of the density from a gamma-gamma log run from the surface to the depth of interest is needed.

The minimum principal horizontal stress (S_{hmin}) can be determined from hydraulic tests, ideally, hydrofracture tests conducted on 1−2 m intervals isolated with packers. However in deep wells it is often not possible to find intervals where the hole is round and suitable for setting a packer. It is also expensive to use drill rigs to place the packers, and wireline-conveyed packer systems are considered to be risky. An opportunity to measure S_{hmin} arises following the running and cementing of casing or liner. It is standard practice in the oil and gas industry to drill a short (5−10 m) length of hole below the casing shoe and hydraulically test the section to determine the pressure at which enhanced leak-off occurs, due to fracture initiation, jacking or shearing. Thus, they are known as Leak-off tests (LOTs). A variation of the test that involves several cycles and is more suitable for S_{hmin} estimation is the extended leak-off tests (XLOT) (Lin *et al.*, 2008). Pressure records during massive stimulation injection can also be used to estimate S_{hmin} if pressure limiting behavior that can be attributed to fracture jacking can be demonstrated.

The maximum principal horizontal stress magnitude (S_{hmax}) remains difficult to estimate. Numerous methods have been proposed in the literature, but all are based on assumptions that involve significant uncertainty. A common approach is to assume that the rock mass is critically-stressed, and verging on failure for fractures which are optimally-oriented for shear failure and have strengths characterized by a Coulomb friction criterion with friction coefficient bracketed to lie between 0.60 and 1.0. With this assumption, knowledge of S_{hmin} then allows bounds to be placed on the magnitude of S_{hmax} (Evans, 2005; Hickman, 2010; Zoback *et al.*, 2003). In practice, the large uncertainty in the frictional strength leads to large uncertainty in the resulting estimate of S_{hmax}. The best approach is to use several methods to estimate S_{hmax} by supplementing the estimates from a critical stress analysis with other methods such as described below (Tan *et al.*, 1993).

The orientation of the maximum or minimum horizontal principal stresses in deep boreholes can usually be estimated with a high degree of robustness from observations of wellbore failure derived from wireline logs. A caveat is that the rock does not have a strong strength anisotropy in the plane normal to the borehole axis. If borehole failure is pervasive along the borehole axis, which is usually the case in deep holes, then the observations provide a unique window into the heterogeneity of stress within the rock mass by revealing how the orientation of S_{hmax} varies along the borehole. All other stress estimation methods provide only point measurements of stress, and thus do not define the variability of stress, unless many measurements are made which is usually not practical.

Several methods to determine stress from measurements on core have been proposed and include anelastic strain recovery analyses, differential strain analysis, or approaches based upon the Kaiser effect (see Evans *et al.*, 1999 for summary). All these methods are based upon the development of microcracks that result from the removal of the core from in-situ confinement, and thus are indirect. Sonic logging tools have recently been developed to detect velocity anisotropy around the borehole wall, which is assumed to reflect stress-induced microcrack damage. (i.e. Schlumberger borehole scanner, Baker X-Mac sonde). The velocity anisotropy can be related to the primary stresses using a model. The resulting stress estimates are critically dependent upon the validity of the underlying model assumptions. Useful estimates of the complete stress tensor averaged on the reservoir scale can be derived from the fault plane solutions of microearthquakes induced in the reservoir during the stimulation (Cuenot *et al.*, 2006; Terakawa *et al.*, 2012).

3.1.2.2.5 Hydraulic characteristics (pre- and post-stimulation)

Hydraulic tests are required to quantify the hydraulic characteristics of the reservoir, both before and after stimulation. How this program is conducted depends upon whether there is a single open-hole section or multiple zones that are hydraulically isolated. The following describes a possible test program that could be performed on a single interval. Following completion of the well, a small-volume, low-rate production test should ideally be conducted to clean out drill cuttings or mud from the feed zones to the reservoir. This would give an estimate of the productivity of the well or zone in question, and also yield a sample of the formation fluid. However, production tests may not be practical if the formation pressure is not artesian, or there is no provision for handling quantities of hot production fluid at the surface. Small volume injection tests may be preferred at pressures sufficiently low to avoid stimulating the reservoir, thereby changing the system under investigation. The pressure-dependence of injectivity can be assessed by performing step-rate (or step-pressure) tests. Pressure dependence of injectivity can arise from turbulent-like flow at the inlet (Chen and Wyborne, 2009) or within the reservoir (Kohl *et al.*, 1997), or from fracture dilation. In all tests, downhole pressure measurement is mandatory if standard well-test analysis methods are to be applied, which is highly desirable. Otherwise, only injectivity or productivity indices can be determined.

3.1.2.2.6 Feed-zone and flow path identification

Feed zones, i.e. borehole sections where flow enters or exits the borehole, can be identified by running spinner logs during production or injection tests. The resolution and sensitivity of such logs are limited, and feed-zones will be identified only if flow entering or leaving them is sufficient. Generally, only the flow at the main feed zones can be quantitatively estimated from spinner logs. However, prior to stimulation, the rock mass permeability and the flow velocities in the well during the tests may be too low to allow spinner logs to be used. In this case, temperature logs should be run a short time after the injections to identify zones of enhanced cooling reflective of a permeable fracture (Schellschmidt and Schulz, 1991). Stoneley reflectivity logs have also proven to be effective in identifying the location of permeable fractures (Evans *et al.*, 2005a).

When more than one borehole is available and circulation can be established between the wells, information on the characteristics of the flow paths can be obtained by tracer tests. Tracer fluids that do not react with the rock provide the residence time distribution of the tracer passing through all flow paths between the wells (Sanjuan *et al.*, 2006). From this, the net 'pore' volume swept by the flow paths between the wells can be estimated (Shook, 2005). Reactive tracers that react with the rock surface in a precisely known way can be used in conjunction with non-reactive tracers to yield an estimate of the swept volume (Chabora, 2012).

3.1.2.3 Gap analyses and research needs

The main gaps for reservoir characterization concern the difficulties of determining the discontinuity distribution in the reservoir and the stress characterization.

For the discontinuity distribution, the primary uncertainty relates to the length distribution of fracture and fracture zones, which has a large impact on the connectivity of the fracture network. Discontinuity length distribution cannot be estimated from borehole data alone. Fracture roughness and waviness are also difficult to assess, and these properties may have significant influence on flow channeling and fracture strength.

For the stresses, robust estimation of stress magnitudes remains challenging, particularly concerning the maximum principal horizontal stress. A key to improving the estimates of S_{hmax} is to better understand the strength of the rock at the borehole wall where borehole breakouts develop. The availability of a reliable failure criterion could allow S_{hmax} to be estimated from the geometry of the breakout (i.e. width and depth).

The characterisation of stress heterogeneity within the reservoir is important because it plays a large part in determining how a rock mass will respond to hydraulic stimulation (i.e. the presence of stress heterogeneity complicates the assessment of fracture criticality − the proximity to failure of shear and normal stresses on fractures). Such heterogeneity seems to be correlated with fractures, and may in part reflect locked-in stress perturbation resulting from slip in the past. The pervasive occurrence of wellbore failure along a borehole provides a direct indication of how S_{hmax} orientation varies along a borehole. By analyzing the nature of the variability, it may be possible to place constraints on scaling of stress variability in the rock mass. Breakout geometry (i.e. width and depth) is also seen to vary along boreholes. To extract a description of stress magnitude variability from this would require improved knowledge of the strength of the borehole wall, including consideration of size effects, stress path effects and progressive failure (pre-failure damage accumulation) effects that are not well understood at present.

Since the discontinuity distribution and stress heterogeneity appear to be closely related, an improvement in the characterization of both could potentially be obtained if these reservoir characteristics were determined jointly. More generally, better integration tools that allow constraining simultaneously various parameters of the reservoir would permit more robust reservoir characterization.

Data collected in a reservoir will most likely remain sparse since the volume investigated by drilling is small compared to the reservoir volume. Generic approaches could be used in parallel to purely statistical approaches, in order to enrich these sparse data sets. Developing an understanding of the formation processes of the fracturing within a rock mass as well as acquiring more complete knowledge on the evolution of stresses with fracture development could allow improved realizations of reservoir characteristics and development of reservoir models that are consistent and robust.

Table 7: *Summary of reservoir characterisation methods.*

Property	Determination approaches	Limitations and other comments	Gap analyses and research needs	References
Temperature	- temperature log	- need to correct for well warming for earl-time data		i.e. Drury (1984)
Lithology / mineralogy / alteration	- combinations of datasets, primarily cuttings and core (if any), supplemented by drilling parameters and wireline log data.	- difficulty to characterised hydrothermally altered zones		Dezayes *et al*.(2003), Dezayes *et al*.(2005)
Rock mechanics properties	- tests on cores are required - qualitative information can be retrieve from interpretation of drilling parameters - dynamic elastic properties can be obtained by combining sonic and density logs			Valley and Evans (2006); Mostofi *et al*.(2011); King (1983); Olsen *et al*.(2008)
Seismic velocities	- sonic log			Holliger (1996)
Density	- gamma-gamma log			
Natural fracturing	- micro-resistivity or ultrasonic imaging of the borehole wall, core inspection			Genter *et al.*(1997) Henriksen (2001)
Fracture sets and spacing	- analysis of borehole wall images	- sampling bias due to drilling direction		
Fracture length	- difficult to assess		- This a main gap in reservoir characterisation	
Connectivity and network description	- difficult to assess		- This a main gap in reservoir characterisation	
Fracture zones	- combination of petrophysical logs, cuttings, and drilling parameters	- difficult to characterise length and average orientation within the reservoir volume	- This a main gap in reservoir characterisation	

Property	Determination approaches	Limitations and other comments	Gap analyses and research needs	References
State of stress				
Pore pressure	- piezometric measurements			
Vertical stress magnitude	- integration of overburden using density logs			
Minimum principal horizontal stress magnitude	- dedicated hydrofracture stress tests or XLOTS			Lin *et al.*(2008)
Maximum principal horizontal stress magnitude	- currently difficult to assess		This a main gap in reservoir characterisation	Zoback *et al.*(2003)
Maximum principal horizontal stress orientation	- analyses of borehole failure			Zoback *et al.*(2003)
Stress variability	- analyses of borehole failure		This a main gap in reservoir characterisation	Shamir and Zoback (1992) Valley and Evans (2010)
Stress & structures, criticality	- proximity to failure has large uncertainty due to uncertainty in fracture strength			Morris *et al.* (1996)
Injectivity, Productivity and permeability	- hydraulic tests			
Feed-zones and flow path identifications	- wireline logging - tracer tests			Evans *et al.* (2005)

3.1.2.4 References

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3.2 Reservoir creation

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The ability to create reservoirs with appropriate heat-exchange characteristics is key to building petrothermal systems that extract energy from the hot, low permeability rocks that underlie large areas of Switzerland at depths that are practical to drill. This section addresses the issue of 'reservoir creation', and is organized into three parts. The first presents summaries of petrothermal (EGS) projects conducted to date. That is, projects that attempt to create a heat exchanger within a relatively low-permeability rock mass through hydraulic stimulation. The primary focus is on describing systems that have been built and tested to date, since only in these cases can the performance of the created reservoir be compared with commercial targets. Thus, projects, such as that at Basel, where hydraulic stimulation operations were conducted without the completion of construction and testing of the reservoir, are not included. The second section summarizes the circulation performance of the built petrothermal systems, and compares them with commercial targets. The lessons learned from the experience to date are briefly listed. The third section outlines strategies and research needs to improve the performance of petrothermal systems.

3.2.1 Descriptions of petrothermal systems built and circulated to date

There are many summaries of EGS projects that can be found in the literature, usually focusing on a specific aspect of the project (e.g. seismic aspects in Section 6.2.4). Here the objective is to describe the operations performed to build the underground system, including reservoir creation, and to report the resulting performance parameters, notably the inter-well impedance to flow, the stability of production temperature, and the net volume of flow paths swept by the flow between the wells. Each section describes the essential site characteristics of rock type, natural fracture families present, and state of stress in the rock mass. Then, the operations performed to create the reservoir, the microseismicity that accompanied the operations, and the resulting performance of the built reservoir under circulation are quantitatively summarized.

The present draft includes summaries of the following projects in the order they appear:

1. Fenton Hill, New Mexico (1972−1996): 2.8 km/3.6 km/ 4.2 km (320 °C)
2. Rosemanowes, Cornwall UK (1978−1991): 2.0 km/ 2.2 km (85 °C)
3. Hijiori, Japan (1985−2002): 1.8 km/ 2.2 km (270 °C)
4. Soultz, France (1987−present): 3.3 km/ 5.0 km (200 °C)
5. Fjällbacka[12], Sweden (1984−1989): 0.5 km (15 °C)
6. Le Mayet de Montagne[8], France (1984−1994): ~0.8 km (33 °C)
7. Habanero site, Cooper Basin, Australia (2003−present): 4.2 km (240 °C)

[12] shallow test facility

In the following, the minimum and maximum horizontal principal stresses are denoted by S_{hmin} and S_{hmax} respectively, and the vertical stress by Sv. Depths measured along the borehole are denoted by Measured Depth (MD, depth measured along borehole trajectory from wellhead), and true vertical depths by TVD.

3.2.1.1 Fenton Hill (New Mexico)

Fenton Hill was the World's first EGS test facility (then referred to as Hot Dry Rock). The project was active from 1974 until 1996 during which time two reservoirs, referred to as Phase 1 and 2, were built and tested. The site is located near the rim of the Quaternary-age Valles caldera in New Mexico where the Precambrian basement lies at 730 m below volcanic and sedimentary cover. The temperature gradient increases with depth giving temperatures of 200 °C at 3 km and 320 °C at 4 km. The Phase 1 reservoir was developed between 2.7−2.9 km depth in a relatively uniform granodiorite, whereas the Phase 2 reservoir was located at 3.4−4.2 km in a complex zone of altered gneiss and metavolcanic rocks. The characteristics of natural fractures in the reservoirs were poorly determined. Structural information was obtained from a small number of cores and early-generation acoustic televiewer logs, whose quality was compromised by the hot conditions, showed high fracture densities. Foliation and fracture orientation varied significantly along the holes, reflecting the complex geological structure (Burns and Potter, 1995). In the Phase 1 reservoir, first-pressurization of the wells tended to activate NW-striking high-angle fractures (Brown *et al.*, 2012). In the Phase 2 reservoir, analysis of microseismicity suggested that activated structures tended to dip at 70° and strike N30°W or N10°E (Fehler *et al.*, 1987). The initial permeability of the rock mass was very low (on the order of 10^{-18} m^2). Cores showed that this was because the fractures were sealed. Very few zones of high permeability were encountered during drilling. Breakouts identified between 3444−3627 m in the EE-3a televiewer log indicated S_{hmax} oriented N29°E±9° (Barton and Zoback, 1988). Hydraulic tests in the Phase 1 reservoir indicate the magnitude of the minimum principal horizontal stress, S_{hmin}, is approximately 50% of the vertical stress, Sv, whereas tests below 3000 m in the Phase 2 reservoir indicate S_{hmin} values that are 20 MPa higher, or 70% of Sv (Kelkar *et al.*, 1986). Brown suggests the higher injection pressure in the Phase 2 reservoir reflects a systematic difference in the dip of dominant fractures rather than a stress contrast. However, since the S_{hmax}-parallel, NW-striking high-angle fractures that control the Phase 1 reservoir behavior are present in the lower reservoir, it would be surprising that they could support an overpressure of 20 MPa.

Development of the Phase 1 reservoir began in 1974 with the drilling of hole GT-2 in stages to 2932 m. The bottom hole temperature was 197 °C. The initial concept of reservoir development was to create a series of new hydrofractures which could be penetrated by the second borehole to produce the heat exchanger. To prove the concept, numerous small-volume (<136 m^3) water hydrofracturing and one sand-frac experiments were conducted through perforations and in 60 m and 12 m open hole zones at 2000 m and hole bottom respectively. The balance of evidence suggested that most if not all of the observed injectivity increases reflected opening of natural fractures. Injection through perforations was seen to require higher injection pressures and thus was discontinued. Microseismic events suggested the geometry of the fractures activated by the injections were sub-vertical with strike approximately NW. A second well EE-1 was drilled in late 1975 to 3064 m MD with the casing shoe at 2926 m MD giving 138 m of 9-5/8" open hole. The bottom hole temperature was 205 °C. After numerous small volume injections failed to establish a satisfactory hydraulic linkage between the wells, in 1977 GT-2 was cemented-off below 2 km and re-drilled twice until the required linkage was achieved. The second side-track, GT-2B had a total depth of 2700 m TVD. Two heat exchanging systems were investigated between EE-1 and GT-2B. The first, known as the 'small system', was inadvertently developed between the wells at 2.7 km (where they are only 10 m apart) as a result of a cement deterioration in the EE-1 casing that offered a flow path from the casing shoe at 2830 m to a stimulated fracture at 2750 m. The system was circulated for 75 days in RS2, but suffered from rapid cooling due to a small swept area of only 8’000 m^2 (Dash *et al.*, 1983). The second system, referred to as the 'large system', was created by re-cementing the EE-1 annulus, and stimulating the open hole with large (~700 m^3), high-rate water injections to establish a connection to the 'small' system. These were by far the largest injections conducted to date. The separation between the two open holes was about 200 m and vertical. A series of circulation were performed, culminating in a 286 day circulation (RS5) that began in March 1980. EE1 was injected at 6 l/s and 9.0 MPa and GT1 produced against a 1 MPa back-pressure. An annulus leak developed at day 150. Prior to this, GT-2B was producing 5.7 l/s from 3 natural fractures near 2700 m, and the reservoir impedance was 1.7 MPa/l/s. Slight cooling was observed on one outlet. This, together with tracer tests, suggested a swept area of 40’000 m^3. Integral mean (i.e. swept) fluid volume from four tracer tests ranged between 400 and 1300 m^3.

Construction of the Phase 2 reservoir at 4 km depth and 320 °C began in April 1979. Two wells, EE-2 (4389 m) and EE-3 (3977 m), were drilled inclined from vertical at 35° towards N70°E below 3 km so that they lay in the same vertical plane with a 370 m vertical separation. The wells were inclined towards S_{hmin}, perhaps with the intention of linking them by a series of newly-driven mode-1 hydrofractures.

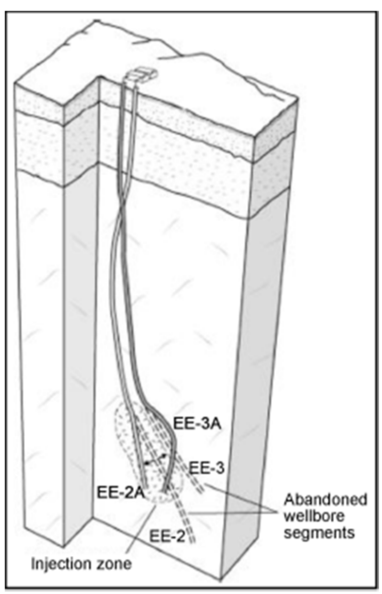

Figure 37: *Trajectories of wells in the Fenton Hill Phase 2 system. The dashed lines denote the original trajectories of the bottoms of the two wells. Well EE-2 reached 4329 m TVD, where the temperature was 315 °C, and EE-3 had a true vertical depth of 3977 m. In plan view, both wells trended to the ENE. EE-3A was drilled to 3940 m TVD (4010 m MD). Figure from (D Brown and Duchane, 2002).*

The lower well, EE-2 was completed to 4660 m MD (4329 m TVD) in May 1980 with a bottom hole temperature of 315 °C. The casing shoe was set at 3529 m MD (3460 m TVD), giving 1131 m of 8-3/4" open hole which pressure tests to 14 MPa showed to be tight. The upper well EE3 was designed for production, and was begun in May 1980. A break in the drill string occurred when the hole was at 3200 m, requiring a side-track to be drilled at 2890 m MD. The hole reached total depth of 4247 m MD (3977 m TVD) in August 1981. The casing shoe was set at 3162 m MD (3124 m TVD), leaving 1085 m of open hole. Pressure testing to 9.9 MPa indicated the presence of a new or reopened fracture just below the casing shoe at 3168 m. In May 1982, an 89 m long scab liner with a polished-bore receptacle was cemented in the open hole of EE2 to isolate the lowermost 136 m of open hole. This interval was then subject to a series of four large-volume, high-rate water injections, the largest of which (Expt. 2016) involved the injection of 5’000 m^3 of slick water at 80 l/s and 48 MPa wellhead pressure. Microseismic activity was monitored by a 3-component geophone locked at 2950 m in EE1. Location of the events showed a volumetric lozenge-like structure that dipped to the west at 45° and did not intersect the well EE3. No flow connection to EE3 was observed. Thus, EE2 was sanded back to 3650 m MD and the 122 m of open hole subjected to three stimulation injections. In the last and largest of these, 3’200 m^3 of slick water were injected at 90 l/s and 46 MPa wellhead pressure with a shut-in pressure of 38 MPa (Expt. 2020). A temperature log run after the first injection showed flow had entered the rock mass at three points with ~30 m spacing near the top of the interval. Seismic event locations scattered around the injection interval but did not extend as far as EE3. No flow connection to EE3 was observed. EE3 was then prepared for stimulation by sanding back to 3587 m and cementing a scab liner from the casing to 3471 m MD, leaving 116 m of open hole. EE3 had been designed as a production well and was not suitable for cold-water injection. Thus it was stimulated by injecting 567 m^3 of hot water at a peak rate of 53 l/s and pressure of 46 MPa (Expt. 2025). Post-injection temperature logs showed the fluid entered the rock mass at three points within the uppermost 30 m of the interval. Microseismic events were observed but did not extend far from the injection interval. No hydraulic connection to EE2 was established. To try to establish a connection, a massive-volume, high-rate injection (Expt. 2032) was performed into EE2, since this well was designed for injection. The well was sanded back to leave a 21 m interval below the casing shoe that was above the fractures opened in the earlier Expt. 2020 injection. A total of 21’000 m^3 of water was injected at a maximum rate of 114 l/s and 48 MPa wellhead pressure over 2.5 days. The injection terminated when a flange on the surface lines failed and led to uncontrolled venting, which resulted in the collapse and rupture of the casing onto the injection tubing at 3273 and 3322 m MD. No hydraulic connection to EE3 was observed during the injection, although the wells of the Phase 1 reservoir began to produce fluid. A microseismic array consisting of four deep borehole stations (GT1, GT2, EE1, EE3) was in operation for the injection. The events defined an oblate elliptical cloud centred on the injection point that extended ±500 m along the hole, ±500 m towards the north and south, but only ±200 m towards the EE3. The upper margin was the Phase 1 reservoir and eastern boundary was the rock immediately around EE3. Maximum event size was 0.0. Seismic volume increased in proportion to injected volume. A further injection into EE3 was made (Expt 2042) by injecting 6’500 m^3 of water at a peak rate of 27 l/s and 39 MPa wellhead pressure. No hydraulic connection to EE2 was observed. Seismicity occurred along the lower reaches of the well and predominantly to the north with no activity between the wells. Attempts to link the wells in their current geometry were abandoned, well EE2 was repaired, and EE3 side-tracked at 2886 m with a trajectory that passed through the seismic cloud developed during the massive stimulation of EE2 in Expt. 2032.

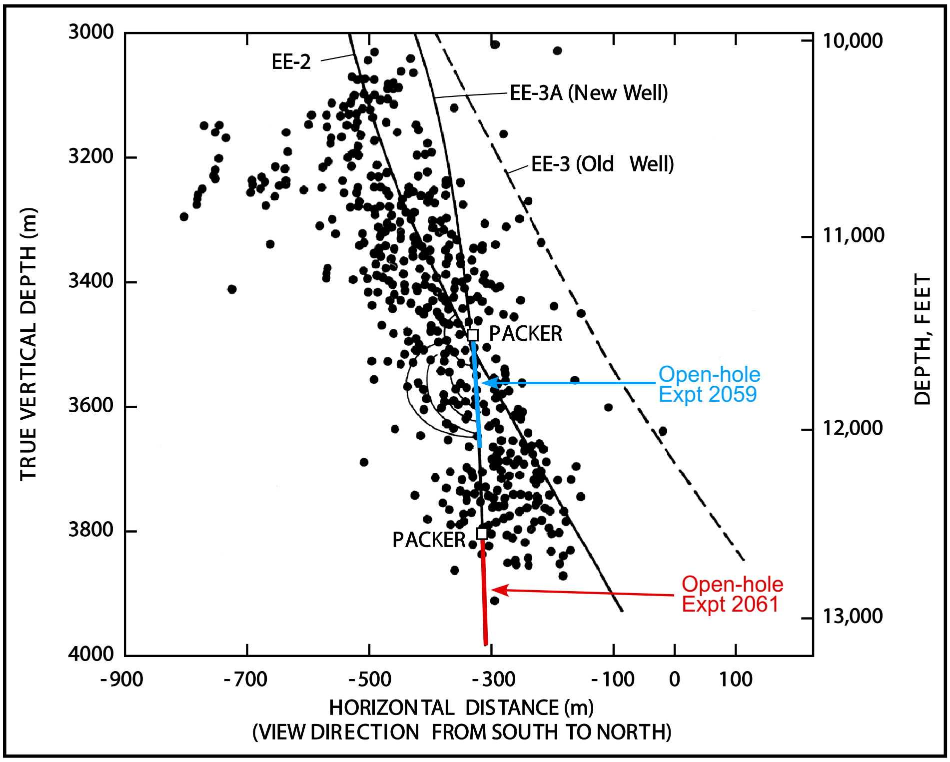

***Figure 38:** North-looking view through the microseismic cloud generated during the so-called 'Massive Hydraulic Fracturing Test' (Expt. 2032) of December 1993. The trajectory of the side-track well EE-3A was designed to intersect structures in the cloud. The sections of EE-3A shown in blue and red denote the injection intervals for Expt 2059 and Expt. 2061 respectively. Figure adapted from Tester et al. (2006).*

Drilling of the side-track EE3a commenced in January 1985. The Phase 2 reservoir was kept at a modest overpressure of 10−13 MPa by injection into EE2. Inflows of hot fluid into the advancing EE3a wellbore indicated communication with the reservoir fractures. In May, with the reservoir de-pressurized and EE3a at a depth of 3720 m MD, the lowermost 203 m was isolated with a packer and 1'600 m^3 of water injected at up to 26 l/s and 40 MPa wellhead pressure (Expt. 2059). The interval lay within the microseismic cloud developed during Expt. 2032, the massive stimulation. Most of the flow entered the rock mass at two fractures at 59 m (3575 m MD) and 120 m (3636 m MD) below the packer. A flow of 10 l/s was produced from EE2, demonstrating communication between wells. Very few seismic events were observed. Well EE3a was then extended to TD at 4018 m MD (3940 m TVD), and the lowermost 191 m isolated with a packer. This interval lay below the microseismic cloud from the massive stimulation of Expt. 2032, and was injected with 5'200 m^3 of water at up to 28 l/s and 48 MPa wellhead pressure (Expt. 2061). Seismic activity was considerable, the cloud being a tabular structure that extended downwards with a dip parallel to the plunge of the wells, but which did not contact EE2. No hydraulic communication with the EE2 well was observed. Thus, the EE3a was sanded back to 3829 m MD, and a packer set at 3650 m, below the lower of the two main outlets in the earlier injection Expt. 2059. The 179 m interval was injected with 5’753 m^3 of water at rates up to 32 l/s and 48 MPa wellhead pressure (Expt. 2062). Most flow entered at two zones at 3658 m and 3’749 m MD. A further attempt was made to connect the lower part of EE3a to EE2 by isolating the interval 3’764−3’917 m MD that lay below the lower of the flowing fractures. The 152 m interval was injected with 3’770 m^3 of water at rates up to 25 l/s and 47 MPa wellhead pressure (Expt. 2061). Seismicity extended across to EE2 but no hydraulic communication was observed. The packer could not be removed and was left in place. The EE3a well extension was completed with 5-1/2" liner leaving open hole between 3600 m and 3690 m.

The reservoir was evaluated in a 30 day circulation (Expt. 2067) known as the Initial Closed-Loop Flow test (ICFT) of May−June 1986. EE3a was injected for the first 2 weeks at 10−11 l/s and 27 MPa wellhead pressure, and then 18 l/s and 31 MPa for the next 2 weeks. Production flow rate from EE2 against a back-pressure of 1.5−3.5 MPa continually increased throughout the test reflecting the filling of the reservoir and reached 14 l/s by the end. Reservoir flow impedance was initially 6.5 MPa/l/s but declined rapidly during the first few days to reach 2.1 MPa/l/s by the end. The initial decline reflects an increase in EE3a injectivity, probably due to thermo-elastic stresses. Temperature logs in EE3a 1 and 2 months after the test showed residual cooling extending 450 m above the open hole, indicating flow along the annulus or fractures, although the strongest cooling was focused over the 150 m section above the interval bottom. Two tracers tests conducted early and late in the test indicated integral mean fluid volumes (i.e. swept volume) of 2200 and 8500 m^3. Following the ICFT, EE2 was recognized as unsound. In Sept. 1987, after an attempt at repair failed, a side-track well, EE2a, was drilled parallel to EE2 from a kick-off point at 2964 m MD so that it remained within 15 m of the original EE2 trajectory over its open hole section. The well was drilled to 3767 m MD and a liner cemented to 3283 m MD leaving 484 m of open hole. A small volume (189 m^3) injection into EE2a (Expt. 2076) at rates up to 40 l/s and 30 MPa indicated an injectivity that was twice as high as the current EE3a wellbore. Thus, there was no need for further stimulation.

During the 2 years construction period of the surface plant required for the long-term flow test (LTFT), the reservoir was pressured by injecting into EE3a with EE2a shut-in to evaluate water loss (Expt. 2077). Between April 1989 and Dec. 1990 pressure was maintained between 15 and 19 MPa. Injection declined as log (time), suggesting radial flow, and reached 0.15 l/s by the end of the test, indicating an essentially closed system. Initial testing began in Dec. 1991, and the first of several prolonged circulations constituting the LTFT series began in April 1992. The first period, denoted as Phase 1, lasted for 112 days and was the longest period of continuous circulation, subsequent periods being hindered by pump failure. During Phase 1, WW3a was injected at 6.7 l/s with 27.3 MPa wellhead pressure, and EE2 produced at 5.7 l/s against 9.7 MPa backpressure. The system impedance was 3.1 MPa/l/s. Assuming 2.5 MPa buoyancy drive in each well, the implied reservoir impedance would be 4.0 MPa/l/s. Production temperature remained stable at 183 °C.

3.2.1.2 Rosemanowes (Cornwall, UK)

The Rosemanowes HDR project was active between 1978 and 1991, and culminated in the development and operation of a circulation system at a depth of ~2 km within the Carnmenellis granite. The pluton is relatively undeformed, and there is no evidence of significant faults in the vicinity of the site. Surface outcrops and acoustic televiewer logs indicate the reservoir hosts two high-angle fracture families which strike ENE and WSW and include members whose lengths exceed 20 m (Whittle and McCartney, 1989). The stress state is strike-slip with S_{hmax} oriented NW-SE and a minimum principal stress level at 2.0 km that is 10 MPa above hydrostatic pressure. The stress is critical inasmuch as only small increases in pore pressure are needed to initiate shearing of the NW-SE striking fracture set. Indeed, if the rock mass strength were represented by a Coulomb friction law, a friction coefficient of 0.85 would be required to prevent failure at 2.0 km under ambient conditions (Evans *et al.*, 1992). The natural Equivalent Porous Medium (EPM) permeability of the rock mass is estimated as 10^{-17}–10^{-18} m^2, several orders of magnitude higher than the intact granite (Pine and Ledingham, 1983). Seismic activity in the reservoir was monitored throughout operations with a surface network of three-component accelerometers and occasionally a string of hydrophones at reservoir depth (Batchelor *et al.*, 1983). The area has low natural seismic hazard (Evans *et al.*, 2012).

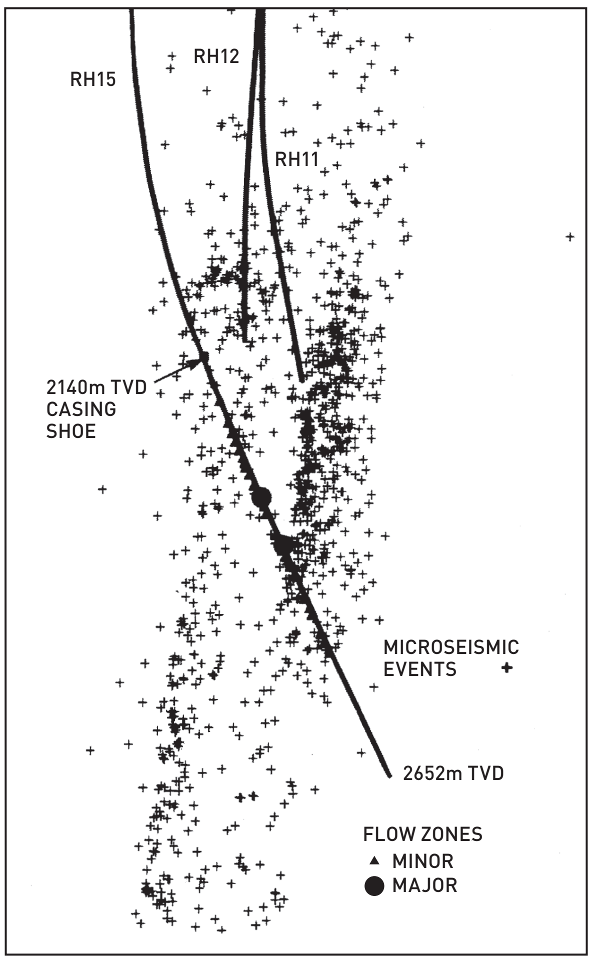

Figure 39: *Vertical view of Rosemanowes reservoir viewed from N143°E (left to right corresponds to SW to NE). The locations of microseismic events triggered by the stimulation injections into RH12 are shown (note subsequent relocation of the events following the discovery of an error in polarity at one station moves the events slightly). The barbs on the trajectory of well RH15 denote locations where evidence of flow was seen. Figure from (Ledingham, 1989).*

Initially, two deviated wells designated RH11 and RH12 were drilled to 2038 and 2156 m TVD respectively (see **Figure 39**). The wells were deviated at 30° towards N55°W in the same vertical plane with a separation of 150m. The open hole section of the upper well, RH11 was 722 m, and lay immediately above that for the lower well, RH12 of 357 m. The wells were stimulated with a variety of methods, including explosive detonation and water injections. The main stimulation involved the injection of 12'000 m^3 of water into RH12 at 90 l/s and pressures of 14 MPa, followed by 2'000 and 4'000 m^3 injections into RH11 at 98 l/s. Many tens of thousands of events of magnitude less than M_L 0.16 were detected, none of which were felt (Evans *et al.*, 2012). Unusually, the seismic activity preferentially grew downward (Richards *et al.*, 1994), which is ascribed to increasing criticality of the stress state with depth (Pine and Batchelor, 1984). The system was circulated by injecting into RK12 at rates up to 33 l/s, but only 7−8 l/s was produced, the loss escalating when injection pressures exceeded the minimum principal stress. The EPM permeability of both wells had been radically increased to ~10^{-15} m^2 by the stimulations, but cross-well impedance remained too high at 1.5−1.8 MPa/l/s. To try to stimulate the intermediate field between the wells, a conventional hydrofracture operation was performed featuring the injection of 400 m^3 of gel into RH11 at rates up to 195 l/s and wellhead pressures of 25 MPa. RH11 injectivity was increased, most permeability enhancement occurring at natural fractures, but the cross-well impedance remained too high.

In 1985, a third well, designated RH15, was drilled on a curving trajectory through the microseismic cloud to 2.65 km depth. Locations where the well intersected permeable features correlate well with the microseismic structures. However, the impedance between RH15 and the other two wells was of the order of 2 MPa/l/s. Thus, RH15 was stimulated with a viscous frac at pressures up to 14 MPa (Parker, 1989a). A tubular cloud of microseismicity extended upwards from the bottom of the injection interval to RH12 (see **Figure 40**).

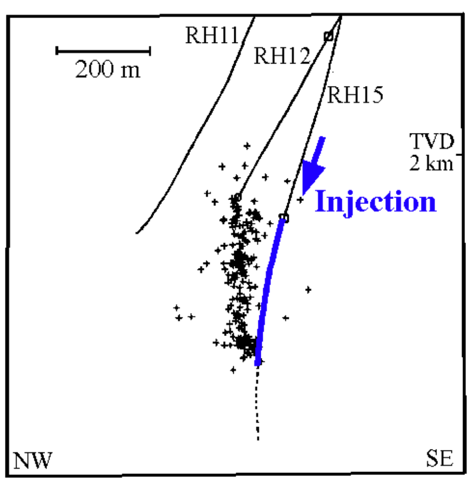

Figure 40: *Vertical view of reservoir viewed from N210°E showing the locations of the microseismic events that occurred during the viscous stimulation. Figure from (Ledingham et al., 1989).*

A program of circulation tests that featured a variety of configurations and flow rates commenced in August 1985, which ran until the end of 1989. Fluid losses averaged about 20%, and thus circulation constituted long-term net injection. Losses and seismic activity increased significantly at injection pressures above 10 MPa (about 24 l/s), when downhole pressures approached or exceeded S_{hmin}, indicating reservoir growth (Baria and Green, 1990). A magnitude M_L 2.0 event that was mildly felt by the local population occurred at 3.1 km depth when the system was being injected at 33 l/s and 11.1 MPa wellhead pressure, with a relatively high loss rate of 8 l/s. Subsequently, the circulation rate was lowered to 10 MPa to prevent reservoir growth. The performance of the reservoir when injecting into RH12 at the maximum of 24 l/s and 10 MPa pressure gave 16 l/s production from RH15 and 3 l/s from RH11, with a loss of 5 l/s. The RH12−RH15 system impedance at this rate was 0.6 MPa/l/s, and the RH12−RH11 impedance was 3.3 MPa/l/s.

The NNW-SSE orientation of the microseismic cloud, numerical simulations and fault plane solutions indicate that permeability enhancement was occurring through shearing of the NW-striking fracture population. This suggests that better results would have been obtained had the first two wells been inclined in the direction of the minimum principal horizontal stress, rather than the maximum since this would have activated a larger number of linkages between the wells (Richards *et al.*, 1994).

3.2.1.3 Hijiori, Japan

The Hijiori project was the first Japanese EGS field experiment to be conducted in crystalline rock. The site is located on the southern edge of a 9000 year old caldera in northeastern Japan where the granodiorite reservoir underlies 1500 m of volcanic strata. Two reservoirs were developed at 1800 m and 2200 m. The first well drilled, SKG2, was intended to explore for hydrothermal targets in the volcanics. When none were found, it was extended to 1802 m where a temperature of 253 °C was measured. Hence it became a HDR development well. Only the lowermost 14 m is open hole. Televiewer logs acquired between 1500 and 1800 m revealed only 14 fractures with dips of 60−70° and a strikes that broadly clustered in directions N160°E and N60−90°E (Hirakawa *et al.*, 1989). Cores from various depths showed that the ENE to E-striking fractures contained euhedral quartz, were often partly open, and crosscut the other families, which tended to be filled with chlorite and epidote. Regarding the state of stress, the E-W orientation of 100 m long drilling-induced tension fractures observed below 1500 m in well HDR1 indicate S_{hmin} is oriented approximately N-S. The magnitude of S_{hmin} estimated from instantaneous shut-in pressures following large injections in SKG2 is 0.56 of the vertical stress (Kobayashi *et al.*, 1987). Focal mechanism solutions indicate predominantly normal faulting. Thus, shear stress in the reservoir is high, and the stress state is critical and favors slippage of the E-W striking fractures in a normal fault sense.

The creation of the upper reservoir at Hijiori began in 1985 with a series of water injections into the lowermost 14 m of SKG2. In the largest of these, 1080 m^3 of water was injected at rates up to 98 l/s and wellhead pressures of 15.4 MPa (Sato *et al.*, 1989). An acoustic televiewer log run following the injection showed the trace of a new E-W striking hydraulic fracture at hole bottom (Hirakawa *et al.*, 1989). In 1987, a second 1805 m deep vertical borehole, HDR-1, was drilled 37 m to the south of SKG2, and was completed with 292 m of open hole. Pressure disturbances in SKG2 during the drilling of HDR1 showed that the holes were linked by a permeable fracture network (Hirakawa *et al.*, 1989). SKG2 was subjected to further stimulation injections, the largest being 1900 m^3 at up to 97 l/s and a 15 day circulation conducted. HDR1 was then extended to 2205 m and a liner with polished bore receptacle (PBR) cemented from 1897 m to 2159 m. When 5" tubing is strung into the PBR, the annulus connects to the upper reservoir and the tubing to the 46 m of open hole at the well bottom that would eventually become the injection well of the lower reservoir. In 1989, HDR2 was drilled to 1910 m and cased to 1504 m. At reservoir depth, it lies 45 m WSW of SKG2. In Oct. 1988, the 3-well system was circulated for 29 days by injecting SKG2 at 16.7 l/s and 4.5 MPa wellhead pressure. Production from HDR1 and 2 against 0.8 MPa backpressure was 9% and 28% of the injection rate, respectively. Tracer tests show the connection to HDR2 was much more direct and less dispersive than HDR1, one outlet in HDR2 showing a temperature decline indicating a short circuit. Some 331 microseismic events were detected by the 8-station surface array augmented with one 3-component sensor clamped in a well. The locations formed a cloud that was elongated to ENE-WSW.

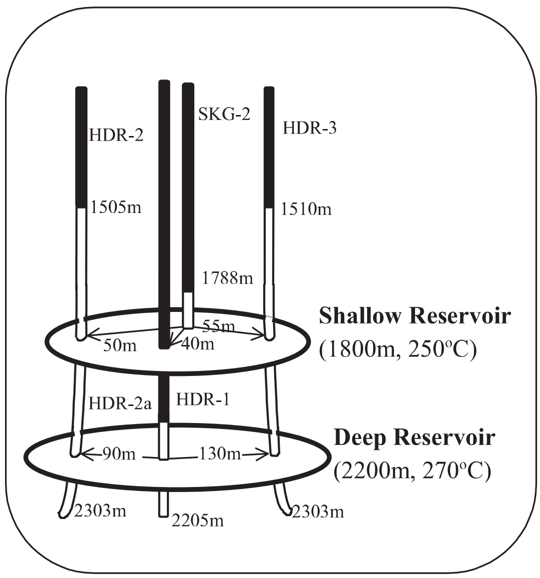

Figure 41: *Well configuration at the Hijiori test site after completion of the shallow and deep reservoirs. The filled parts of the trajectories denote casing. Both reservoirs have a central injection well and two peripheral production wells. Figure modified from (Tenma et al., 1999).*

In 1990, a further well, HDR3, was drilled to 1907 m and cased to 1510 m at a location 60−70 m ESE of SKG. At this time, the construction of the shallow reservoir was essentially complete (note that only SKG2 had ever been subjected to stimulation injections!). Over the next year, several interference tests were performed, with volumes in the range 39−372 m^3. In August 1991, a 90 day circulation of the upper reservoir began by injecting SKG2 at 16.7 l/s and 3 MPa. By the end of the test, production from HDR1, 2 and 3 against back-pressures of 0.5−1.5 MPa were 2.5, 5.1 and 5.2 l/s respectively, giving a net recovery of 76%. The inter-wellhead system impedances were 0.66 MPa/l/s (SKG2-HDR1), 0.45 MPa/l/s (SKG2-HDR2) and 0.37 MPa/l/s (SKG2-HDR2) (Evans *et al.*, 1992)

Deep reservoir creation began in 1992 with the stimulation of the HDR1 open hole with 2100 m^3 of water at 72 l/s and 8.8 MPa wellhead pressure. The microseismic cloud was elongated E-W and the maximum magnitude was M_L 0.0. Well HDR3 was then extended to 2303 m TVD although the casing shoe remained at the top of the upper reservoir at 1516 m. An oriented core taken on a fracture at 2183.3 m MD that had hydraulic communication with 60−70 m distant HDR1 open hole showed it had a dip of 64° and strike of N112°E, and was partially open. In 1994, HDR2 was extended to 2297 m TVD by sidetracking at 1613 m and renamed HDR2a. The casing shoe remained at 1513 m, and so the open hole included both shallow and deep reservoirs. Pressure disturbances in the 65−70 m distant open hole of HDR1 during drilling indicated E-W connected permeability in the lower reservoir, and a core taken at 2105.5 m showed open fractures with millimetre aperture. Lower reservoir creation was concluded by permanently closing HDR1 to the upper reservoir. Thus, the upper reservoir consisted of SKG2 as the injection well and HDR2 and 3 as the production wells, whereas the lower reservoir had HDR1 as the injector and HDR2 and 3 as producers. In 1994/95 a number of small-volume injections were performed into HDR1 to evaluate the response at the other wells.

In August 1995, a 25 day circulation of the lower reservoir was conducted at a nominal injection rate of 16.7 l/s, but this was interrupted by two 1 day 'stimulation' periods when rate was increased to 42 and 57 l/s, and a 9 day period at 33 l/s. HDR1 injectivity increased from at least 1.2 to 2 l/s/MPa as a consequence of the stimulations, but recovery from HDR2a and 3 remained unchanged at 30% and 23% of injected flow. Flow entered HDR2a and 3 from the shallow and deep reservoirs in approximately equal measure. A further 29 day circulation was conducted at 16.7 l/s a year later and yielded similar results, with only 50% fluid recovery. A prolonged circulation of the deep reservoir lasting 300 days commenced in November 2000. Water was injected into HDR1 at 16.7 l/s and 5.2 MPa with SKG2 remaining shut-in. At the end of the test, production from HDR2a on open flow was 3.7 l/s, and that for HDR3 against 0.8 MPa back-pressure was 2.1 MPa implying a net recovery of 36%. The inter-wellhead system impedances were 1.38 MPa/l/s (HDR1-HDR2a) and 2.1 MPa/l/s (HDR1-HDR3). Production temperature of an outlet in HDR2a in the lower reservoir began to decline after 2 months, indicating a short circuit.

Operations at Hijiori concluded with a 3 month circulation of both shallow and deep reservoirs with power production from a binary plant. HDR1 was injected at 12.1 l/s and 4.0 MPa, and SKG2 at 4.3 l/s and 1.0 MPa. HDR2a produced 5.6 l/s, and HDR3 2.3 l/s, both against a back-pressure of 1.0 MPa. The binary plant produced 130 kW of electricity.

3.2.1.4 Soultz-sous-Forêts, France

The Soultz-sous-Forêts site is located in a geothermal anomaly within the Upper Rhine Graben (URG), some 40 km NNE of Strasbourg, France. A summary of reservoir development at the Soultz site is given in (Genter *et al.*, 2010). At the Soultz site, the granitic basement lies below 1.4 km of sediments. The temperature gradient in the sediments was known to be as high as 110°/km, but that in the basement was uncertain. Graben-parallel faults produce a horst-and-graben structure within the basement. Natural fractures in the granite are invariably high-angle and have a broad range of strikes within ±45 of N-S. Small-scale fractures are pervasive and are thought to be mode-1 and have little connectivity. Of greater importance for reservoir creation is a connected network of larger-scale fracture zones with lengths of tens of meters up to fault-scale (>kilometer) that are also high-angle and strike on average N160°E and have suffered hydrothermal alteration (Dezayes *et al.*, 2010). These fracture zones represent the conduits through which fluids move through the rock mass under ambient conditions, and some members that have a very high hydraulic capacity (Evans *et al.*, 2005a). The stress-state is transitional between normal and strike-slip with

S_{hmax} oriented on average N170°E. The magnitude of S_{hmin} is about 0.5Sv down to 5 km depth and thus shear stress is very high. A strength equivalent to a friction coefficient of 0.85 is required to prevent failure of the principal fracture population (Evans, 2005). Thus, the rock mass, and many of the large-scale structures within it, are critically stressed at all reservoir depths (Valley, 2007). The region has low-to-moderate seismic hazard (Evans *et al.*, 2012). In 1954 a series of events with magnitudes up to M_L 4.8 occurred 10−20 km southeast of Soultz (Helm, 1996).

Activity at the Soultz site began in 1987 with the drilling of a 2002 m deep vertical exploration well, GPK1, to probe the granitic basement below 1.4 km (Kappelmeyer *et al.*, 1992). The casing shoe was set at 1420 m. One permeable structure was identified at 1813 m. A series of water injections was performed on isolated intervals, after which attention focused on stimulating the lowermost 35 m of hole. This was initially tight, but had become permeable after a hydrofracture had been inadvertently induced (Jung, 1991). Three stimulation injections were performed, the largest involving the injection of 2700 m^3 at 15 l/s and 6.6 MPa overpressure. As a consequence, injectivity increased from negligible to 4−5 l/s/MPa. Microseismic activity was observed which indicated a preferred flow to the north (Beauce *et al.*, 1991). The hydraulic testing program also suggested the existence of porous and permeable fracture zones that gave the granite attributes of a hydrothermal reservoir, and spawned the term 'Hot Wet Rock' system. Most findings from the shallow exploration experiments were found to be valid at greater depth.

Development of the 3−3.5 km reservoir began in 1992 with the extension of GPK1 to 3.6 km depth. The casing shoe was set at 2.85 km leaving 750 m of open hole. Several hydrothermally-altered fracture zones were intersected that were very slightly permeable, and one at 3.5 km that had substantial permeability. The well was stimulated by first injecting 20'000 m^3 of water into the low-permeability section above 3.5 km at rates that were stepped-up to a maximum of 36 l/s. Downhole overpressure quickly rose to 9 MPa and thereafter remained stable despite the higher rates (93SEP01). Such pressure-limiting behavior suggested the level of S_{hmin} had been reached. Flow entered the rock at fracture zones whose permeability increased to accommodate the increasing flow rates. Permeability enhancement was initially greatest at deeper zones, but became focused near the casing shoe as the injection progressed − a pattern also seen in the microseismicity that tended to grow upwards in later phases of the test (Jones *et al.*, 1995). Shortly thereafter, the entire well was subjected to a further water injection of 20'000 m^3 at 40 l/s and 9 MPa downhole overpressure. Subsequent injection and production tests showed that stimulations had increased well injectivity at 1 MPa overpressure from 0.6 l/s/MPa to 9.0 l/s/MPa (Evans *et al.*, 2005a), and that penetrative turbulent flow occurred within the reservoir at all but the lowest flow rates (Kohl *et al.*, 1997). Many tens of thousands of microseismic events were recorded on the downhole array. The microseismic cloud was elongated to NNW-SSE and had lateral and vertical dimensions of ±400 m. The largest event which occurred during the entire stimulation program was assigned a magnitude of M_L 1.9 from the surface array, and occurred 9 days after the first GPK1 stimulation injection (Helm, 1996). At Soultz, magnitudes greater than M_L 2.0 can felt by the nearby population under ideal conditions.

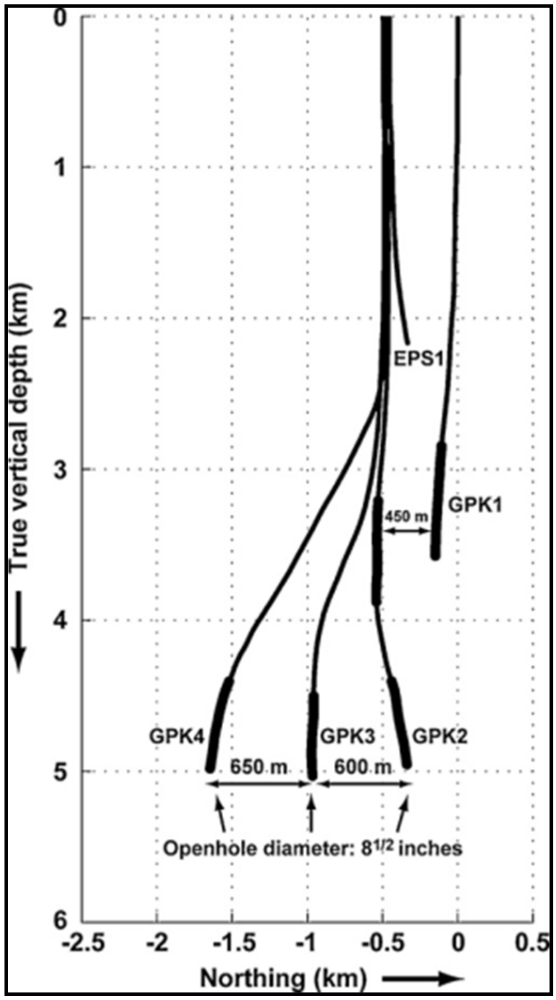

Figure 42: *N-S cross-section through the Soultz site showing the trajectory of the boreholes. The thicker parts of the trajectories denote open hole sections. The upper reservoir was developed between GPK1 and GPK2, the latter of which only extended to 3.8 km at that time. This reservoir was circulated in 2005. GPK2 was then extended to 5 km and became a production well of the deep reservoir. Figure from (Genter et al., 2010).*

The second well, GPK2, was drilled to 3876 m in 1995 to intersect the microseismic cloud 450 m SSE of GPK1. It was cased to 3211 m, leaving 660 m of open hole. The initial injectivity was 0.4 l/s/MPa, implying an EPM permeability of $4x10^{15}$ m^2 (Jung *et al.*, 1995). The entire open hole was then subject to a stimulation injection commencing with 250 m^3 of heavy brine (density of 1.18 gm/cc) followed by 10'000 m^3 of formation fluid (density of 1.18 gm/cc) and finally 20'000 m^3 of water at rates up to 55 l/s and overpressures of 12 MPa (95Jun14 & 95Jun16). A step-rate test after the stimulation indicated an injectivity at 6 l/s of ~10 l/s/MPa, but this decreased at higher rates owing to turbulent effects. A series of circulations were then conducted with GPK2 injected at 15 or 21.5 l/s and GPK1 produced with buoyancy drive (95Jul09) and downhole pump (95Aug01). The reservoir impedance was 0.45 MPa/l/s. A further stimulation of GPK2 was performed in 1996 at flow rates up to 79 l/s and overpressures of 13 MPa (96Sep18). This resulted in a 30% increase in injectivity, although the impedance remained turbulent-like. The built system was circulated for 120 days in 1997 by injecting GPK1 at 25 kg/s and producing GPK2 at the same flow rate with a downhole pump (Baria *et al.*, 1997). GPK1 injection pressure declined from 4.5 MPa at the start to 2.0 MPa at the end of the circulation, giving a reservoir impedance of 0.2 MPa/l/s. A tracer test conducted during the circulation indicated that only 20% of the injected tracer was produced, indicating substantial mixing of circulating fluid with the formation fluid. The integral swept volume was estimated as 16'000 m^3.

Development of the deep system began in 1999 with the extension of GPK2 to 5024 m TVD with the casing shoe set at 4400 m TVD. Stimulation of the wells of the deeper reservoir involved comparable injection volumes to those used in the upper reservoir, and again pressures appear to be limited at the minimum principal stress level (Valley and Evans, 2007). Stimulation of GPK2 began in June 2000 with the injection of 22'000 m^3 of water at rates of up to 50 l/s and 14.5 MPa wellhead pressure. Some 700 events with magnitudes between M_L 1.0 and 2.5 occurred during injection, but a magnitude M_L 2.6 occurred some ten days after shut-in (Dorbath *et al.*, 2009).

Stimulation of the second deep well, GPK3, took place in May 2003 and involved the injection of 34'000 m^3 of brine and water into GPK3, for the most part at 50 l/s with occasional increases for a few hours of up to 90 l/s which produced the maximum wellhead pressure of 17.9 MPa. Midway through the stimulation, some 3400 m^3 of water was simultaneously injected into GPK2 for about 40 hrs at a rate of 20 l/s (Baria *et al.*, 2004). GPK2 wellhead pressure rose to 7.9 MPa. Some 200 events with magnitudes between M_L 1.0 and 2.5 occurred during this injection (Charléty *et al.*, 2007), and a magnitude M_L 2.9 event occurred two days after shut-in, despite an attempt to avoid this by a stepwise injection rate reduction (Baria *et al.*, 2004).

The stimulation of the third deep well, GPK4, began in September 2004. The injection rate was maintained at 30 l/s with a few short increases of 2 hrs duration to 44 l/s. Peak wellhead pressure was 17.5 MPa. The injection was terminated after injecting 9000 m^3 due to a pump failure. The stimulation program resumed in Feb. 2005 when a further 12'500 m^3 of water was injected at up to 45 l/s and peak wellhead pressures of 18.5 MPa (Dorbath *et al.*, 2009). Some 128 events with magnitudes between M_L 1.0 and 2.7 were recorded during injection, but none larger than M_L 2.0 occurred during shut-in.

Of the three deep Soultz wells, GPK3 appeared to be the most prone to produce large events in response to injection. (Dorbath *et al.*, 2009) found the b-values for the GPK2 and GPK3 seismicity to be 1.23 and 0.94, respectively (although only over the respective limited magnitude ranges of M_L 1.0−1.9 and 1.0−2.3), and suggested the difference reflected the activation of a major fracture zone intersecting GPK3. In 2005, the three-well system was subjected to a six-month close-loop circulation test at 15 l/s using only buoyancy drive, and GPK3 as the injection well. Seismicity began soon after injection commenced, and a total of 32 events reaching or exceeding M_L 1.3 were recorded during the entire period, the largest being M_L 2.3.

A two-month closed-loop circulation test of wells GPK2-GPK3 was performed in 2008 at 25 l/s using a production pump in GPK2. No seismicity was observed for five weeks during which time the GPK3 injection pressure rose steadily to 6 MPa. Seismicity began once that pressure was exceeded, and included four events having magnitudes in the range M_L 1.3−1.4 (Cuenot *et al.*, 2010).

3.2.1.5 Fjällbacka, Sweden

The Fjällbacka site is a shallow (~500 m) facility located on the coast of western Sweden where the Bohus granite outcrops. It was established in 1984 as an in-situ laboratory for studying hydromechanical aspects of HDR reservoir development together with addressing geological and hydro-geological questions (Wallroth, 1992; Wallroth *et al.*, 1999). The reservoir consists primarily of the Grenville age Bohus granite, although a gneissic xenolith is encountered in one borehole. Natural fracture density is high (2.7 /m in Fjb1), the majority being high-angle, with strikes of NW and NE predominant, although a sub-horizontal set is also present. Trace lengths for the NW-striking high-angle set are longest at 5−15 m, and shortest at 2−4 m for the sub-horizontal set. The NW-striking high angle set tends to be rougher, undulating and show evidence of hydraulically active. Hydrofracture tests, and inversion of focal mechanism solutions suggests the minimum stress is vertical, and the maximum stress is oriented N20−40°E (A Jupe and Green, 1988). The stress state is sub-critical in as much as an overpressure of a few MPa above hydrostatic is sufficient to produce shearing of a fracture set (Jupe *et al.*, 1992). Natural seismicity is low, although the historical record indicates that several events of magnitude approaching M_L 4.0 and intensities up to Io 5 occurred within 25 km of the site.

Initially three boreholes, Fjb0, Fjb1 and Fjb2, were percussion drilled to 200, 500 and 700 m respectively to characterize the prospective reservoir. A series of shallow (<200 m) and deep injection tests were conducted to evaluate the response of the virgin rock mass. These culminated in an attempt to develop a reservoir at 450 m depth by a carefully planned series of injections into Fjb1 between 447 and 478 m depth. Some 150 m^3 of water was followed by the injection of 200 m^3 of medium-viscosity gel and finally 21 m^3 of gel and proppant at rates up to 21 l/s. Most fluid entered the rock mass at a sub-horizontal fracture at 455 m. A significant increase in injectivity was observed. Microseismicity was monitored with an array of 15 vertical-component instruments on granite outcrop and a 3-component instrument clamped near the bottom of Fjb0. A total of 74 events were detected with magnitudes M_L -1.3 to -0.2 that defined a sub-horizontal structure extending 200 m from the well (Eliasson *et al.*, 1988b).

An additional well, Fjb3, was then drilled to 500 m depth in 1988 to intersect the micro-seismic zone some 100 m to the west of Fjb1. Flow tests indicated a hydraulic connection to Fjb1, but flow was limited by an impedance in the vicinity of Fjb3. A 14-day circulation test was conducted with water injected into Fjb3 at 0.3 l/s and 1.1 MPa, and produced from Fjb1 against 0.3 MPa back pressure. Recovery reached only 0.22 l/s implying a system impedance of 12.2 MPa/l/s, which is high. Thus Fjb3 was stimulated by injecting 36 m^3 of gel with proppant at 16 l/s and wellhead pressures of up to 19 MPa. A further 50 events were recorded. The injection succeeded in reducing the flow impedance, at least in the near field. The system was circulated for 40 days during 1989. Water was injected into Fjb3 at 1.8 l/s and produced from Fjb1 against a 0.3 MPa back-pressure. Injection pressure at Fjb3 rose quickly to 3 MPa within a few hours and then progressively more slowly to reach 5.2 MPa by the end of the test (Eliasson *et al.*, 1990). Production was 55% of the injection flow, compared to 0.22 prior to stimulation, and the system impedance was reduced to 4.9 MPa/l/s. Several hundred microseismic events were recorded at distances up to 400 m from the injection point, the largest of which was mildly felt onsite (Evans *et al.*, 2012).

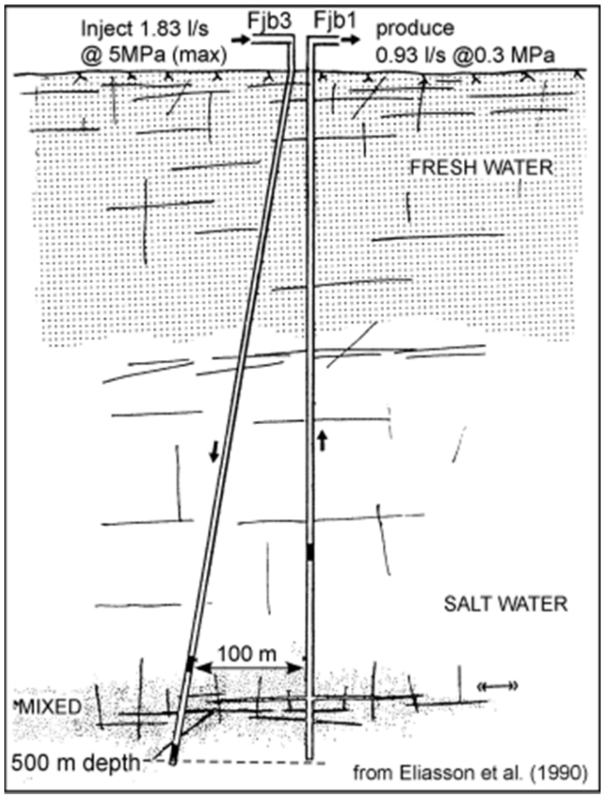

Figure 43: *Illustration of the geometry of the wells and reservoir at the Fjällbacka test site at the time of the circulation test.*

Important features of the work at Fjällbacka are the detailed reservoir characterization and the design of the stimulation program that included proppant injections. An unusual aspect of the project is that the state of stress in the reservoir is such that the least principal stress is vertical and hence horizontal fractures are the preferred conduits for fluid flow. A comprehensive description and analysis of the work conducted at Fjällbacka can be found in (Wallroth, 1992).

3.2.1.6 Le Mayet de Montagne, France

The Le Mayet site is located 25 km southeast of Vichy, France, at the northern fringe of the Massif Central. Granite extends to the surface, forming undulating topography of height less than 100 m and offering exposures of fractures in the outcrop. The facility was established in 1985 with two boreholes to ~800 m depth to study rock- and hydro-mechanical aspects of EGS reservoirs. The reservoir hosts a complex pattern of natural fractures, most of which are high angle (Thomas, 1988) and fall into two groups: one predominant set is tightly clustered about an orientation of N170°E. The other group consists of fractures oriented between N65°E and N115°E and appears to include several sets. The fractures in the outcrop show evidence of hydrothermal alteration with various mineral infillings whose form suggests they formed in large open voids at depth (Desroches and Cornet, 1990). The fracture population characteristics vary significantly: the section between 650−780 m in well INAG 111-8 is highly fractured and altered whereas the same section in INAG 111-9, some 100 m away, showed a very low fracture density. Stress at the site is well characterized using the Hydraulic Testing on Preexisting Fractures (HTPF) method. At reservoir depths below 650 m, S_{hmax} has about the same magnitude as the vertical stress and is oriented N140°E. The magnitude of S_{hmin} is about 0.55 of the vertical stress, a value so low that favorably oriented fractures whose strength is given by a friction coefficient 0.8 would be verging on failure. Favorably oriented fractures are present in the reservoir, and thus the rock mass is critically stressed. Natural seismicity is low, although the historical record indicates that two events estimated to be M_W 4.3 have occurred at distances of 16 and 27 km from the site over the last 130 years (Grünthal *et al.*, 2009).

Two near-vertical boreholes were drilled approximately 800 m deep and 100 m apart along a line striking N140°E, which is aligned with S_{hmax} but not the principal vertical fracture set that strikes N170°E. Well INAG 111-8 (780 m depth) lies to the northeast of INAG 111-9 (840 m depth). A diverse series of high-rate injection experiments with and without proppant were conducted on selected intervals to try to create/enhance the hydraulic linkage between the two wells. The first phase of reservoir development attempted to link the relatively unfractured lower section of 111-9 to the fracture network intersected between 650−780 m in 111-8. Three fractures in 111-9 at depths of 645, 720, and 730 m were individually isolated and injected with 200−400 m^3 of water gel at up to 22 l/s and 11 MPa. Shut-in pressures of 7.5−9 MPa were observed, considerably higher than the wellhead pressure of 3.5−4 MPa required to attain S_{hmin} levels downhole. A 70 hour circulation with 111-9 injected at 8 l/s and 8.2 MPa wellhead pressure was conducted that yielded 33% recovery with 111-8 on open flow and a reservoir impedance of 2.9 MPa/l/s. A further gel injection was performed on an isolated fracture at 758 m in which 2 tons of proppant were injected.

The next phase of reservoir development attempted to stimulate the fractured section of 111-8 below 650 m by injecting 200 m^3 of gel and 7 tons of proppant at 30 l/s and 12 MPa wellhead pressure. The system was circulated for 21 days by injecting 111-9 at 8 l/s and 9.2 MPa which yielded a recovery of 58% and an impedance of 1.9 MPa/l/s. A classical hydrofracture operation was then by conducted by injecting 111-8 with 200 m^3 of gel and 40 tons of proppant at 73 l/s and wellhead pressures up to 25 MPa (Cornet, 1989). The instantaneous shut-in pressure was 16 MPa. A 69 day circulation was then performed by injecting 111-9 at various rates of 5.3, 8.3 and 16.7 l/s and corresponding wellhead pressures of 8.3, 9.2 and 10.5 MPa. Impedance and percentage recovery at 8 l/s injection were unchanged from the values seen in the previous 8 l/s circulation, implying that the hydrofracture had not improved linkage. However, recovery improved to 83% when injection rate was reduced to 5.3 l/s, whereas it decreased to 49% and was accompanied by the drop in impedance to 1.3 MPa/l/s when the rate was increased to 16.7 l/s. These observations indicate changes in fracture aperture in response to small changes in reservoir pressure, indicating the system was being operated close to the minimum stress level. However, a network of tiltmeters operating on the surface failed to detect any signal, even during the stimulation injections, suggesting dilation was small (Desroches and Cornet, 1990).

Microseismic events induced during these experiments were monitored on a 15 station array (mostly 3-component with two downhole) which allowed event locations to be determined to within 4.5 m horizontally and 10 m vertically. The seismic dataset features the best sampling of the seismic radiation field ever attained in a HDR field experiment. Relatively few events were recorded during the stimulations, although 140 were detected at depths of 400−800 m during the various circulation tests conducted on the doublet system (Evans *et al.*, 1992). The events were small, and none were felt by site personnel. More than 35 events were recorded on sufficient stations to yield fairly well-constrained focal mechanism solutions. Some of these solutions were inconsistent with the reservoir stress characterization from the HTPF measurements, indicating local stress heterogeneity.

3.2.1.7 Habanero site, Cooper basin, Australia

The Habanero site is located in the Nappamerrie trough of the Cooper basin, some 10 km south of the town of Innamincka, South Australia. The target reservoir is a radiogenic granite whose top lies beneath 3670 m of sediment cover composed largely of shales and coal deposits (Wyborn *et al.*, 2005). The sediments are hydrocarbon bearing, and there are several deep exploration wells in the area. Data from these wells indicates that the regional minimum stress is vertical, the maximum principal horizontal stress magnitude, S_{hmax}, is approximately E-W (Reynolds *et al.*, 2005), and that formation overpressures in excess of 20 MPa are commonly found below 2.7 km (Reynolds *et al.*, 2006). The granite is medium-to-coarse grained white two-mica variety of age 320 Ma, and has a heat productivity of 7−10 $\mu W/m^3$. Gravity modeling indicates a thickness of at least 10 km, which is consistent with an estimated surface heat flow of 103 MW/m^2 (Beardsmore, 2005). The high heat flow and the low thermal conductivity of the shales and coal present in the sediments give a temperature gradient in the latter of 60 °C/km. The temperature at the granite top is 230 °C and the gradient below is 35 °C (Chen and Wyborn, 2009). The granite surface was exposed to glacial erosion some 300 Ma ago and has subsequently undergone hydrothermal alteration (Chen, 2010). Microseismicity during the project was detected on a network of seven 3-component stations in boreholes 100−450 m deep, augmented by a 3-component station at 1800 m in an nearby abandoned well (Baisch *et al.*, 2006).

Reservoir development began in 2003 with the drilling of the Habernero-1 vertically to 4421 m (below rig floor) where the static bottom-hole temperature was 250 °C (Wyborn *et al.*, 2005). A 7 inch casing was run and the shoe set at 4139 m, before drilling a further 282 m of 6 inch open hole. The hole was designed as an injection well, and was completed with a 4-1/2 inch high-pressure tubing string 'stung' into a mechanical casing packer at 3091 m to prevent damage to the 7 inch casing during high-pressure injections. Several shallowly dipping fractures or fracture zones with spacing of the order of 100 m were encountered in the granite. During the drilling of the open hole, permeable fractures at 4209 m and 4254 m were encountered that had unexpectedly large overpressure of 35 MPa. The operations to balance the overpressure by adjusting mud weight up to 1.9 gm/cc led to 326 m^3 of barite-weighted mud entering the fractures (Chen and Wyborn, 2009). Attempts to clean out the barite from the fractures were not obviously successful, and it is believed the barite still limits the injectivity of the well. The well was initially subject to an extensive series of small volume injection tests that generated microseismicity. Most flow was taken by the fracture at 4250 m. Salt was used as a diverter in some test to try to initiate flow at higher fractures (Wyborn *et al.*, 2005). The main stimulation was conducted on the entire open hole in Nov. 2003. A total volume of 16’000 of fresh water was injected over 10 days at rates stepped from 13 to 24 l/s and wellhead pressures up to 65.5 MPa (Baisch *et al.*, 2006). Some 11’000 locatable microearthquakes with a maximum magnitude of M_L 3.7 were recorded. The hypocentres define a sub-horizontal structure with lateral dimensions 1.5−2.0 km, and an apparent thickness of 150−200 m (Baisch *et al.*, 2006). Waveform similarity studies suggest a structure that dips at 20° to the SW and is composed of two parallel structures, 100 m vertically apart (Kumano *et al.*, 2006). To conclude the stimulation program, the open hole was filled with salt and the 7 inch casing was perforated at four points between 4136 m (first) and 3994 m (last). Following perforation, each interval was subjected to high pressure injection to attempt to drive a fracture. Only the lowermost interval which coincided with a fracture zone accepted significant flow. This interval appeared to be linked to the stimulated zone developed during the main stimulation. A further large stimulation injection was conducted on the open hole and perforations in September 2006, with the objective of extending the reservoir and increasing the permeability enhancement. Some 22'500 m^3 of fresh water was injected over 13 day period at flow rates of 31 l/s and wellhead pressures up to 62 MPa (i.e. 27 MPa above the shut-in pressure) (Baisch *et al.*, 2009). Some 8886 locatable events were recorded with magnitudes in the range M_L -1.2 to 2.9. The hypocentres define the same sub-horizontal structure that activated as in the earlier large stimulation, the first events occurring around the rim of the earlier structure and subsequently migrating outwards and inwards. Analysis of p-wave amplitude and polarity from all events generated in the large stimulations suggests focal mechanisms that are consistent with shear failure of shallowly-dipping fractures with the prevailing stress field. Cumulative moments suggest net slip across the thickness of the structure of several centimeters (Baisch *et al.*, 2009).

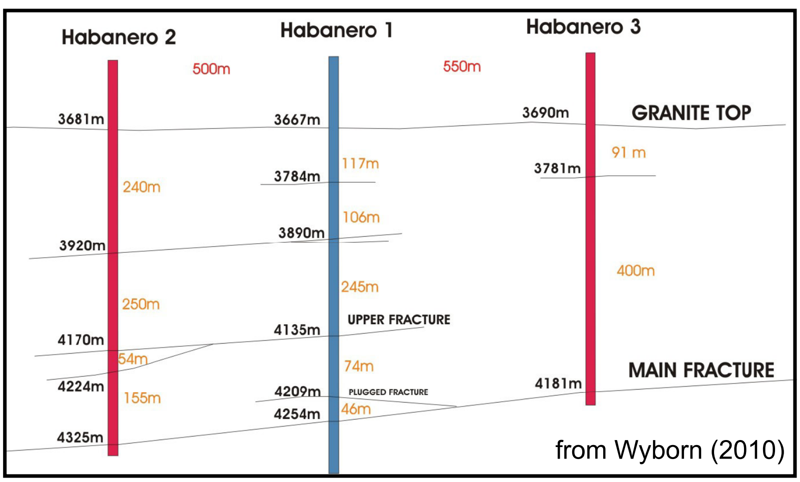

Figure 44: *Illustration of the depths of sub-horizontal fractures/fracture zones intersected by the wells in the granite at the Habanero site. The wells lie along a NE-SW trend with Habanero-3 to the NE. Fracture zones for which there is evidence of continuity between wells are drawn linked.*

Habanero-2 was drilled 500 m to the SW of Habanero-1 in 2004. Permeable fractures were encountered at 4170 m, 4224 m and 4325 m, the latter coinciding with the expected depth of the microseismic structure developed during the Habanero-1 stimulation. The feature was so permeable that significant mud loss into the zone occurred (Chen and Wyborn, 2009). Flow tests of Habanero-2 at rates up to 20 l/s produced a disturbance on Habanero-1, demonstrating connectivity (Wyborn, 2007). The fractures at 4170 and 4224 m that lay above the main zone were stimulated in August 2005 by injecting 7'000 m^3 of fresh water

(Wyborn, 2010). Microseismicity defined an activated structure that was parallel to and just above the main zone, and appeared to intersect Habanero-1 at a depth that coincides with the fracture zone stimulated through the lowermost casing perforations. Operational problems resulted in the drilling of several side-tracks and eventually led to the abandonment of Habanero-2 (Chen and Wyborn, 2009).

Habanero-3 was drilled vertically to 4221 m at a location 550 m NNE from Habanero-1, the opposite direction to Habanero-2. Only one impermeable fracture zone at 3781 m and one permeable fracture zone at 4181 m were encountered (Chen and Wyborn, 2009). The well was completed in January 2008 with a 9-5/8 inch casing shoe set at 4054 m, and the 8 inch open hole below protected from spalling by a 7 inch slotted liner hung from the casing shoe (Wyborn, 2010). The well was thus open to the fracture at 4181 m, which was believed to connect to the major permeable zone in Habanero 1 (see **Figure 44**). Production tests showed the well produced 16.2 l/s for a wellhead drawdown of 7.2 MPa implying a productivity index 2.3 l/s/MPa. This increased to 3.0 l/s/MPa at 19.7 l/s when Habanero-1 was injected at 18.5 l/s. The estimated circulation impedance using wellhead pressures is 1.33 MPa/l/s (indicating a reservoir impedance of 1.5 MPa/l/s). In April 2008, Habanero-3 was stimulated by injecting 2'200 m^3 of fresh water at flow rates up to 66 l/s and wellhead pressures of 63 MPa. Commencing in December 2008, the system was circulated for 6 weeks in balanced mode with Habanero-1 as the injector, Habanero-3 as the producer, and Habanero-2 shut-in. Initial flow rate was 12 kg/s but this increased to 15.5 l/s (Chen and Wyborn, 2009). Barite and granite particles were present in the fluid, indicating that some of the barite clogging the fractures was being removed. At the end of the test, the flow rate of 15.5 kg/s was driven by a pressure difference between wellheads of 11.0 MPa, implying a surface impedance of 0.71 MPa/kg/s. Assuming buoyancy drives of ~2 MPa in each well would give a pressure difference across the reservoir of 15 MPa, and hence a reservoir impedance of 0.97 MPa/kg/s. A tracer test conducted in December when the flow rate was 14 kg/s using both naphthalene trisulfonate and uranine (Yanagisawa *et al.*, 2009) showed breakthrough times of ~4 days, and peak recoveries 5−10 days after injection. The mean residence time was returned fraction was 78% and the tracer-swept pore volume between wells was estimated as 18'500 m^3 (Yanagisawa *et al.*, 2009). Reservoir assessment concluded with a step-rate test where production from Habanero-3 was increased in steps from 5 to 30 l/s with Habanero-1 shut-in (Wyborn, 2011). The estimated drawdown in downhole pressure was seen to increase as the square of flow rate, indicating turbulent-like impedance. Pressure build-up tests show indicate that this impedance is localized around the wellbore, probably due to convergence of the flow field (Chen and Wyborn, 2009). Nevertheless, the productivity of the well was only 35% of that prevailing prior to the stimulation (Wyborn, 2011).

3.2.1.8 Application of hydraulic stimulation to hydrothermal wells

From 1979 until 1984, the United States Department of Energy supported well stimulation experiments at eight conventional geothermal (i.e. hydrothermal) fields in the US (in addition to supporting the Fenton Hill petrothermal project). The objective was to apply hydrofracturing and chemical stimulation methods routinely used in the oil and gas industry to improve the injectivity/productivity of poorly performing geothermal wells. The DOE program and the outcomes of the experiments are summarized in (Campbell *et al.*, 1981; Entingh, 2000). Three of the tests were hydrofracture stimulations with proppant performed in fracture-dominated reservoirs: two in a quartz-monzonite reservoir at Raft River, Idaho, and one in an impermeable tuff at Baca, New Mexico. All three treatments resulted in significant enhancement of the productivity of the wells which is ascribed to an improvement in the linkage of the wells to the natural fracture system (Campbell *et al.*, 1981).

More recently, there has been a surge of interest in applying hydraulic stimulation to enhance to productivity/injectivity of wells in hydrothermal settings. Examples are Landau (Schindler *et al.*, 2010) and Insheim (Teza *et al.*, 2011) in the Upper Rhine Valley of Germany, the Salak Geothermal Field in Indonesia (Pasikki *et al.*, 2010), the Berlín field, El Salvador, the Geysers (Garcia *et al.*, 2012) and the Coso fields in California (Rose *et al.*, 2005), and the Desert Peak field in Nevada (Chabora, 2012). The latter three projects are cost-sharing ventures supported by the operators and the USDOE's Geothermal Technologies Program on Enhanced Geothermal Systems. Such experiments provide an opportunity to develop EGS stimulation technology while potentially increasing the exploitable energy in the field. A good example is the stimulation experiments conducted at the Desert Peak field, which are described below.

Desert Peak, Nevada: The Desert Peak geothermal site is located 80 km NE of Reno, Nevada, within in the Basin and Range province, which characterized by E-W extension and Tertiary volcanism. The reservoir has no surface expression, and is formed by the fracture/faults within a step-over between normal faults (Faulds *et al.*, 2010). The stimulation experiments were conducted on well 27−15 that was drilled to a depth of 2137 m in the northern margins of the field as an injector, but was found to have insufficient injectivity for commercial operation. The well was cased to 918 m, with a 12-1/4 inch open hole below. The temperature at 918 m was 182 °C increasing to 206 °C at 1700 m (Zemach *et al.*, 2010). A PTQ log run during an injection test of 8 l/s with 0.7 MPa wellhead pressure in 2008 showed the principal exit at a shale horizon at 1'474 m, although numerous other exits were identified from temperature perturbations. The interval selected for stimulation was 141 m long and extended from the casing shoe to the top of a cement plug that was set at 1059 m (Hickman and Davatzes, 2010). The interval consisted of silicic rhyolite tuff and meta-mudstones (Lutz *et al.*, 2010), and included several minor permeable zones identified from temperature perturbations (Zemach *et al.*, 2010). The static water level in the well was 116 m deep (Hickman and Davatzes, 2010). A mini-frac test was conducted on a 25 m section of open hole between the casing shoe and a temporary cement plug and yielded an estimate for the minimum principal horizontal stress S_{Hmin}, which was 0.61 of the vertical stress (Hickman and Davatzes, 2010). The orientation of S_{hmin} was determined from drilling-induced tension fractures as N114°E±17° (Davatzes and Hickman, 2009). The magnitude of the maximum stress principal stress S_{hmax} was not well-constrained, but was taken to be less than the vertical stress because focal mechanism solutions of local earthquakes are invariably normal faulting. Numerous fractures were present in the well that were optimally oriented for failure in the stress state, although a friction coefficient of 0.45 would have been required for them to be verging on failure for a minimum stress ratio of 0.61. After the temporary cement plug used for the minifrac test was drilled through, the 141 m interval below the casing shoe was subject to a series of different types of stimulation. Microseismicity occurring near the well was monitored by a 14 station array. Increases in injectivity were used to index the success of the stimulations. The initial reservoir injectivity (i.e. flow rate per unit downhole pressure increase) was 0.1 l/s/MPa. The test sequence and injectivity improvements are as follows (taken mostly from Chabora *et al*, 2012):

- Shear stimulation (August − October 2010): This was a prolonged step-pressure where the maximum pressure remained below the 5.2 MPa required for jacking. The injection began with 1.7 MPa wellhead pressure, which was subsequently increased in steps of 0.7 MPa, each held for one week. Reservoir injectivity remained unchanged until midway through the 3.1 MPa stage when flow rate began to increase from a rate of 0.25 l/s, consistent with the initial injectivity, to reach 4.4 l/s by the end of the stage, implying an injectivity of 1.2 l/s/MPa. After a break in injection for at least a week, injection resumed at 3.8 MPa wellhead. Flow rate was initially only 2.5 l/s but eventually reached 6.3 l/s, giving a reservoir injectivity of 1.4 l/s/MPa. Most flow entered the rock mass at depths of 1027 and 1042 m. The improvement was only temporary. After several months shut-in, the interval was again injected at 3.8 MPa wellhead, but this time the injectivity was only 0.37 l/s/MPa. No microseismic events were observed.
- Chemical stimulation (February 2011): Prior to the chemical treatments, and after several months of shut-in, a repeat injection test at 3.8 MPa wellhead pressure, showed the injectivity had declined to 0.37 l/s/MPa. The first chemical treatment was the injection of 136 m^3 of chelating acid followed by 83 m^3 of water to displace the acid. After a 48 hr reaction period, a step-rate test showed the injectivity essentially unchanged at 0.46 l/s/MPa. The second treatment, 48 m^3 of regular mud-acid (12% HCl, 3% HF) was injected at 3.8 MPa and flushed with 76 m^3 of fresh water. Following the treatment, the reservoir injectivity was found to have increased only slightly 0.64 l/s/MPa. No microseismic events were observed during either treatment. A wireline survey of the well showed that the lowermost 63 m of the 141 m interval, which included the principal flow zones, was blocked with debris. This might explain the reduction in injectivity during the 4 month shut-in period between the hydraulic and chemical stimulation operations. The well was cleaned out.
- Controlled hydraulic fracturing (April 2011): Hydraulic fracturing operations involved injections at rates high enough that downhole pressure exceeded that required to create and extend mode-1 hydraulic fractures. The test sequence began with a step-rate test to evaluate formation reaction. The initial rate of 13.6 l/s at 6.2 MPa was followed by a rate of 19.9 l/s at 6.55 MPa, with a reservoir injectivity of 2.9 l/s/MPa. Most fluid exited near the casing shoe. There followed a medium flow-rate injection of water and then brine at a flow rate of 31.5 l/s sustained for 1 week. During the course of the injection, 33 microearthquakes were detected, and the injectivity increased to 4.8 l/s/MPa. The 70% of fluid entered the rock mass in the 23 m section below the casing shoe, and 30% below 991 m. Immediately thereafter, a high flow rate treatment was conducted wherein flow rate was increased from 36.2 l/s at 6.9 MPa to 45.7 l/s at 5.7 MPa over a 13 day period. A further 7 microearthquake events were recorded. Several days later, injectivity was evaluated by conducting a step-rate test at rates of 13.1, 16.7 and 20.2 l/s. Wellhead pressure at the highest rate was 3.1, significantly less than required for jacking. The reservoir injectivity was 5.7 l/s/MPa.
- High-rate hydraulic fracturing (January 2013): After more than a year, the interval was subjected to a further hydrofracturing treatment that featured flow rates up to 101 l/s. By the end of this stimulation, wellhead pressure was only 4.8 MPa, and the injectivity was 19.2 l/s/MPa (Chabora and Zemach, 2013). The well exceeded the initial target injectivity of 9.1 l/s/MPa, and was commissioned as an injection well for the field.

3.2.2 Performance assessment of previous petrothermal projects and lessons learned

3.2.2.1 Summary of circulation parameters

Most petrothermal systems built and circulated to date were subjected to circulations lasting several months to a year or two. This is sufficient to evaluate the thermo-hydraulic performance of the built system, but not to evaluate the long-term chemical changes arising from fluid-rock interactions.

Table 8: *Hydraulic parameters of the longest circulations performed on each of the petrothermal systems described in Section 3.2.1.*

Reservoir (depth) year	wells[13]	well separ-ation [m]	Circ. dur-ation [days]	Q_{prod} [l/s]	Reservoir Imped-ance [MPa/l/s]	Therm. break-through	Swept 'pore' volume 1000 m^3	Loss [%}
Targets				40	0.2			10%
Fenton Hill 2-well (2.8 km): 1980	GT2a to EE1	200	282	5.5	1.7	Slight	0.4-1.3	10
Fenton Hill 2-well (4.2 km): 1992	EE3a to EE2a	200±50	183	5.7	4.0	No	2.25	16
Rosemanowes 3-well (2.2 km): 1988-89	RH12 to 11/15	120/ 150−250	200	3/16	3.3/0.6	Yes	13−19	21
Hijiori, Japan 4-well (1.8 km): 1991	SKG2 to HDR1/2/3/4	40/50/55	90	12.8	0.4−0.7	No		23
Hijiori, Japan 3-well (2.2 km): 2000	HDR1 to HDR2a/3	90/130	300	5.8	1.4/2.1	Yes		64
Soultz, 2-well (3.5 km): 1997	GPK1 to 2	450 m	135	25	0.2	No	16	0
Soultz, 3-well (5 km): 2005	GPK3to2 GPK3to4	600 600	150	12 3	0.6 1.9	No	10.4/0.1	0
Soultz, 2-well (5 km): 2008	GPK3to2		60	25	~0.55[14]	No		0
Fjällbacka, 2-well (~0.5 km): 1989	Fjb3 to Fjb1	100	40	1.0	4.9	No		45
Le Mayet, 2-well (0.8 km): 1987	INAG 1119 to 1118	100	66	5.2	1.7	No		38
Habanero, 2-well (4.2 km): 2009	Habanero 1 to 3	560	60	17[15]	0.7	No	18.5	0

[13] Injection well given first; production wells delimited by '/'

[14] with downhole pump

[15] converted from 15 kg/s using production fluid density of 890 kg/m^3

The primary interest here is in the hydraulic characteristics of the reservoir, and the thermal changes that took place (i.e. observations of thermal breakthrough). Key performance parameters for the longest circulations conducted on each of the built systems described in the preceding section are listed in **Table 8**.

For hydrothermal systems, such as Desert Peak, the objective of stimulation is to improve the linkage of a well to the natural reservoir fracture/fault systems that contain significant quantities of fluid and have high hydraulic capacities (i.e. significant volumes of fluid can be added or removed from the structures without significantly affecting the fluid pressure). Injection and production wells drilled into hydrothermal systems usually have separation of at least a kilometre, and do not hydraulically 'feel' each other, except in the long term (weeks and longer). The injectivity/productivity indices of such wells are the key parameters that describe the performance of the system. In contrast, 'classical' petrothermal systems have relatively little fluid in place, and so it is essential that the injection and production wells 'feel' each other in the sense that the flow and pressure fields between wells interact (i.e. essentially no production without injection). In this situation, the production flow rate depends primarily upon the injection rate and the collective resistance to flow offered by the various flow paths within the rock mass between the wells. The latter is characterised by the reservoir impedance, which is the pressure difference between the wells required to drive unit flow. Lower values of reservoir impedance mean smaller pressures are required to achieve the required flow rate, and thus indicate better system performance. For this reason, cross-well reservoir impedance is the single most important parameter describing the hydraulic characteristics of petrothermal systems. The long-standing target value for reservoir impedance is 0.2 MPa/l/s. Evidently, only the 3.0−3.5 km deep system built at Soultz meets this objective. The lower production flow rates of the other systems are a consequence of higher-than-desired reservoir impedance between the wells.

Fluid loss is observed in all reservoirs that do not benefit from the presence of pre-existing, highly-permeable fracture zones and faults that contain a significant volume of formation fluid, such as at Soultz or in hydrothermal systems. In pure petrothermal systems, it is likely that some fluid loss to the far field must be accepted, although this could be reduced by well development patterns that have several production wells surrounding each injector. Fluid loss during operation can be problematic in locations where make-up water is not readily and cheaply available, and it can also engender a higher seismic risk (Ellsworth, 2013; McGarr, 1976).

The data given in **Table 8** show that thermal breakthrough was observed at several sites despite the relatively short duration of the circulations. This issue, and others arising from the collective experience (excluding seismic risk), are discussed in the following section.

3.2.2.2 Lessons learned

3.2.2.2.1 Permeability enhancement and system impedance

Hydraulic stimulation has been found to be effective in radically and permanently increasing the *injectivity or productivity* of wells in crystalline rock. This implies that substantial enhancement of the permeability of feed zones can be accomplished, in at least the near field of the wells. However, questions remain as to the degree of permeability enhancement that can be accomplished deeper into the reservoir.

It has so far proved difficult to create a 'classical' petrothermal reservoir with *sufficiently low impedance* to allow commercial flow rates, without the benefit of pre-existing, highly-permeable fracture zones and faults, such as at Soultz or in hydrothermal systems such as Desert Peak. A 'classical' petrothermal reservoir is here taken to represent a rock mass that does not have significant fluid in-place within large structures such as faults (e.g. Rosemanowes). The inadequate post-stimulation hydraulic linkage of the wells in 'classical' petrothermal reservoirs probably reflects:

- An insufficient number of stimulated flow paths between the wells
- Insufficient permeability enhancement in the 'far-field' region between the wells.

Permeability enhancement appears to occur primarily on existing fracture and fracture zones activated in jacking or shearing or both. Thus hydraulic linkage between the wells must be established predominantly by enhancing the permeability of the natural fracture system.

Experience to date suggests that it is difficult to drive classical mode-1 hydrofractures over distances of hundreds of metres in most fractured crystalline rock masses. The interaction between the propagating hydrofracture and the natural fracture system is believed to be an important factor in limiting this distance. In most high-rate hydraulic stimulation injections, downhole pressures attain what is believed to be the level of the minimum principal stress. This suggests that pressures are limited by the mode-1 fracture opening, either through jacking of existing discontinuities oriented sub-normally to the minimum principal stress or through the creation of new hydrofractures driven from the well. However, such inferences of mode-1 opening may be limited to the vicinity of the well where pressures are high. Further into the rock mass, where pressures are lower, shearing may become dominant since this can occur at fluid pressures less than required for mode-1 opening (Cornet and Jones, 1994). Support for this comes from the experience in conducting high-rate, high-pressure gel injections, occasionally with proppant, at Fenton Hill, Le Mayet and Rosemanowes (see Section 3.2.1). The treatments usually result in an increase in injectivity, in most cases through the enhancement of permeability of natural fractures intersecting the treated zone, but without affecting inter-well impedance. To address the issue of how far jacking or hydrofracture propagation can extend from the wellbore requires an improved understanding of the pressure distribution within reservoirs under stimulation conditions (Section 3.2.2.2.3).

Non-Darcy (i.e. turbulent-like) flow impedance was observed following stimulation at the Falkenberg site in Bavaria (Jung, 1987), in the Soultz 3.0–3.5 km reservoir (Kohl *et al.*, 1996), and at the Habanero site in the Cooper basin (Chen and Wyborn, 2009). The effect is due to the high fluid velocities, which in the Falkenberg and Habanero cases is believed to be localized around the inlets/outlets at the wellbore where fluid velocities are high.

In some situations such as Soultz, downhole pumps have been used to increase production from reservoirs. However, there is a limit to the maximum allowable drawdown in a well (not to mention higher parasitic losses that it engenders). Moreover, in Rosemanowes and the deep system in Fenton Hill, the best circulation characteristics were obtained by operating the production well with a back-pressure (as opposed to a drawdown from a pump). This situation arises if the feed-zones of the production well have pressure-dependent permeability. Increasing the pressure in these fractures results in greater aperture (i.e. the effective stress seeking to close the fracture is reduced) and hence lower resistance to flow (Kojima *et al.*, 1995).

Almost all petrothermal systems have featured long open hole sections in both injection and production wells. Stimulation injections performed into such sections invariably resulted in the activation of only a few fracture zones, one of which usually dominated. Commonly, the dominant inlet/outlet to the reservoir is seen to lie near the top of the open hole section, reflecting stress control of the stimulation. In most reservoirs, the vertical gradients of the principal stress magnitudes usually favour upward growth of stimulation, whether it be through shearing or hydrofracture or both (a notable exception is the Rosemanowes reservoir where the stress gradients favour downward growth (Pine and Batchelor, 1984). In the case where upward growth of stimulation is favoured, the rock mass surrounding the lower and perhaps intermediate sections of the open hole (i.e. the majority of the open hole length) will tend to be only weakly stimulated.

3.2.2.2.2 Rock surface area swept by flow between wells

Thermal breakthrough was observed at relatively early times (weeks to months) during circulation of several systems that had well spacing of 90−150 m (i.e. Hijiori, Rosemanowes, Fenton Hill Phase 1 reservoirs in **Table 8**). This implies that at least one significant flow path linking the wells swept a relatively small surface area. This result suggests that the distances between injection and production wells substantially greater than several hundred metres are required to avoid premature thermal breakthrough. It is also desirable to develop remedial measures to close-off feed zones in production wells that suffer from thermal breakthrough.

Estimates of the *net volume of flow paths* linking the injection and production wells at the sites examined are listed in **Table 8** when available. These estimates stem from the residence-time distribution of non-reactive tracer tests (Shook, 2005). The parameter of greatest interest from the viewpoint of reservoir longevity is the rock surface area swept by the flow. A target value of 2 x 10^6 m^2 is most often cited for commercial petrothermal systems, although this is likely to be a lower bound. The estimation of swept area from swept volume is difficult, owing to uncertainties in flow path aperture. Reactive tracers combined with non-reactive tracers can give a direct estimate of swept area.

Channelling of the flow field is almost certainly occurring, but it is difficult to quantify. Early thermal breakthrough is a manifestation of channelling, and demonstrates its effect on heat-transfer.

3.2.2.2.3 Uncertainty in fluid pressure distribution within the reservoir during stimulation

The pressure distribution within the reservoir under stimulation conditions is an important factor governing the types of stimulation mechanism that can be activated and hence the degree of stimulation accomplished. For example, the distance out from the well to which hydrofracturing or jacking can occur is set by the penetration distance of pressures that reach the minimum stress level (Cornet and Jones, 1994). Beyond that distance, shearing-activated mechanisms dominate (i.e. shear-induced dilation (Esaki *et al.*, 1999), wing-cracks (Jung, 2013) and fracture step-over related pull-apart features (Evans *et al.*, 2005b)). The magnitude of slip that occurs, and the resulting permeability increase, is likely to be dependent to some degree on the pressure increase. Unfortunately, the pressure distribution in a fractured crystalline reservoir undergoing stimulation is not well known.

Mapping of microseismicity during hydraulic stimulation often shows *shear failure* occurring at distances of up to a kilometre from the injection interval. However, this does *not necessarily* imply that *large increases in formation pressure* penetrate to such distances, since deep crystalline reservoirs are usually close to shear failure under ambient conditions (i.e. critically-stressed).

An example of the diversity in estimates of reservoir pressure distribution under stimulation obtained using different approaches to analysing seismic data is given by the Basel reservoir. (Goertz-Allmann *et al.*, 2011) fitted the spatio-temporal form of the seismic migration front during the stimulation using a linear diffusion model and inferred that pore pressure increases at distances beyond 40 m from the well remained less than 0.5 MPa. In contrast, (Terakawa *et al.*, 2012) analysed the orientation of fault plane solutions in the prevailing uniform stress field and found pressures of ~10 MPa extending out to 700 m from the well were required to explain failure.

3.2.2.2.4 Identification of hydraulically-significant structures within the reservoir

Precise mapping of microseismic events has proven to be a valuable tool for imaging activated structures within reservoirs undergoing stimulation (Evans *et al.*, 2005b; Moriya *et al.*, 2003; Niitsuma *et al.*, 1999). Microseismically active structures can be assumed to be permeable, since the occurrence of microseismicity suggests a direct pressure diffusion link to the injection wellbore. The degree to which structures can be imaged depends upon the seismic network used to record the waveforms of events. Analysis of waveforms from the vast majority of events induced by stimulation of petrothermal reservoirs in crystalline rock indicates predominant shear failure. The imaging of distinct microseismic structures, combined with the determination of the sense of slip on the structures from fault plane solutions (Deichmann and Ernst, 2009) can provide valuable insights into geomechanical aspects of reservoir creation, as can estimates of stress drop (Goertz-Allmann *et al.*, 2011).

Evidence suggests a significant component of aseismic slip occurred during stimulation of the 3.0−3.5 km deep reservoir in granite at Soultz (see (Evans, 1998) and references therein) and the reservoir in metamorphic tuff at Brady Field, Nevada (Davatzes *et al.*, 2013). The occurrence of aseismic slip is in accord with expectations based upon constituent laws of friction at the stress levels appropriate for the reservoirs in question (Marone and Scholz, 1988, Gargash, 2012). In cases where aseismic slip occurs, then the net slip occurring on a structure in the reservoir will be greater than estimated from the seismic moment of events defining the structure (Cornet *et al.*, 1997).

3.2.2.3 Zonal isolation technology

As noted in Section 3.2.2.2.1, it has been common practice to complete petrothermal wells with long, vertical open-hole sections in the reservoir. Stimulation injections performed into such sections invariably resulted in the activation of only a few fracture zones. Usually, the uppermost zone becomes the more dominant, because the natural stress gradients in most reservoirs favour upward growth of stimulation for both shear and hydrofracturing/jacking. As a consequence, a large volume of rock around the open hole will not be stimulated. A solution is to complete the well within the reservoir in such a way that zones of interest are hydraulically isolated from each other, but each can be selectively accessed from the well. Such *'Zonal Isolation'* technology would allow *the sequential, focussed stimulation* of *multiple zones* along the well, including zones that require a higher treatment pressure and thus would not be stimulated if the completion were open-hole. In this way, the volume of rock that is stimulated could be increased. Technology that accomplishes this is now routinely used in shale gas wells and is one of the factors that proved decisive in allowing the exploitation of *gas-shales*.

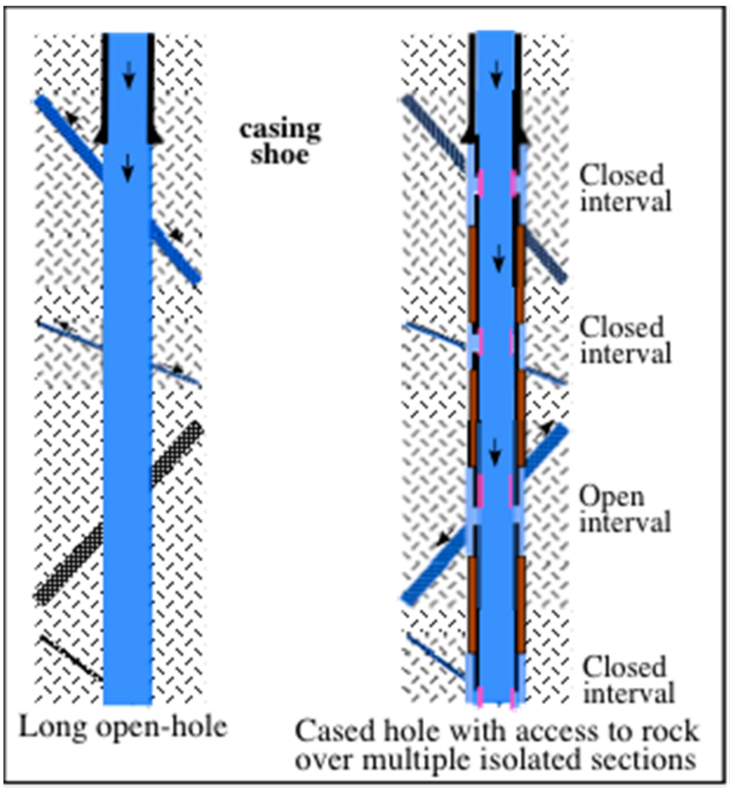

Figure 45: *Illustration of a well completed open-hole (left) and with idealized zonal isolation technology (right).*

The incorporation of *controllable valves* at each section of the well is also desirable since it would allow the flow between the well and the reservoir to be *managed*, alleviating to some degree the problem of short-circuits.

Some adaption of the mature gas-shale technology is required for use in petrothermal wells. The principal difference that distinguishes deployment in the two situations is that the reservoir in gas shales is generally massive, whereas in petrothermal systems the access points to the reservoir are localized where fracture zones cut the well. A summary of the issues and potential solutions for realizing zonal isolation in deep geothermal wells is given by (Walter *et al.*, 2012).

3.2.2.4 Sub-horizontal wells

Deviation of the well trajectory from vertical to sub-horizontal in the reservoir could also have a large impact on the engineering of petrothermal systems. By appropriate choice of the direction of the well in the target reservoir, the well could be drilled in the optimum direction with respect to the direction of stress and the sub-vertical fracture families to maximize the stimulation effectiveness. It could also be designed to have a long section in the reservoir. The vast majority of gas-shale wells are now drilled sub-horizontal and completed with zonal isolation technology. There are some concerns that sub-horizontal drilling of granite with its higher abrasion will be more difficult than for sedimentary rocks, but sub-horizontal wells have already been drilled in granite reservoirs in offshore oil fields in Vietnam (Lu *et al.*, 2013).

3.2.2.5 Knowledge gaps/key research needs

A basic high-level research objective is the development of numerical models that yield useful production of the long-term thermal performance of the built system. Such models must incorporate essential features of the flow-field that have a bearing on long-term production temperatures and impedance trends arising from fluid-rock interactions. Realistic representation of the permeability structures within the rock mass that result from the stimulation is thus essential. Thus, ideally, the permeability framework of the long-term performance model should be defined by the outcome of a 'stimulation model' that simulates the reservoir creation process. The development of realistic stimulation models conditioned by measurable reservoir parameters is important because they might, in principle, allow the well trajectories and stimulation operation to be designed so as to give a viable permeability enhancement without generating unacceptable seismicity (see Work Package 5.1 on seismic risk). Significant progress in developing such models has been made in the past decade e.g. (Kohl and Mégel, 2007), but further advancement is hindered by basic uncertainties in the mechanisms underpinning the permeability creation/enhancement process. To progress further, a program of basic research is needed that includes the following elements:

- Improvement in our understanding of the mechanisms of permeability creation/enhancement process (e.g. shear-induced dilation of rough surfaces, and the opening of channels due to pull-apart structures such as jogs in fractures and wing cracks). *Experiments conducted at scales of 50–100 m within an underground laboratory in fractured crystalline rock with diverse and dense monitoring systems could prove decisive in this regard. Such experiments could bridge the gap between those conducted at conventional laboratory scale and the full-scale reservoir scale of the foreseen pilot and demonstration projects.*
- Establish the relevance to the stimulation of crystalline rock of classical hydro-fracturing and the methods of permeability enhancement routinely employed in the oil and gas industry. This issue is also of interest to the mining industry that uses hydraulic injections to attempt to relax high differential stress and fragment rock. *A research program to address this issue is currently on-going within the mining industry, with involvement of ETH-Zürich personnel.*

- Improvement in our knowledge of channelling at both the fracture and fracture-network scale, and its effect on impedance, fluid transport and heat transfer. *Again, controlled experiments at various scales in conventional and underground laboratory settings are needed, not least to improve the interpretation of tracer tests that will be conducted in the full-scale P&D projects.*
- Detailed *studies of microseismicity including data from near-field instruments, from injection experiments conducted under controlled conditions in underground laboratories.*
- Improvement in our understanding of the *pressure distribution* within reservoirs during hydraulic stimulation. Since the pressure field within a fractured crystalline rock mass undergoing stimulation is likely to be highly heterogeneous as a result of strong localization of the flow field, it is difficult to measure the pressures directly in a full-scale reservoir. *The issue is best addressed through experiments in an underground laboratory which would allow the near-field monitoring of the hydraulic and deformational fields as well as microseismicity. These data would ultimately be used to constrain a realistic numerical model of the reservoir.*
- Assess whether *aseismic slip* (or aseismic tensile fracture opening) contributes significantly to permeability enhancement. This lends importance to monitoring deformation resulting from reservoir processes.

3.2.3 References

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3.3 Drilling and completion

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3.3.1 Conventional drilling and completion methods for geothermal applications

Among all sustainable energy sources geothermal energy has the important advantage that its energy production is independent of climatic conditions and thus baseload electricity can be provided. However, there are still a lot of challenges attributed to EGS (Tester, 2007; Rybach, 2010; Edwards *et al.*, 1982; Augustine, 2009; Carson and Lin, 1981; Carson and Lin, 1982). One of the major issues is that drilling costs for EGS power plants account from 30% to more than 70% of the total capital investment, depending on the accessed reservoir (Tester *et al.*, 1994). In EGS projects, wells can reach depths below 5000 m, where drilling must be completed in hard polycrystalline, abrasive, granitic rocks and therefore the drilling costs increase sharply with depth (Tester, 2007; Augustine, 2009; Augustine *et al.*, 2006). One of the reasons for these high drilling expenses is the mechanical wear of the drill bit, leading to long and expensive down times in the drilling process necessary for bit replacement. In conclusion, drilling and well completion are the primary cost drivers in EGS projects, and the related technologies are the subject of the following section of this document.

Geothermal drilling has adapted considerable knowledge from the oil and gas industry. Nevertheless there are some important differences as larger borehole diameters or higher temperatures distinguish the different drilling processes.

The overall objective of all drilling processes is to access a reservoir for exploitation: in the case of oil and gas drilling hydrocarbon reservoirs must be accessed downhole, in comparison to geothermal drilling where an aquifer or hot dry rock (HDR) must be developed. Onshore drilling is normally done with mobile and conventional land rigs (Finger and Blankenship, 2010; Ngugi, 2008) (see **Figure 46**). These rigs have been improved continuously by the oil and gas industry and so the major challenges of geothermal drilling must be tackled in the underground. The next sections give an overview of the drilling process itself and leave out detailed information about the drilling rig. Only the blowout preventer is explained in detail as many difficulties in both geothermal and oil/gas drilling are related to problems with this component.

Figure 46: *Conventional drilling rig at the geothermal project in St. Gallen*[16].

3.3.1.1 Conventional drilling

The technical term “conventional drilling” normally implies a drilling concept that is based on the mechanical abrasion of rock by rotation of a drill bit under weight (Finger and Blankenship; 2010,Ngugi, 2008). A major criterion for the drill bit selection in conventional rotary drilling is the type of formation to be drilled, as the bit performance varies significantly within different rock types. Two types of bits are most frequently used: the roller-cone bit (see **Figure 47** left) crushes and gauges the rock underneath with its teeth. This bit is applied for drilling deep wells in hard, fractured formations (i.e. EGS wells). The drag bit (see **Figure 47** right) cuts the rock by shear. Its advantage is that there are no moving parts compared to the roller-cone bit, where the three roller-cones need bearings and seals. Drag bits with hard polycrystalline-diamond-compact (PDC) cutters outperform other types of drilling bits in rather soft sedimentary rock formations (based on rate of penetration and wear). Nowadays, both systems are frequently applied in the oil and gas industry. Further information linked to the different drilling approaches and their bits can be found in the literature (Tester, 2007; Edwards *et al.*, 1982; Finger and Blankenship, 2010; Ngugi, 2008; Cromling, 1973; Glowka, 1997).

[16] www.geothermie.stadt.sg.ch

Figure 47: *left: Two examples for roller-cone bits (Finger and Blankenship, 2010); right: Two examples for drag bits (G. Mensa-Wilmot; et al., 2001).*

The necessary rotary motion of the bit, the weight on the bit and the supply of drilling fluid is provided by the drill string, which connects the drill bit with the rig on the surface (see **Figure 48**). The drill string consists of the following main components: bit sub, drill collars, drill pipes and kelly drive (Ngugi, 2008).

The bit sub is mounted directly above the drilling bit, connecting the bit with the first drill collar. In geothermal applications the bit sub usually contains a no return valve to prevent hot, high-pressure fluids from rising inside the drilling pipe to the surface. After the bit sub, drill collars are installed. These stiff steel components with a length of about 10m and a weight of 2 to 3.5 tons provide weight for the bit, minimize bit stability problems from vibrations and problems with directional control by providing stiffness to the bottom hole assembly (Ngugi, 2008). As the diameter of a drill collar is usually fairly close to the diameter of the wellbore, a spiral is integrated to prevent the drill string from getting stuck.

The remaining large distance between the bottom hole assembly and the drill rig is spanned by numerous drill pipes, which are large tubes connected by joints with a tape thread. These threads provide the sealant between the drill pipes to prevent drilling fluid losses.

The so-called “kelly drive” that is placed on the surface, consists of the kelly, drive bushing, master bushing and rotary table, completing the drill string assembly.

The kelly is a heavy tube string that is connected to the top joint of drill pipe and has a square or hexagonal cross section. Hexagonal Kellies are more expensive but also provide more strength to the drill string and are therefore often used in deep drilling processes. This device is fitted into the drive bushing which is connected with a master bushing to the rotary table. These two bushings transfer the required rotary movement from the rotary table to the kelly. During the drilling process the kelly moves down according to the rate of penetration. When the end of the kelly tube is reached, the drilling process stops, the kelly is disconnected and another drill pipe is installed before the process can start again.

In recent years conventional drilling with a kelly drive has sometimes been replaced by a so-called Top Drive System, which rotates the drill pipe from top of the drill string. The main advantage of this technology is that it enables drilling with a three-jointed drill string instead of one. This reduces the handling time and so enhances the drilling efficiency and the safety on the drill rig.

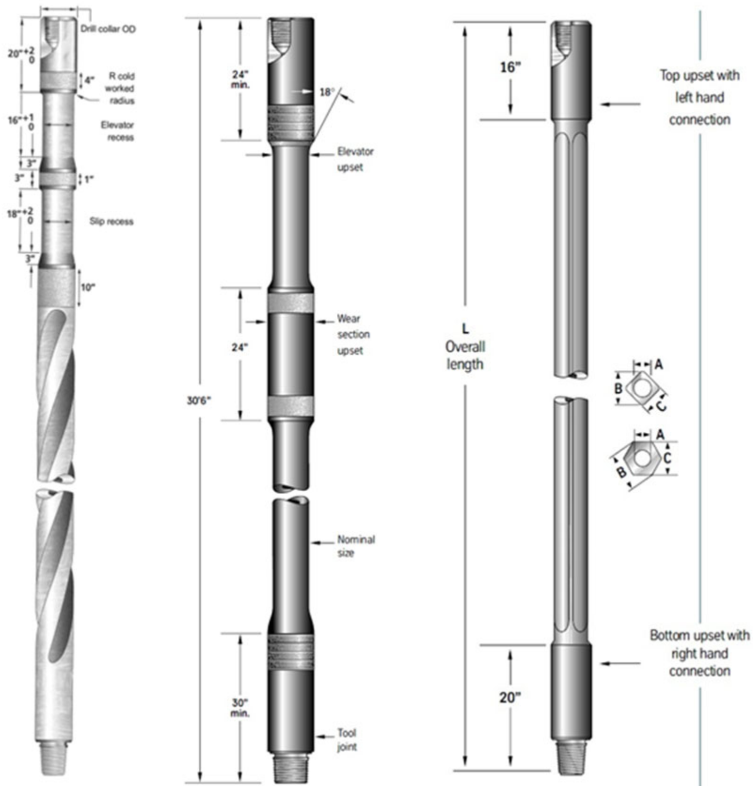


Figure 48: *left: Spiral drill collar middle: heavyweight drill pipe with wear section; right: square or hexagonal kelly*[17]*, assembly sequence from bit to surface: collar, drill pipe, kelly.*

During the design process of the drill string configuration some major considerations must be taken into account, e.g. the drill string must provide the necessary strength to prevent failure or fatigue of the downhole assembly during the drilling process. The applied load comes from the torque necessary to rotate the bit and the tension of its own weight during the lifting process (Ngugi, 2008). Another important matter is the size of the drill string as the internal diameter of the string must be large enough to avoid an excessive pressure drop in the drilling fluid and to allow the passing of logging tools (Finger and Blankenship, 2010). On the other hand the outer diameter determines the size of the annulus between borehole and drill string. The annulus must be small enough to guarantee the transport of cuttings to the surface and large enough to prevent blocking of the drill string.

As many formation fluids in geothermal drilling are corrosive and the formation is usually extremely abrasive, corrosion and wear are major challenges over the whole drilling process (Finger and Blankenship, 2010). Failure of the drill string can lead to a significant increase of the time and cost required for the project or in worst case to the decommissioning of the

[17] www.thyssendrillingtools.com

whole borehole. In order to prevent this, frequent string inspections, application of thread protectors and proper tool handling are important measures.

3.3.1.2 Drilling fluids

The use of a suitable drilling fluid is essential for a successful drilling operation. Drilling fluids are circulated through the well in order to remove the cuttings produced from the bit (well cleaning) and transport these rock particles continuously to the surface. Therefore, in general, every fluid (gas and/or liquid) can be used.

The fluid is normally pumped down inside the drill string and ejected through holes in the bit to flush away the cuttings produced. Afterwards, it is returned back to the surface in the annulus between drill string and wellbore wall. Subsequently, on the surface, the rock cuttings are filtered out and after the fluid cools down its properties are adjusted and the fluid is again injected into the well (Finger and Blankenship, 2010; Ngugi, 2008).

The properties (especially density and viscosity) of the fluid can be adjusted with different functional additives (liquids, solid powders or gases). The continuous adaption of the drilling fluid properties to meet the current needs of the drilling process is executed by the so-called "mud engineer" at the site.

In general, three different classes of drilling fluids are distinguished (Ngugi, 2008): water-based drilling fluids (different kinds of muds and emulsions), oil-based drilling muds (oil muds and inverted emulsions) and gaseous drilling fluids (air, aerated muds and foams). Fresh water mud as one of the water-based drilling fluids is frequently used for drilling deep wells in geothermal applications. It mainly consists of three compounds: water, active solids and inert solids. Active solids, also known as viscosifiers, are clays and polymers that control the required viscosity and thereby guarantee the transport of cuttings. Inert solid powders like barium sulfate (barite) and calcium carbonate (chalk) are used as weighting materials to adapt the density of the fluid without significantly affecting the viscosity (Finger and Blankenship, 2010; Ngugi, 2008; Annis, 1967; Hilscher and Clements, 1982).

Figure 49: *Example of a water-based drilling fluid*[18]*.*

[18] www.bakerhughes.com

Apart from the transport of cuttings, the drilling fluid has other important tasks to fulfill in deep (geothermal) drilling: cooling and lubricating of the drill bit prevents overheating and reduces wear. The hydrostatic pressure in the well is controlled with the density of the drilling fluid in order to prevent formation fluids from entering the borehole and to avoid the collapse of weak formation parts into the well.

In case of difficulties in the drilling process, the whole drilling operation including fluid flow will stop. The drilling mud then turns from a free-flowing, low-viscosity fluid to a kind of gel that “freezes” the flow and holds all the rock cuttings in place. This fluid behavior hinders suspended rock particles from deposition downhole and thus prevents plugging of the downhole assembly.

When a porous or fractured rock formation is being drilled, special additives (i.e. fibers or bentonite) are added to lower the permeability of the drilling fluid and thereby limit the invasion of the drilling fluid into the formation. The additives prevent the fluid from saturating the high permeability formation by forming a “filter cake”, avoiding significant drilling fluid losses to the formation and guaranteeing borehole stability.

Another problem that occurs during the drilling process is “lost circulation”, where large amounts of drilling fluid can be lost to the formation through large fractures and pores and must be replaced. Especially in the fractured environment of geothermal wells, lost circulation can be an issue and can account for up to 10% of the total well costs (Finger and Blankenship, 2010). Apart from the costs linked to this problem, lost circulation can lead to a pressure decrease in the borehole, leading to instabilities, blocking of the drilling assembly or in worst case a blowout (see 3.3.1.6).

Selecting appropriate drilling fluid properties for a given drilling project is a complex task and further information linked to this crucial issue which is only shortly discussed above can be found in the literature (Tester, 2007; Edwards *et al.*, 1982; Carson and Lin, 1982; Finger and Blankenship, 2010; Ngugi, 2008; Cromling, 1973; Annis, 1967; Hilscher and Clements, 1982; Aung, 1986; Bottai and Cigni, 1985; Dorman, 1991; Geehan *et al.*, 1991; Zilch *et al.*, 1991).

3.3.1.3 Casing and cementing

In the casing and cementing step, an artificial layer is created inside the borehole to protect the well during further drilling and during the entire production life from damages and risks, i.e. pollution of fresh underground water, fluid losses, well collapse and blowouts (Tester, 2007; Finger and Blankenship, 2010; Ngugi, 2008). The casing consists of several casing strings (metal pipes with a certain diameter, thickness and length, see **Figure 50**), which are fitted into a recently drilled section of the well and are afterwards connected to the borehole wall (rock formation) in a cementing process. The cement is used as mechanical support for the casing strings (connection to the rock formation) and additionally protects the outside of the casing from often corrosive in-situ formation fluids (Tester, 2007; Finger and Blankenship, 2010; Ngugi, 2008). The cementing process downhole is one of the critical operations during well drilling. The success of this step finally defines the lifetime of a well and the production rate. Both casing string and cement must withstand the mechanical (pressure, forces), thermal (linear thermal expansion and contraction) and chemical (brine, formation fluids, corrosive chemicals) impacts on the well (Edwards *et al.*, 1982; Carson and

Lin, 1981; Carson and Lin, 1982; Finger and Blankenship, 2010; Bottai and Cigni, 1985; Kalousek, 1979; Ostroot, 1964; Shryock and Smith, 1981; Sugama, 2006).

In the conventional casing process all casing sections start to be implemented at the surface. After interrupting the drilling process at the end of a drilling section, the drill string is removed and a casing is placed in the finished section and cemented to the formation. The length of a section and thereby the number of casing strings is determined by several factors, i.e. the stability of the formation or the drilling risk, which may deviate from subsurface and geological data. The hole diameter of the well is always larger than the outer casing diameter, because space for cement is needed to connect the casing string to the rock formation. After the casing and cementing process for a section is completed, the drilling is resumed with a smaller diameter to prevent damage of the completed casing structure. Thus the drilling diameter gets smaller with every section.

On the other hand, every drilling project is basically defined by the expected mass flow rate of the product (hot brine, steam, gas, oil, etc.) and the final well depth. This production rate directly defines a suitable diameter for the production casing of the well (Tester, 2007; Finger and Blankenship, 2010; Ngugi, 2008) and thereby the outer diameters of the different sections that must be drilled. A generic drawing of a possible wellbore design (without scale) is illustrated in **Figure 50**.

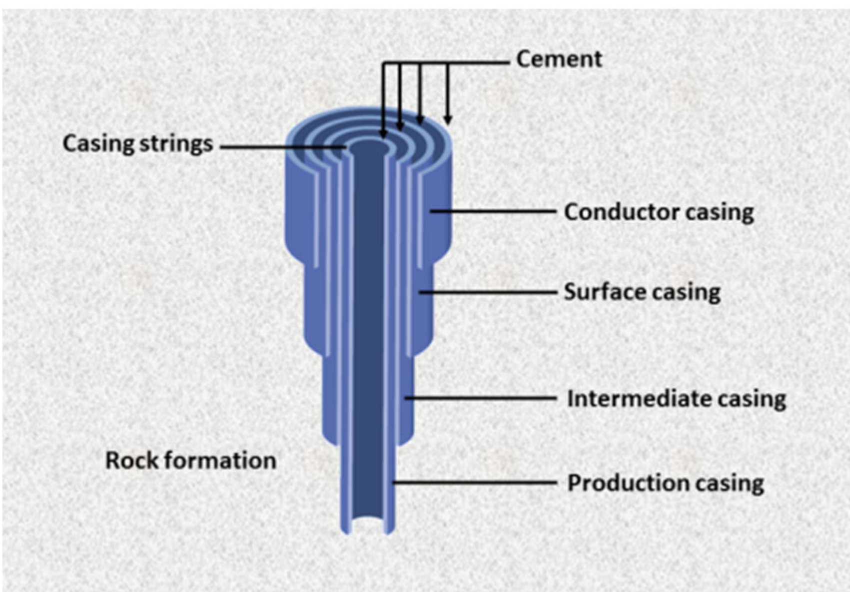


Figure 50: *Sketch of a possible wellbore design including the different drilling sections and casing strings (Ngugi, 2008).*

In oil and gas drilling, a rather low standard for casing and cementing is used compared to drilling for deep geothermal applications. Oil and gas casings are often only fixed at the bottom of the well. In case of geothermal wells, all casing strings are often completely cemented from the surface to the final production diameter (Tester, 2007). The casing procedure additionally depends on the present rock and the conditions of the formation. In soft sedimentary rocks casing is more important than in hard granite rocks, where casing is sometimes not even necessary. These high efforts in casing and cementing of geothermal wells also have a significant impact on the well costs. Due to the large casing diameters applied in geothermal applications, the casing and cementing step can account for more than 40% of total well costs (Finger and Blankenship, 2010). One possibility to cut these costs is the development of new techniques that reduce the amount of steel used. Lean casing designs such as expandable tubulars (see Section 3.3.2.1) are now reaching the stage of commercialization in the oil and gas industry. An example of a possible well design for a deep geothermal application with a final depth of 4267 m is given in **Table 9** (Finger and Blankenship, 2010). The well starts with a casing diameter of 91.4 cm and a hole diameter of 102 cm and after 5 casing intervals, the final casing diameter of 24.4 cm (hole diameter 31.1 cm) is reached in a depth of 3658 m.

Table 9: *Example of well design for a deep geothermal application (Finger and Blankenship, 2010).*

Casing diameter [cm]	Hole diameter [cm]	Setting depth [m]
91.4	102	15
71	81.3	244
50.8	61	1067
34	44.5	2286
24.4	31.1	3658
slotted liner	21.6	4267

3.3.1.4 Directional drilling and multi-branch wells

Directional drilling enhances the conventional drilling process by the feature that the drilling bit can change its direction from a direct vertical borehole to a more horizontal orientation. Directional drilling can thereby enable the exploitation of a resource if the territory above it is not accessible. It also allows the possibility to drill multiple wells from one drilling site and it enhances the ability to precisely reach the area of interest. Additionally, this technology provides the possibility to drill horizontal wellbores, which enlarge the exchange area between wellbore and production formation and thereby enhances the production rate of a geothermal well, especially in impermeable, relatively thin, naturally fractured or anisotropic formations (Samuel O. Osisanya, et.al., 1996). Furthermore, it allows the drilling engineers to adapt the drilling direction if unforeseeable problems with the formation occur (unstable zones, gas formations, large fractures etc.).

Directional drilling systems have made a significant impact on the drilling industry since their development in the 1970's, as they can drill faster, farther and more accurately than non-directional drilling systems (Schaaf; *et al.*, 2000). Nowadays, many onshore and nearly all offshore drilling sites in the oil and gas industry are using this technology. The directional drilling technology was also applied in the geothermal projects in St. Gallen and Soultz-sous-Forêts, France.

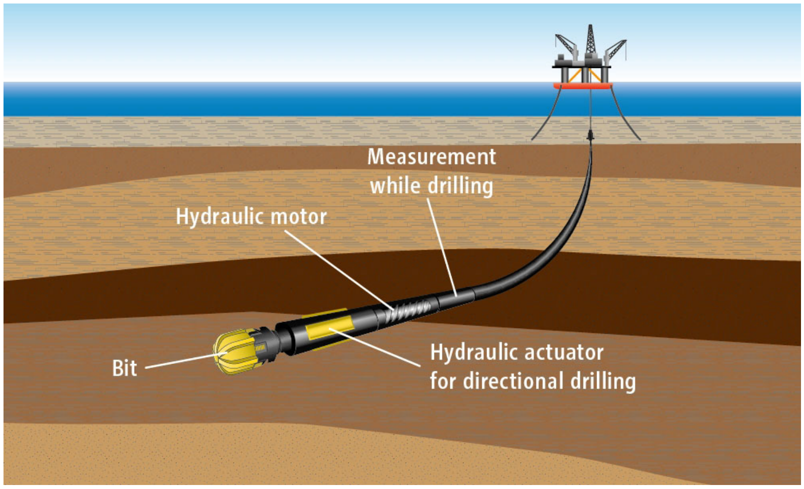


Figure 51: *Directional drilling technology enables bends and straights during the drilling process[19].*

Well trajectories are drilled by pointing the drill bit from the vertical axis to the desired direction. Two steering concepts exist: point-the-bit and push-the-bit (Schaaf; *et al*., 2000). Push-the-bit tools apply a lateral side force against the formation in the drilled-bore hole, by circularly positioned hydraulic fins or pads. The power for the movement of the actuators is provided by the pressure of the drilling mud. At the center of the actuation system a rotary valve open and closes the supply of mud to the single actuators in accordance to the drill string rotation (Downton, 2003).

Point-the-bit systems operate by creating a bend in the system (see **Figure 52**). A bent housing and a stabilizer allow the motor to drill in sliding or rotary mode. In the rotary mode, both, drill string and drill bit rotate and therewith negate the effect of the bend. In sliding mode, only the bit rotates and so the drilling course is changed in the direction of the bend, thereby the drill string slides down the hole behind the bit (Schaaf; *et al*., 2000).

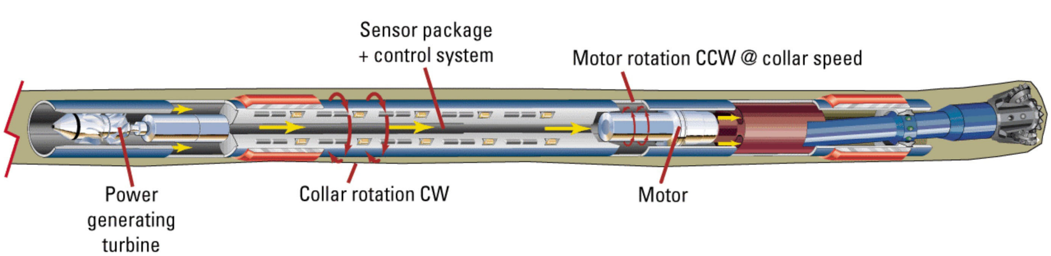


Figure 52: *Example for a point-the-bit system (Schaaf; et al., 2000).*

[19] Source: www.rwe.com

All steering concepts require additional instrumentation to implicitly or explicitly know the actual divergence from the vertical axis and in which geographic direction the drill bit is pointing.

Steerable drilling systems have shown in recent years the potential for reducing drilling costs, increasing the accuracy of the drilling process and enhancing the production rate of a geothermal well. Additionally, directional drilling enables the possibility of accessing different reservoirs from the same main drill hole (multilateral drilling).

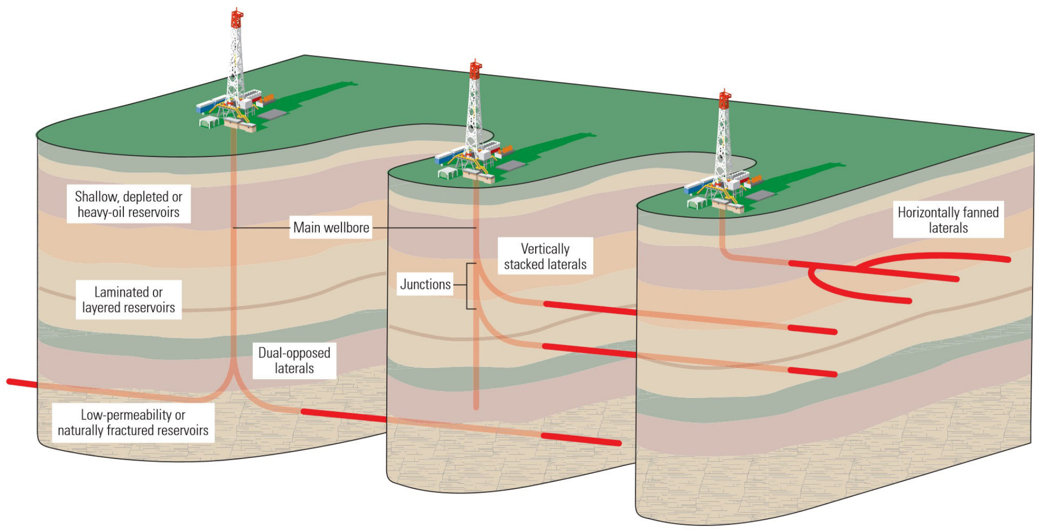


Figure 53: *Possible forms of multilateral wells in use today*[20].

Multi-branch drilling reduces the costs of the drilling process as the total accumulated length of the well is decreased. This saves time and investment costs in the drilling process itself and in the casing-cementing process.

3.3.1.5 Monitoring of drilling data

The goal of geothermal drilling is to access permeable zones with desirable physical characteristics. Detailed information on the different rock formations and the reservoir is mostly limited in advance. Therefore, all possible information during the drilling process is gathered to get an overview of the actual drilling process. Parameters that are recorded continuously versus time include for example: depth, weight on bit, rotation of the bit (rotary and motor if used), penetration rate, torque of the drill string, pressure of the pumps, pump rate of the circulation fluid, fluid temperature downstream and upstream and fluid composition downstream and upstream (Gudmundsson, 2005).

The monitoring of these parameters mostly focuses on the following three sectors (Patterson; *et al*, 1994):

[20] www.schlumberger.com

1. Physical properties of the penetrated rock formation:
   The drilling fluid composition is continuously and automatically plotted in a "mud log", which includes the analysis of formation gases (methane, carbon dioxide, hydrogen sulfide) and information about lithology and alteration of the penetrated rock formation.
2. Drilling penetration rate and bit performance:
   The penetration rate displays the progress of the drilling process. Additionally, weight on bit, rotational speed and torque are monitored to enhance the understanding of variations in the penetration rate.
3. Hydrostatic pressure and drilling fluid circulation:
   The hydrostatic pressure and the density of the drilling fluid are constantly observed to ensure borehole stability and to prevent a blowout. Moreover, the drilling fluid circulation is analyzed in order to detect drilling fluid losses and to guarantee a sufficient lubrication and cooling of the drilling bits and the drilling string.

Additionally, in seismically active areas several measuring stations around the drilling rig can be installed to monitor seismic activity and to record earthquakes triggered by the drilling process (see geothermal project in St. Gallen (Stadt St. Gallen, 2013)).

A broad knowledge and experience is necessary to interpret the accumulated data in the right way and to deliver an appropriate response. For example, considering the pressure of the drilling fluid pumps, a rapid pressure decrease can have several meanings: a transient circulation loss, a total circulation loss or damage in the drill string (Stadt St. Gallen, 2013). It is the task of the engineers to interpret this behavior in the right way. If an aquifer has been penetrated it is for example common to drill several hundred meters with total circulation.

As geothermal drilling processes are performed at great depth and in a high temperature environment, problems with overheating of instrumentation frequently occur. Heat shields have been successfully used since a number of years to protect the downhole instrumenttation (Tester, 2007). Nevertheless, even heat shields cannot prevent the increase of the temperature until the threshold for operation of the electronic components is breached (Tester, 2007). Therefore, further development of the instrumentation protection must be done, in order to reduce temperature-related problems with the instrumentation.

3.3.1.6 Blowout and blowout preventer

During the drilling process, zones of unexpected high pressure (e.g. aquifers, or gas/oil reservoirs) can be encountered, leading to a dangerous release of this pressure at the surface. Additionally, if this so-called "blowout" contains flammable substances, an uncontrollable fire can be triggered. In order to avoid this, a Blowout Preventer (BOP) is installed on top of the borehole, consisting of a number of fast-reacting valves that close if a rapid pressure increase is detected to keep the fluid inside the well. The resulting pressure in the borehole is then released gradually in a safe manner.

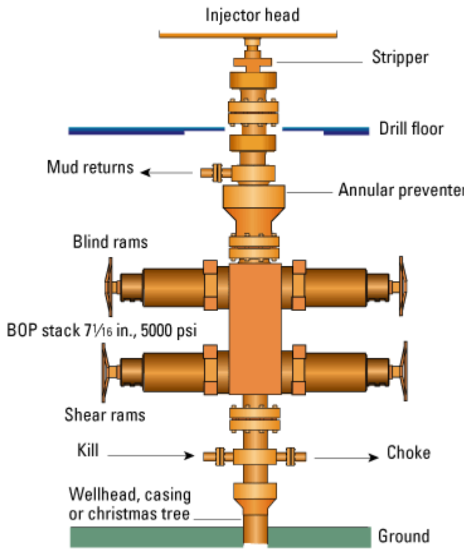


Figure 54: *Sketch of a blowout preventer, a combination of annular preventer and rams (Source: Knight Science Journalism at MIT).*

The BOP consists mainly of two different valve types (see **Figure 54**). First, if a blowout is detected, an annular preventer closes the gap between the housing and drill pipe. Should this measure not be sufficient, blind and shear rams cut through the drill string, guaranteeing a safe sealing of the drill hole. As significant damage to the drill string is created, an intervention of the BOP is the last possible resort to prevent a blowout.

An appropriate design and a continuous maintenance of the BOP are of significant importance to the safety of the drilling process. Recent drilling accidents have been related to broken or insufficiently designed BOPs. A blowout and a failed BOP led to the explosion of the "Deepwater Horizon" oil drilling rig in 2010, killing 11 workers and leading to the largest environmental disaster in US history.

Considering geothermal drilling activities, at the St. Gallen project after a scheduled cleaning activity at a depth of 4450 m, a rapid and massive pressure increase and a short discharge of a water-gas mixture out of the borehole was detected (Stadt St. Gallen, 2013). In order to prevent a blowout, and probably the destruction of the drilling facility, the borehole was filled with water and drilling fluid to establish a counter pressure. Due to this rapid pressure increase, seismic activities with a magnitude of 3.5 on the Richter scale were triggered, leading to the interruption of the project (Stadt St. Gallen, 2013).

3.3.1.7 Completion of drilling holes

This component of well construction is required to enable either production, injection or observation of the reservoir. Completion engineering aims to optimize inflow from the reservoir into the well, and outflow from the inflow regions to the wellhead and on to the production facilities. This task is divided into the upper and lower completion processes. Lower completion refers to work provided at the wellbore, which has the task to connect the final production casing with the downhole heat exchanger in the rock formation. It is important to decide if the production area of the well is stable enough so that it can be left as an open-hole completion or if special liners must be integrated in order to protect the wellbore against sloughing or caving (Finger and Blankenship, 2010) (see **Figure 55**).

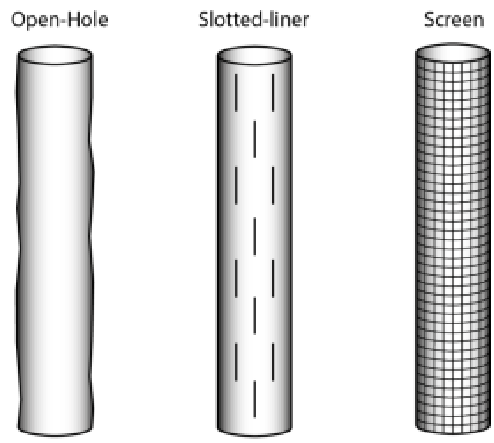


Figure 55: *Different completion possibilities for geothermal wells.*

An open-hole completion reduces the total costs and enhances the possibility for a later deepening of the well, which might be necessary if the expected production rate is not reached.

If the stability of the wellbore is insufficient, different liners (i.e. slotted-liner) must be integrated in order to prevent sloughing or caving. Screens are installed to prevent sand and fine material from entering and plugging the well. An integrated liner or screen does not only increase the time consumption and the costs of the completion process, but also reduces the well productivity due to its limited open area. Open areas of continuous slot screens typically range from approximately 16% to 50% and for slotted pipes 1% to 12% (Lienau and Lunis, 1991). Therefore, it might be necessary to increase the borehole diameter in order to achieve the planned productivity. It is a challenging task to determine early in the well design stage of an EGS whether a liner is necessary or not, as detailed geological data is not always available in advance.

Zonal isolation technology that allows selective access to sections of the reservoir is recognized as a potentially important development for EGSs as it allows the individual stimulation of multiple intervals (see Section 3.2.2.3). Zonal isolation is commonly accomplished in oil and gas shale completions by running a series of swellable packers on a tubing string into the open hole section.

The upper completion process refers to tasks from the production zone upwards, ensuring a reliable transport of the fluid to the power station, such as cleaning activities to remove cement residues and to wash the liner. Artificial lift of geothermal brine and steam to the surface are sometimes required to operate the geothermal power plant. Various technologies ranging from gas lift, to electro-submersible pumps, line-shaft pumps and turbine pumps are employed. In addition scale and corrosion inhibition is commonly employed downhole using capillary tubing that is run along production liners. Finally, completion techniques are also gaining increasing importance with the possible use of zonal isolation for stage-wise stimulation of geothermal wells.

Finally, a wellhead is installed (see **Figure 56**), providing an interface between the borehole and power production equipment. The wellhead consists of a number of valves for different purposes and an expansion spool, as there is usually some residual relative axial thermal expansion between the casings at the surface.

Figure 56: *One of the wellheads of the EGS-project in Soultz-sous-Forêts[21].*

3.3.1.8 Differences between oil-gas and geothermal drilling

Thousands of wells are drilled every year all over the world by the oil and gas industry to exploit hydrocarbons. Due to their huge experience in drilling processes, these companies are the driving force for further developments in drilling technologies. In comparison to oil and gas drilling, only a small number of deep geothermal wells have been drilled up to now, resulting in a lack of experience in drilling these challenging wells. Consequently, the current state of the art in geothermal drilling is an adaption and modification of conventional oil and gas drilling technologies towards new downhole conditions (hard abrasive rocks, large hole sizes, high temperatures). In the review of completed well costs done by MIT (Tester, 2007), it is generally stated that the costs for geothermal wells are considerably higher (2 to 5 times) compared to standard oil and gas wells of comparable depth. This fact has several reasons that are directly linked to the differences between geothermal and conventional oil and gas drilling.

First, hard fractured, crystalline rocks at great depth (i.e. granite) must be drilled for geothermal wells with state-of-the-art drill bits. The wear rates of these bits can be significantly high, depending on the local conditions in the formation, resulting in a low rate of penetration and a short bit lifetime (e.g. average bit life of less than 50 hours in the EGS-project in Soultz-sous-Forêts (Baumgaertner *et al.*, 2007). Thus, long and expensive down times are unavoidable in the drilling process (Tester, 2007).

Typical geothermal production sections have a final diameter in the range of 21.9 cm to 34 cm. This is in contrast to the oil and gas production, where final production diameters are

[21] Source : www.ipat.uni–erlangen.de

normally below 20 cm for the same depth (Tester, 2007; Finger and Blankenship, 2010; Ngugi, 2008). This significantly larger final downhole diameter of geothermal wells is required to achieve the high flow rates needed for a commercially successful electric power generation. This results in enlarged diameter casing strings (see **Figure 50**) with an increasing consumption of cement and steel. Furthermore, a more powerful and thus expensive rig is needed, including bigger pumps, compressors, blowout preventers, mud coolers and so on. In conclusion, the generally larger diameters of geothermal wells and the required high standards in casing and cementing are two reasons for the significantly higher costs of geothermal wells (compared to oil and gas wells) (Tester, 2007; Finger and Blankenship, 2010; Ngugi, 2008).

Additionally, in geothermal wells the downhole equipment (i.e. drill string, bit, centralizers and packers) and electronic instrumentation (i.e. logging tools) are exposed to high temperatures compared to rather shallow drilling operations. Therefore, all downhole equipment and all electronic devices must be adapted to withstand these harsh conditions, which results in additional costs for the drilling process (Tester, 2007).

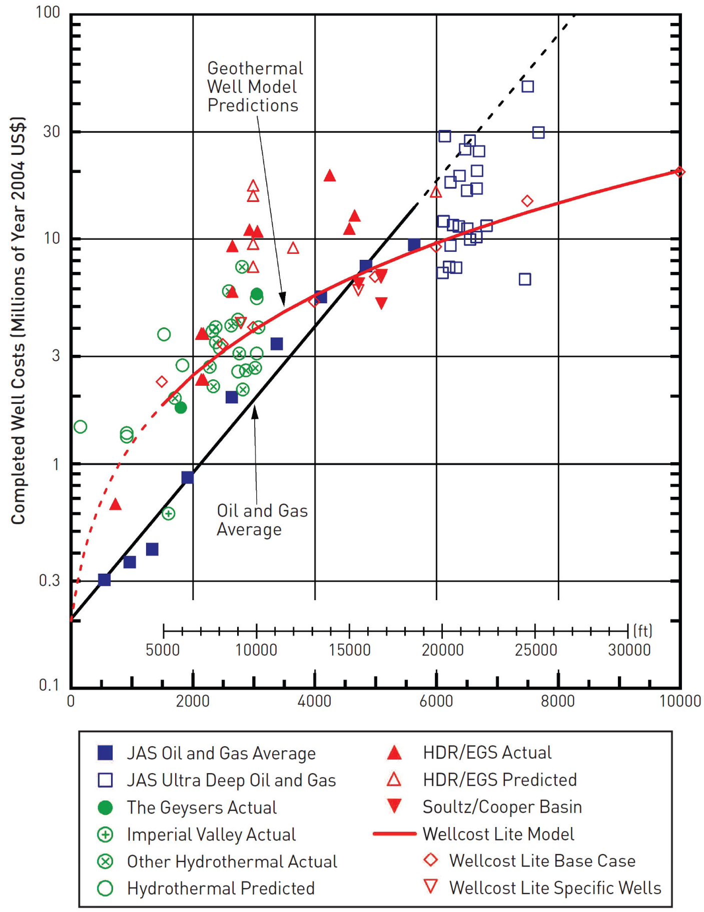
During the heat-up of the casing in geothermal applications (due to the hot production flow), thermal expansion can cause buckling of the casing and finally failure. In the injection line, on the other hand, the casing can be significantly cooled down by the injected cold fluid, leading to possible damages in the casing due to thermal contraction. Therefore, the selection of appropriate casing strings and cement types is of significant importance for the production rate and lifetime of a geothermal well. One possibility to prevent overheating situations is the integration of “mud coolers” in deep drilling projects, which cool down the drilling fluid before sending it back to the well (Tester, 2007).

Furthermore, new oil or gas wells are often exploited in developed production fields, where numerous other drilling processes have already been accomplished in the surrounding area, providing detailed information about lithology and alteration of the penetrated rock formation. In contrast, geothermal wells are mostly drilled in unknown fields as standalone facilities. This scales up the risk of a geothermal project and increases the costs, as the planning of the drilling process cannot rely on detailed data.

Typically geothermal wells have a significantly longer lifetime compared to wells for the production of oil or gas. Therefore the casing and cementing task must be done more extensively. More sections are necessary to guarantee the stability of the well over the long production period. The different casings are completely cemented compared to oil wells, where mostly only the bottom of a casing is cemented. These procedures further increase the total costs for the drilling process.

3.3.1.9 Completed well costs

The drilling process in EGS can count for up to 70% of the total investment (BMU − Institut für Energetik und Umwelt GmbH, 2007). Therefore a closer analysis and a reduction of the costs are important tasks to enhance the development of geothermal power. In **Figure 57** a comparison of the well costs between geothermal and oil-gas wells is presented (Tester, 2007). A drilling cost index, taking into consideration both well depth and the year of drilling, is applied to display the costs of the completed wells.



1. JAS = Joint Association Survey on Drilling Costs.
2. Well costs updated to US$ (yr. 2004) using index made from 3-year moving average for each depth interval listed in JAS (1976-2004) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depths greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2000).
4. "Other Hydrothermal Actual" data include some non-US wells (Source: Mansure 2004).

Figure 57: *Comparison of completed well costs for geothermal and oil-gas wells as a function of depth in the year 2004. Calculated costs for different drilling scenarios based on the "Wellcost Lite" model are also presented (Tester, 2007).*

The data on average costs for drilling oil and gas wells (black line) in the United States were taken from the joint association survey (JAS) on drilling costs (1976–2004). "HDR/EGS Actual" data are the actual costs of geothermal wells in hot dry rock in New Mexico (USA) and Cornwall (UK). "Soultz/Cooper Basin" are the actual costs of geothermal wells in hot dry rock in Soultz-sous-Forêts (France) and the Cooper Basin (Australia). "HDR/EGS Predicted" are predicted costs for drilling in hot dry rock based on various investigations according to the literature (Augustine *et al.*, 2006). "The Geysers Actual" are actual costs of geothermal wells drilled in the steam field reservoirs of The Geysers (California, USA). "Hydrothermal Predicted" are predicted costs of hydrothermal wells determined by the computer-based program IMGEO originally developed for the US DOE. "Other Hydrothermal Actual" are additional actual costs of hydrothermal wells with respect to literature.

For a statistical cost estimation of geothermal wells, the available data in the literature is insufficient (Tester, 2007; Augustine *et al.*, 2006). Hence, a sophisticated model to estimate well costs was developed by B. J. Livesay *et al*. (Tester, 2007; Bloomfield and Laney, 2005; Mansure *et al.*, 2005) in the form of an EXCEL spreadsheet. This model, called the "Wellcost Lite Model," calculates the well costs for every drilling section individually. For every drilling interval, a lot of detailed information is needed to run the model. Typical input parameters are for example the specifications of the casing intervals, the expected ROP, bit-life and so on. Based on all the given inputs, the model calculates, for example, down times of the rig, and drilling fluid and cement consumption. At the end, the total well costs are determined by summing up all the costs of the different drilling sections. In **Figure 57**, estimated well costs for geothermal wells based on the Wellcost Lite Model are presented by the red line. A lot of detailed input parameters are necessary to run the model, which can only be given with a certain experience in drilling at a certain location. Thus, to predict trustworthy individual well costs, many high quality input parameters are needed. Further information about the Wellcost Lite Model can be found in the literature (Tester, 2007; Bloomfield and Laney, 2005; Mansure *et al.*, 2005).

The Geothermal Electricity Technology Evaluation Model (GETEM) was developed for the US DOE to quantify the costs of power generation from individual geothermal sources (also in the form of an EXCEL spreadsheet). With this model, cost drivers in geothermal power production can be identified and estimates made of how technology advances in the future might influence electricity generation costs. Based on input data for a given geothermal project (economic parameters, exploration, confirmation, well field development, reservoir definition, operation and maintenance, power plant), the total cost of the project and the price per kWh are calculated. The model itself and additional information on it are available via the Internet[22].

All these models show that the costs grow exponentially with well depth. As EGS normally requires deep wells, the drilling process is the driving cost factor for total investment in these systems. Well costs for geothermal applications are normally significantly higher compared to oil or gas wells of similar depth (see Chapter 4.5 where principal cost drivers are identified and discussed such as well cost). Compared to oil wells, geothermal applications need a higher production flow rate. Therefore, larger borehole diameter and more powerful drilling equipment (drill rig, pumps, compressors etc.), more concrete and steel for the casings are necessary in EGS. Additionally, geothermal wells cannot rely on experience from other wells in the same field, compared to oil wells where often other drilling processes have been done before in the same field (Finger and Blankenship, 2010).

There are of course many other factors apart from drilling that influence the drilling costs: for example, the price for diesel fuel, inflation, currency rates or the availability of suitable drilling rigs (Tester, 2007).

Challenges for the incremental reduction of drilling costs are: to increase of bit and tool life, to speed up the ROP, to avoid drilling hazards (see geothermal projects in Basel and St. Gallen) and to optimize the well design (diameter, casing and directional drilling). More radical reductions in drilling costs are likely to require the development of new and improved drilling technologies.

[22] http://www1.eere.energy.gov/geothermal/getem.html

3.3.2 Optimization of conventional drilling technologies

The special characteristics of crystalline, high temperature rock formations impose certain challenges on existing drilling technologies for geothermal applications. As a result, innovative steps in several aspects of the drilling procedures must be taken. It may be even necessary to make fundamental changes in the drilling methods applied for future EGS projects, in order to make them economically viable and competitive.

As the drilling industry is using a mature technology, only small continuous steps in the improvement of the drilling process can be expected in the future. In the last years the development of drag bits and directional drilling were the most important advances. Additionally, as the use of new technologies is connected with higher risks and costs, it is difficult for improvements to be established on the market. Nevertheless, the drilling industry is focusing on enhancing the actual technology to reduce the costs and thereby enable the exploitation of economically less interesting reservoirs. Therefore, the companies are focusing on small developments in all drilling areas, especially logging processes to increase the efficiency and control possibilities during the drilling process, new drill bits with lower wear rates especially for hard rock drilling and new completion techniques for deep boreholes. In the next years it can be expected that these small improvements will continuously reduce drilling costs. Nevertheless, extensive changes are unlikely to happen.

As the drilling companies are investigating many different new technologies a complete overview over the developments is not possible. Therefore, in the following sections only present some examples of new developments that are improving the actual technology.

3.3.2.1 Monobore drilling and expandable tubulars

The percentage of the costs spent on the casing process of the borehole increases with depth, as the well design becomes more complex and much more effort must be invested in solving the casing problem with the decreasing diameters of the well along its depth. Especially in deep geothermal wells, the cost of the casing and its design may even account for 40%−50% of the total costs of the drilling process (Finger and Blankenship, 2010; Teodoriu, 2013). Monobore drilling is a term used to characterize a well drilled with the same diameter from the surface to its bottom. This technology could drastically reduce the geothermal drilling costs, while at the same time a larger bottom diameter could be achieved, thus allowing a better exploitation of the energy resource.

The most promising technique to realize an almost monobore well is to implement expandable tubing for the casing and adapt their design to the conditions prevailing in the well at each point (see **Figure 58**). The expandable tubulars are inserted through the existing casing and are expanded once they reach the correct depth. This technology makes it possible to run casing strings with negligible clearance between successive casings, thus reducing the changes of the inner diameter of the hole from one casing string to the next. Cement is injected in the same way as for conventional cementing applications and as the liner expands, it forces the cement upwards until the liner annulus is completely cemented.

The sealing between two consecutive casings is typically realized with elastomers, which is also the main drawback of expandable tubulars. The company Enventure brought this technology on the market in 2000 for oil drilling processes.

Nevertheless, it is necessary to improve the technologies and the materials used for the expandable casing tubing and their high temperature and corrosion compatibility, before a wide application in geothermal wells is possible.

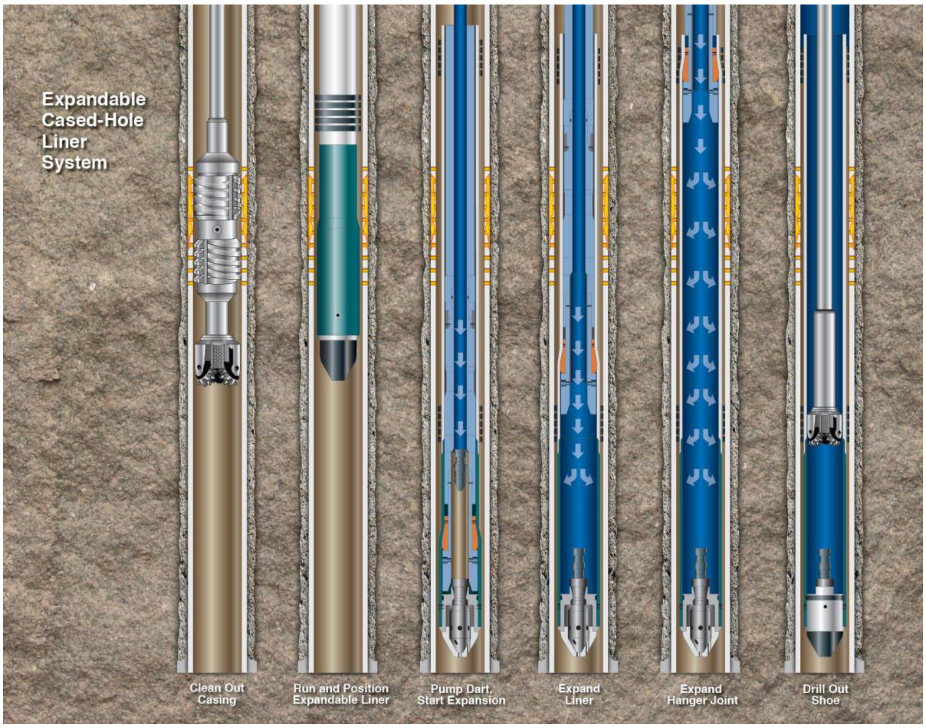


Figure 58: *Illustration of the expandable tubulars system marketed by Enventure Global Technology*[23].

A breakthrough of the monobore concept allows a better adaptation of the drilling diameter to the well flow performance and also reduces the costs for deep wells with diameters higher than those of typical oil wells. Therefore, this kind of improvement in geothermal drilling could be considered valuable in the mid-term.

3.3.2.2 Automation

Although automation technologies have reached a mature industrial level and are implemented in various aspects of everyday life, drilling rigs are only partially automated. The implementation of new control systems for the automated operation of drilling rigs would reduce the cost of resolving any accidents and problems and will make it possible to take preemptive actions, if the behavior of the drilling rig and the well does not act as expected. Automated operation of drilling rigs would also reduce the personnel costs and increase the reliability of the systems, by reducing the human interaction with the relevant procedures.

[23] Source : www.enventuregt.com

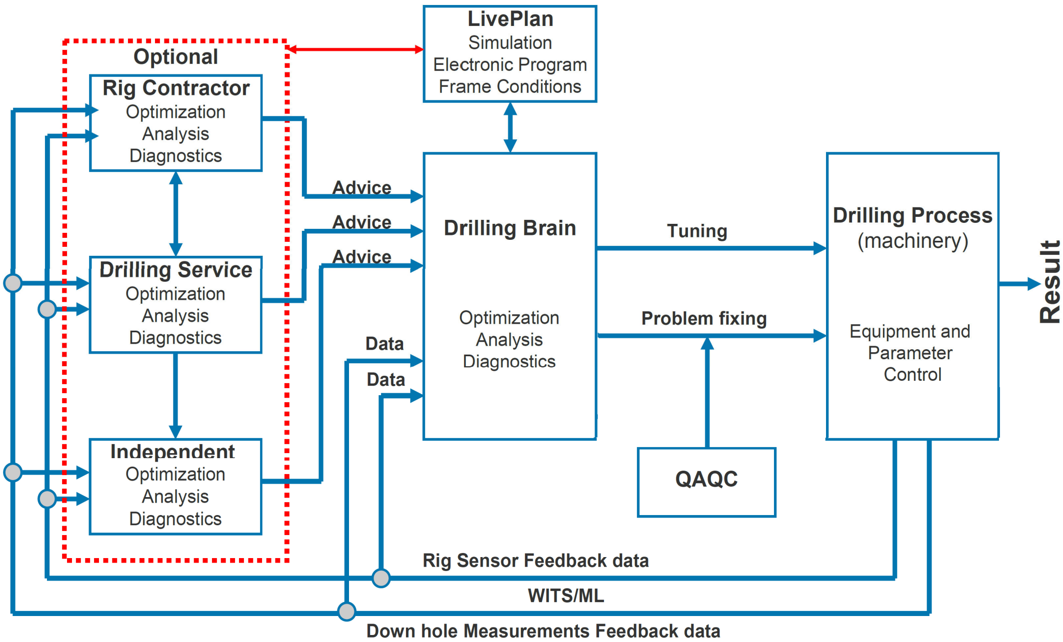


Figure 59: *Automation concept presented by Statoil (Strøm, 2009).*

However, several technical obstacles must be overcome to achieve total automation in drilling rigs. The automated drilling processes require downhole sensors that are more reliable and accurate. Additionally, telemetric-wired pipe, which is currently a very expensive piece of equipment, should become a standard part for drilling operations (Strøm, 2009). The operations connected to the drilling fluids, their composition and flow rate could also be automated if the data produced from the respective sensors are more reliable (Zamora, 2009). Fast identification of loss of circulation could especially reduce many environmental problems and cost parameters connected to these fluids and their loss in the underground.

Several projects launched by the bigger oil and gas companies are currently ongoing with the goal to develop fully automated systems. The geothermal drilling sector could possibly profit from these developments and even contribute to them.

3.3.3 Innovative drilling technologies

In conventional rotary drilling the casing of the wells accounts for approximately 20–40 % of the total well costs, while the rest are costs produced by the wear of the drilling bits and the necessary working time invested in their replacement (Finger and Blankenship, 2010). Therefore, most of the novel drilling technologies presented in this section try to tackle these aspects of drilling.

Apart from the continuous progress in conventional rotary drilling and casing/cementing/completion technologies, many revolutionary drilling approaches are under investigation all over the world. Rock can generally be excavated by mechanical breakage, thermal fragmentation, chemical reactions, melting or even evaporation. For all these excavation methods, many different innovative drilling approaches have been investigated and have finally reached different stages of development. Up to now, these novel concepts have never been applied and tested for deep drilling applications. Generally, a quite promising idea is to combine an innovative approach with the state-of-the-art in drilling to a single technology that incorporates the strengths of both methods. A few innovative drilling technologies that are still under development are shortly summarized below.

3.3.3.1 Laser assisted rotary drilling

This technology (see also **Table 10**) is already marketed by the American Company "Foro Energy" and it is based on the implementation of strong, concentrated laser beams supporting the mechanical drill bits (see **Figure 60**). A high energy laser beam is transferred via optical fibers inside the drilling string and focused on the bottom of the drill hole by specialized lenses. The heat flux transferred from the beam to the rock is adjusted to either spall the surface of the rock or reduce its hardness due to thermal stresses induced in it.

The procedure leads to a considerable reduction of the required pressure/torque compared to conventional rotary drill bits for the same rock and rate of penetration. Reductions of the WOB (weight on bit) by a factor of 20 and of the torque by a factor of 10 have been reported from the supplier of the system. The resulting lower strain on the drill bit extends its operational life and reduces personnel and material costs.

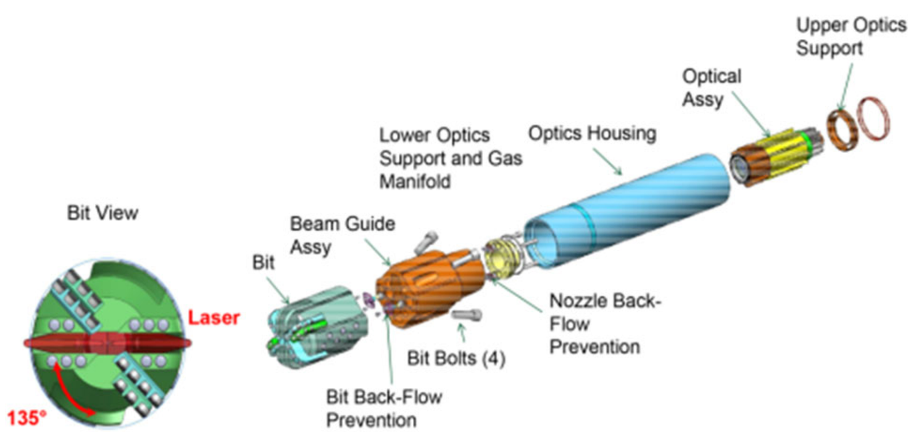


Figure 60: *Illustration of the Laser integration system in the drilling bit (Bommer, 2012).*

The main drawbacks of this technology are connected with the laser power transmission and drilling fluid absorbance. Power losses in the optical fibers currently limit the range to 1.5 km. Higher lengths are always connected with considerable power losses due to Rayleigh scattering (Bommer, 2012). The drilling procedure is also restricted to the use of transparent drilling fluids, like nitrogen. In any other case, a considerable percentage of the laser energy transmitted to the drill bit is absorbed by the drilling fluid and does not reach the rock surface.

The Foro Energy Company is currently improving the optical fiber power transmission system and has managed to transfer 20 kW power over a length of 1.5 km with power losses of less than 2 kW. They also focus on the development of drilling fluids with acceptable optical properties and higher densities, so that deeper boreholes could be drilled and supported. In conclusion, the concept of this technology has been proven and the company is currently closely working together with specialized drilling companies to commercialize the system.

3.3.3.2 Hydrothermal spallation drilling

Spallation drilling (Williams, 1986) is a promising technology that could prove to be economically advantageous over rotary technologies in hard rocks (see also **Table 10**). In this technology, the rock surface is impinged upon by a highly energetic flame or fluid jet, in order to induce thermal stresses in the upper rock layer and to finally cause rock disintegration in form of small disk-like fragments. The absence of contact between the bit and the rock results in reduced wear and a longer life expectancy of the drilling head. Furthermore, higher rates of penetration have been demonstrated with this technology, especially for some crystalline rock types (Browning *et al.*, 1965). These two main advantages, together with reduced down time, are expected to lead to a considerable reduction in drilling costs once this technology becomes commercially available.

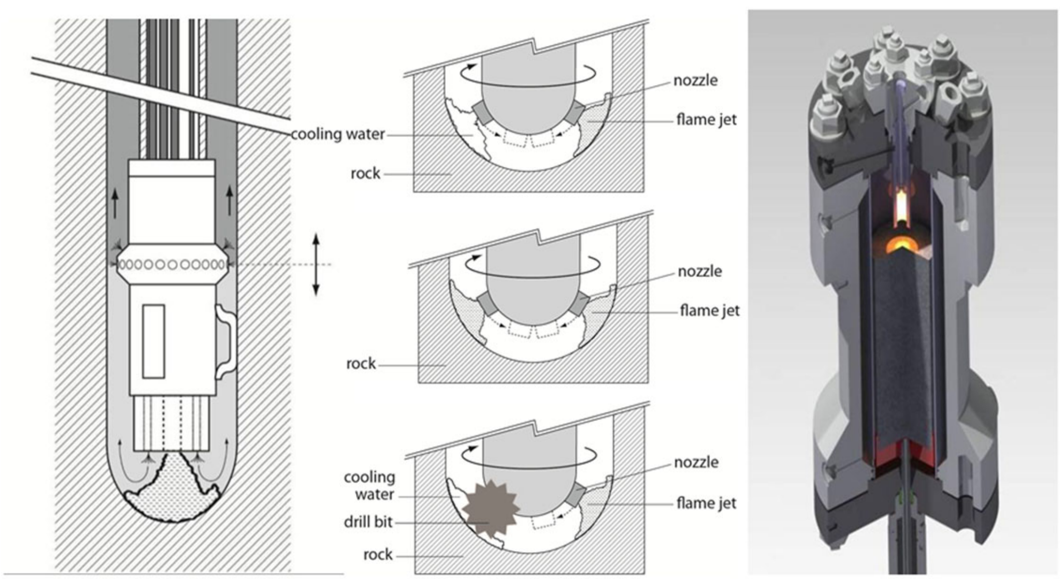


Figure 61: *Illustration of the possible implementation strategies for hydrothermal spallation drilling and the high pressure vessel used at ETH Zurich for the associated experimental investigations (Rudolf von Rohr et al., 2010).*

In water-filled boreholes of a certain depth, water exceeds its critical pressure (221 bar) and hydrothermal flames can provide the required heat to spall the rock.

A hydrothermal spallation drilling head consists of a combustion chamber and a nozzle, where the high temperature combustion products are formed into a hydrothermal jet. This flame-jet is directed to the rock surface to induce the spallation process. Various possibilities can be identified for the actual implementation of the technology, for example its integration with existing rotary drilling technologies, in a way similar to that of the laser unit presented in the previous section. Moreover, rotating flame and cooling water nozzles could be added to the bits, in order to produce an alternating cooling and heating effect, benefiting the overall ROP. Possible hydrothermal spallation drilling concepts including the experimental setup at ETH Zurich are illustrated in **Figure 61**.

A research group at ETH Zurich[24] works on the process fundamentals, mainly on the jet formation in an aqueous environment and the heat transfer optimization from the nozzle to the rock surface. Ethanol-oxygen flames with a thermal power up to 120 kW can be operated in the laboratory and the first small cavities have been drilled. Heat flux values up to 6 MW/m^2 have been measured from the impinging jet, showing that the technology could be viable also in high pressure aqueous environments. However, many aspects of the actual implementation of this technology remain open and the approach can be considered as a possible solution for the drilling problem only in the long term.

3.3.3.3 Electro pulse drilling

This technology (see **Table 10**), also known as spark drilling, uses multiple electrodes as a drilling bit (see **Figure 62**). The electrodes are submerged in a high resistivity fluid, such as diesel oil, that is also used as drilling fluid. Various circular arranged electrodes are in contact with the rock. The high voltage fed to the electrodes is conducted directly through the rock. Rock exposed to the voltage pulse breaks due to the imposed stresses and is removed by the drilling fluid. Depending on the rock type drilled and the pre-existing fault structure, various voltage pulses at different frequencies can be applied to adapt and optimize the drilling process.

Figure 62: *Picture of electro-pulse drilling bits (Bommer, 2012).*

The main advantages of this method are its relatively high energy efficiency compared to other drilling methods and the opportunity to case the borehole during drilling (because the borehole diameter is typically larger than that of the drilling bit). Furthermore, the weight on

[24] www.ltr.ethz.ch

bit necessary to achieve the required contact quality of the electrodes on the rock surface is significantly lower than for conventional drilling bits. This may lead to much smaller, lighter and safer drilling rigs. Generally, the rate of penetration with this technology is significantly higher compared to state-of-the-art drilling technologies in granite (see **Table 10**). Additionally, the wear of the drill bit occurs at an acceptable rate, allowing convenient drilling as deep as 6000 m.

However, several technical limitations must be overcome prior to commercialization of the technology. Since the bits require contact with the rock at the same places as the mechanical drill bit, it will be difficult to adapt existing systems, in order to combine them with the electro pulse technology. Additionally, the electricity supply system must be optimized to transfer DC voltage of several kilovolts for distances of up to 6 km with minimal losses.

A research group in Norway (Norwegian University of Science and Technology, Arlid, Rodland) and one at the ETH Zurich (High Power Electronic Systems, Juergen Biela) are currently trying to develop this drilling technique. According to Prof. Arild Rodland, a technology platform has been established between 1996 and 2011 and the first engineering stages for the field application are finished (Rodland, 2012). Consequently, this technology could be considered in the intermediate-term future.

3.3.3.4 Percussion drilling

In percussion drilling (Finger and Blankenship, 2010; Finger, 1984), a hammer system applies vertical impacts on the rock for fragmentation (see also **Table 10**). Rock formations typical in geothermal applications do not go through any plastic deformation during their breakage, due to their extreme hardness and crystalline structure and are therefore well-suited to this technology. The technology uses a reciprocating downhole piston assembly to apply impact stresses on the rock surface either through a conventional roller-cone bit or by a one-piece bit set. Normally, air-driven hammers are used in a low-density environment and quite promising ROP can be achieved in hard granitic rock not only in the laboratory but also in civil engineering applications. The experiments performed in a project of Sandia Laboratories (Finger, 1984) demonstrated ROP above 20 m/h in granite. The same experiments demonstrated the high temperature compatibility of these systems and have also shown that the failure mechanisms of the bits did not correlate directly with temperature. In conclusion, all of the tests with this technology have reached higher penetration rates than conventional drilling at comparable drilling conditions.

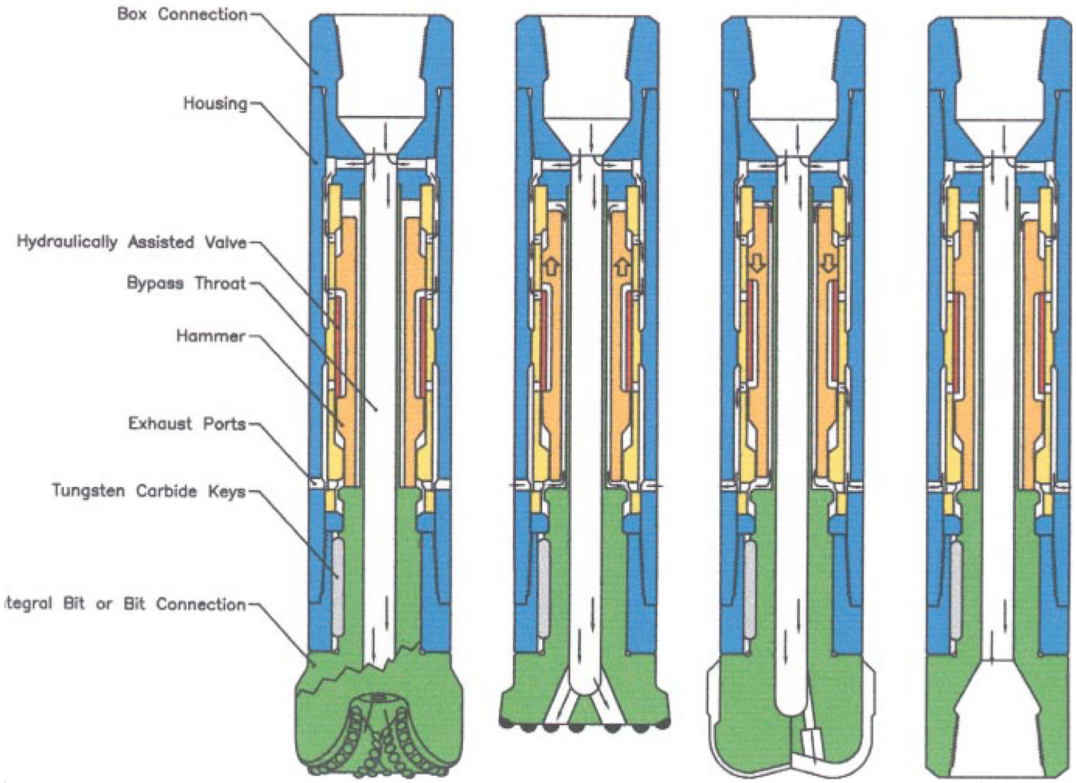


Figure 63: *Operation of the mud hammer drilling system presented in (Hall).*

On the other hand, air-based percussion systems are not applicable in dense drilling fluid environments. The piston system does not function properly and thus the transport of the cuttings cannot be guaranteed with the air hammer when deeper boreholes are drilled. The combination of this problem with the necessity for accurate WOB control and the difficulties encountered in fishing broken equipment hindered the commercialization of this technology. Nevertheless, research to develop hydraulic hammers suitable for dense environments is still ongoing but has not yet reached commercialization (Finger and Blankenship, 2010). With the growing interest in EGS geothermal systems, this alternative drilling technology should be re-evaluated in the intermediate-term.

3.3.3.5 Comparison of the different drilling approaches

Table 10 summarizes the different novel drilling approaches introduced and discussed above. All these technologies are not yet applicable at great depths and further intensive research and development must be done to bring them on the market and to make them competitive to conventional rotary drilling. Nevertheless, these technologies could have an impact on oil/gas and geothermal drilling in the future.

Table 10: *Summary of all the drilling technologies mentioned above (similar to Bommer, 2012).*

	Conventional rotary drilling	Percussion drilling (air driven)	Hydrothermal spallation drilling	Electro pulse drilling	Laser assisted rotary drilling
Development status	state of the art, benchmark	under development for deep wells	under development (laboratory)	under development, shallow tests	under development, shallow tests
Rock disintegration	mechanical abrasion of rock with a rotating bit under weight	mechanical abrasion of rock by a hammer system	heat shocks of a impinging flame jet	sparks due to high voltage pulses	thermal weakening before mechanical abrasion
Approx. ROP in hard rock	3–5 m/hr	20 m/hr	16 m/hr,	35 m/hr,	2–4 times ROP of benchmark
	Baumgaertner *et al.* (2007); Dey and Kranz (1985)	Finger and Blankenship (2010)	Browning (1969), Browning; et. al. (1965)	Bommer (2012)	Bommer (2012)
Main advantage	state of the art in drilling	higher penetration rates	contact-free, reduced wear, enhanced ROP	massive rock excavation capacity, unlimited diameter	enhanced ROP, less weight on bit, reduced wear, longer bit-life
Main disadvantage	high bit wear and low ROP in hard rock, thus short bit-life and long down times	high bit wear in hard rock, weight-on-bit control, only air or foam drilling fluids	significantly lowered drilling performance in sedimentary rock formations	hard to combine with state of the art in drilling, downhole power transmission	power losses in optical fibers, only transparent drilling fluid, complex optical components
Downhole conditions	all kinds of state of the art drilling fluids	air or low density drilling fluids	preferably water based drilling fluids	high resistivity drilling fluid	transparent drilling fluids

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3.4 Plant and well life

Warren Schenler (PSI)

3.4.1 Introduction

In addition to the exploration, reservoir creation and drilling technologies described above, there are also other technologies that can have significant cost implications for geothermal energy. In particular, it is of interest to extend well life (i.e. by the choice of materials and well maintenance) in order to reduce the number of well sets required during the life of the geothermal plant, and also to extend the life and/or increase the efficiency or capacity factor of the surface generation plant, in order to spread all costs over a larger amount of electricity generation. Overall the technology is mature and any improvement is incremental. Currently no game-changing technologies appear on the horizon. In terms of power conversion, a potentially interesting technology is the thermoelectric generator, but it is not yet envisaged for geothermal applications. This section of Chapter 3 discusses the problems and technological solutions related to these areas.

3.4.2 Well life related technologies

The primary problems limiting well life (as opposed to reservoir life) are corrosion and scaling due to materials interactions with the geothermal fluid. Corrosion is of course the loss or erosion of materials (pipes, pumps and heat exchangers) in the geothermal fluid loop caused by chemical reactions, while scaling is the deposition of solid materials on the inside surfaces of the fluid loop due to the precipitation of chemicals from the geothermal fluid. Both of these problems are well known from past experience with hydrothermal flash-steam and binary plants, and are the subject of ongoing research for EGS applications (Muller. J *et al.*, 2010; Francesca Baticci, 2010).

Scaling and corrosion both depend critically upon the composition, concentration and temperature of the geothermal fluid. Some of the key characteristics are the major dissolved elements (cations), their concentrations, the pH, the redox potential driving possible reactions, and the content of dissolved gases such as CO_2, O_2 and H_2S. Naturally, the higher temperatures so desirable for geothermal power production also promote higher concentrations of dissolved minerals. Even though normal surface water may be used for the fracturing and production fluid in an EGS plant where no normal groundwater is present, the residence time in the reservoir and continued reinjection means that the fluid composition will approach that found for groundwater in similar mineral deposits. Dissolution and precipitation can also play a role over the reservoir life by either expanding fluid flow cracks (possibly leading to channelization) or by blocking cracks.

Figure 64 below shows results from different surveys of geothermal fluids (Huenges, 2010) Graph a) on the left shows the dominant chemical species (sodium, calcium and chloride) present in sedimentary formations at different depths (note that the horizontal scale is logarithmic). Graph b) on the right shows the depth distribution of total dissolved solids for a survey of both sedimentary basins and crystalline rock formations. Note that at shallower depths the crystalline formations can have much lower concentrations, but the sample depth is limited to less than 3 km, whereas the sedimentary formations show considerable variation even at greater depths. Greater depths are partially correlated to higher concentrations of salinity due to higher temperatures. Of particular interest, the Malm limestone formation of the south German Molasse Basin is specifically mentioned as having one of the least saline brines, and this formation also continues on south into northern Switzerland.

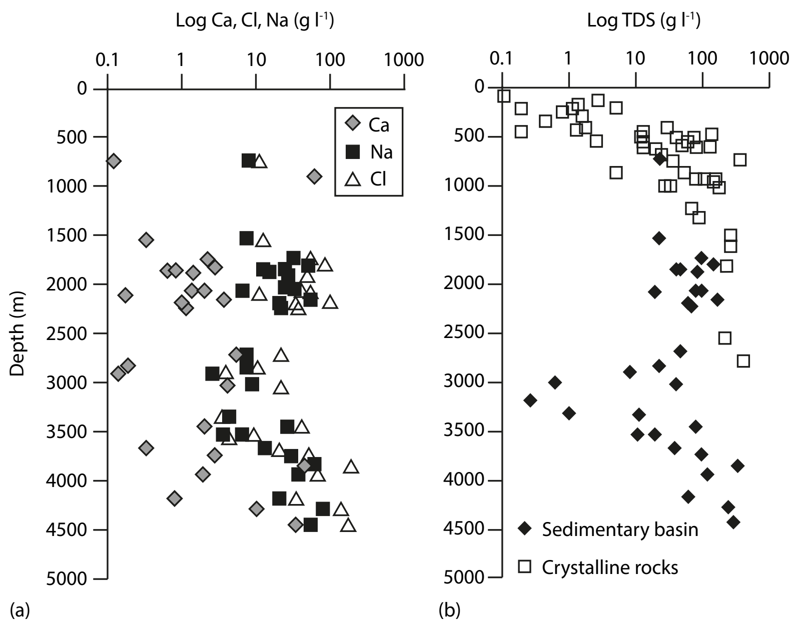

Figure 64: Chemical species and total dissolved solids (TDS) by depth (Huenges, 2010).

Corrosion may occur may occur uniformly across a surface, or be concentrated in the form of pitting or cracks related to galvanic, intergranular or stress-related corrosion. In particular, the dissolved gases play a larger role here − dissolved O_2 causes oxidation, dissolved CO_2 forms carbonic acid, and dissolved H_2S causes sulfide stress cracking. Corrosion is accelerated by higher temperatures, so it is of most concern in the production well, pumps and in the surface plant heat exchanger. Ongoing EGS-related corrosion research is reported in the literature and **Figure 65** below shows a corrosion test sample from Soultz showing results due to dissolved CO_2 and high temperatures.

***Figure 65:** Corrosion test sample from Soultz (carbon steel exposed for 10 days in non-alkaline brine with 0.02 m CO_2 at 200 ˚C (Muller et al., 2007).*

There are several main ways of combatting corrosion, including the following.

Choice of materials – The main issue here is the choice of suitable steel alloys that are not only corrosion resistant, but also meet requirements for strength and cost.

Coatings – Surface coatings to resist corrosion may be applied before installation of pipes and other equipment. Test results show that applied coatings (i.e. Saskaphen, and red or green Teflons are very effective. However such coatings must also be abrasion resistant to resist entrained solids in the fluid.

Geothermal fluid chemistry – Chemical additives may be added to the geothermal fluid to reduce corrosion directly, or it may be possible to alter the fluid chemistry either to promote surface coatings (stable corrosion layers that prevent further corrosion), adjust pH or to reduce dissolved gases (i.e. CO_2). In addition, dissolved O_2 may also be controlled by maintenance of seals to prevent air ingress. Tests at Soultz showed one proprietary additive (Mexel) to be ineffective. Additives are most needed in the production well, but may be diluted, adsorbed or lost in the reservoir before reaching the production well.

In general, it is a question of economics which of these methods are chosen either alone or in combination to reduce corrosion problems.

Scaling occurs when a decrease in temperature reduces the solubility of the chemicals dissolved in the fluid or brine, and these are precipitated or deposited on the inside of heat exchangers, pumps or pipes (particularly the well casing). As opposed to corrosion, the problem is most likely in the injection well. Scaling reduces fluid flow in pipes both by increased wall roughness (viscous drag) and by reduced flow area (requiring higher velocity to maintain flow rate). Scaling also reduces heat transfer efficiency in heat exchangers, but of course this does not pose the same difficulties in maintenance as in the reinjection well. **Figure 66** below shows two instances of pipe scaling at Soultz.

Figure 66: *Pipe scaling at Soultz EGS research facility (Muller et al., 2007).*

There are several approaches to the problem of mineral scaling in wells, including the following.

Mechanical – Mechanical methods to remove scale include abrasive fluids (i.e. muds), brushing, scraping, blasting and even ultrasound. Effectiveness depends in large part on the mechanical strength of the precipitated scale.

Chemical – Some scaling (i.e. carbonates) is easily removed with mild acids, but other scaling like silicate deposits may have much higher chemical resistance that requires strong acids like hydrofluoric acid. This process is expensive, uses toxic chemicals, requires additional well maintenance leading to plant downtime and lost generation, produces large amounts of waste that need proper neutralization and disposal, and also risks damage of the base material (the pipe).

Reinjection temperature – Another approach is to control the reinjection temperature, raising it above a temperature limit determined by the brine chemistry (type of minerals and concentration). This reduces the amount of available energy from the geothermal fluid.

There are obviously tradeoffs between these different possible approaches, depending upon local conditions. The tradeoffs are based on the cost to descale (economic cost and production downtime required by the different methods), the cost of running at reduced fluid production (lower flow and/or higher pumping losses), and the cost to run at a higher injection temperature (lower thermal efficiency and reduced heat sales). The economic model developed and presented in the following section presents a way to compare these different options and identify the least cost solution.

With all this discussion of possible corrosion and scaling problems, it is comforting to recall that many geothermal plants do operate successfully over long time. For example the hydrothermal well in Riehen, Switzerland has been operating since 1989 to provide district heating without geothermal generation[25].

With all this discussion of well life problems and solutions, it still appears that uncertainty in the reservoir life appears to dominate well life problems as the major concern for geothermal economics. The expected reservoir life in other reference geothermal cost models can range from 5 years (GETEM) to 30 years (prior DOE models). This is largely based on the uncertain and unproven characteristics of the geothermal heat exchanger, including the volume of rock, the evenness and effectiveness of the fracturing and the amount of heat exchange surface.

3.4.3 Plant technologies

There is significant experience with surface plant technologies for EGS plants from the use of the binary cycle in hydrothermal plants where brine chemistry does not allow a flash steam cycle. Surface plant costs and life are therefore relatively well characterized.

The initial economic analysis made it clear that total costs are dominated by well costs rather than surface investments. Increasing plant efficiency can thus be more important than simply lowering the plant capital cost, so that all costs can be spread across a larger amount of generation. This section is therefore not just about extending plant life but also about other choices that can be made to reduce plant costs or improve overall plant economics. A survey of plant technologies shows the following major possibilities:

Improved efficiency – There are actually a range of variations upon the flash and organic Rankine cycles (ORC), as well as the possibility of using the more complicated and expensive Kalina cycle. These have been modeled at EPFL (Gerber and Maréchal, 2012), to find the

[25] http://www.info–geothermie.ch/index.php?id=96

least cost design for a combination of different depths and district heating demands. This model has a rather different and complementary approach to the PSI model.

Heat sales – Due to the relatively low thermal efficiency of geothermal generation, any credit for use of waste heat that would otherwise be rejected is of major importance. Possible heat markets are dominated by district heat, but other potential uses include greenhouse heat, aquaculture, drying lumber, etc. A heat sale credit has been incorporated in the PSI geothermal economics model and is further discussed in Chapter 4.

Additional geothermal heat exchangers – If lower temperature geothermal heat recovered from shallower depths can be used to “preheat” the geothermal fluid and then combined with heat recovery at a higher temperature from a deeper heat exchanger, this could extend overall reservoir life. This work has been initially developed at ETHZ and is being monitored, but has not yet been integrated into the PSI model for analysis across a range of geological conditions (Karvounis and Jenny, 2012).

Life extension – Although 30 years is a fairly standard estimate of geothermal plant life, there may be cases that may warrant the investment for life extension. For example, if reservoir life turns out to be 20 years it may be of interest to extend the plant life for either another 10 or 30 years to make it possible to fully use either 2 or 3 sequential sets of wells. This option basically consists either of component rebuilds, upgrades or replacements for the surface plant above and beyond normal maintenance.

Upgrading site capacity – Geological resource uncertainty is a significant barrier to new geothermal construction. Therefore if a successful plant can be created with a proven reservoir based on known local geology, there is a significant incentive to extend its size by drilling additional well sets horizontally from the existing site, and operating them all together at the same time rather than successively one after another (as with the life extension option above). Industry Begleitgruppe members have expressed their interest in this option, stating that expanding the existing turbine capacity by reblading would be a reasonable, economic option.

Except for the geothermal preheat option, all of these possibilities can be analyzed using the economic model already developed and described in Chapter 4, with some additional cost and/or efficiency assumptions. Multiple geothermal heat exchangers at this point remain an interesting possibility, but are not likely to be seriously considered for actual, initial implementation.

3.4.4 References

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4 WP3: Economy

Warren Schenler (PSI)

The great attraction of geothermal energy has always been the great size of the potential resource, plus of course the facts that it is domestic, renewable and reliably and constantly available. However, the quality of the resource in different locations is uneven and uncertain, and the technology to produce electricity from petrothermal resources is unproven and has uncertain costs. These considerations mean that it is important to be able to link geological conditions and economic cost assumptions with a physically-based model of geothermal heat production and electricity generation, so that it is possible to say what the cost of geothermal generation may be, how generation costs are sensitive to a range of different factors and to a more uncertain extent how much generation potential exists at different generation costs levels.

This section of the TA-SWISS report describes the basic economic methodology underlying the geothermal model, discusses the scope of the Swiss geothermal resource, presents the model of geothermal economics that has been developed, and discusses different areas of costs that are particularly relevant. It then presents the different cases that have been analyzed and the key assumptions related to them, and gives results for Swiss geothermal costs, cost sensitivity analysis and geothermal generation cost supply curves.

4.1 Methodology: Levelized Cost of Electricity (LCOE)

The basic economic methodology underlying the geothermal model is to use a physical model with detailed component costs calibrated to a reference case, and to scale these linked costs under different conditions as the size of the individual elements changes (e.g. scaling well costs with depth). The assumed rate of interest is used to bring all costs to their present value at t=0 (start of operation). This includes planning, exploration, drilling and reservoir development costs before generation starts, and operation and maintenance costs afterwards. The present value of the costs is then amortized forward over the life of the plant, and divided by the annual generation to obtain the average generation cost, or LCOE. There are of course no fuel costs for geothermal generation, but if additional wells are required over the life of the plant, then these are included. The analysis is generally carried out using costs expressed in a constant, base-year currency, and the interest rate is then the real rate of interest without including inflation. In this case, the analysis has been carried out in 2010 US Dollars (USD), and results converted to Swiss Francs (CHF).

This analysis ignores many financially relevant factors, including taxes, depreciation, subsidies, and in particular future revenues. In particular, this analysis has not considered the form of subsidy where the generator is paid according to his gross generation, and the power to operate the plant and downwell pumps may be purchased at market prices from the grid. A geothermal generator should obviously pursue this subsidy when it is available, but for the purposes of a general analysis of whether geothermal power is an economic choice for society as a whole and how it can compete with other generation options, this was not considered appropriate.

The assigned focus of this project was on geothermal electricity generation, rather than on heat production. However, this analysis has included consideration of a heat credit from the sale of what would otherwise be waste heat from EGS generation plants. Although there is always the question of how to allocate costs between two or more co-produced products (here electricity and heat), the heat has been counted in this case as a “negative cost” that is fixed per unit of heat energy (kWh_t) delivered at the plant boundary to the heat customer.

The LCOE method is commonly used and is acceptable for a general comparison of generation technologies where the value of the electricity produced is constant. However for any single, individual plant or project where local financial factors are known, a more detailed analysis should be performed.

There are many other cost and operation characteristics that are relevant to an overall comparative analysis of geothermal power, including the availability, reliability and dispatchability of the plant, the variable cost of operation (dispatch cost), total capital cost, and cost-related risks including planning delays, drilling costs, possible seismic damage, etc. However this chapter focuses on average cost because it is generally regarded as the most important, and because for geothermal power it can vary so widely based on a range of relevant factors.

4.2 The Swiss geothermal resource

Geologically based energy *resources* (and in particular coal, oil and gas) are estimated based on a scale from the total theoretical resource potential to known, economic *reserves*, based on the state of knowledge and the economic production cost. For example, economic reserves of a finite resource can continue to increase even while a resource is being depleted (e.g. as with shale gas), if exploration confirms new deposits, if changing technology reduces their estimated production cost, or if the expected market price increases.

For geothermal energy, the technical resource potential is based on the amount of heat in-situ in the rock below us. This technical resource must then be reduced by the fraction of the heat that can be extracted, and further by the amount of electricity that can be generated. **Table 11** below shows the technical heat and generation potential for all of Switzerland (approximately 41’000 km^2), assuming an average annual surface temperature of 10 ˚C and an average temperature gradient of 30 ˚C/km. The resource is divided into 1 km layers, from 3 km deep (100 ˚C is a rough minimum for electricity generation) to 10 km deep (based on reasonably available drilling technology). If all the rock in these layers for all of Switzerland was cooled down to 40 ˚C, the in-situ heat resource is on the order of 10^{23} Joules. However the fraction of heat that can be recovered is limited to about 1% to 5% by the drilling geometry, plus the generation plant’s design temperature range. Plant generation efficiencies are also low, based on relatively low geothermal production temperatures, and range from about 9 to 16%, giving a technical generation resource (if one drilled everywhere is Switzerland) of about 7×10^{20} Joules.

Table 11: *Technical potential of geothermal heat and generation in Switzerland.*

Depth interval [km]	Temp. range [°C]	Average Temp. [°C]	Surface area [km2]	Density [kg/m3]	Heat capacity [J/kg*K]	Heat in Place T_{rej}= 40 °C	Heat recovery factor	Recoverable Heat [J]	Cumulative Heat [J]	Generation efficiency	Electricity Generation [J]	Cumulative Generation [J]
3 – 4	100 – 130	115	41000	2600	840	6.7E+21	1.0%	6.7E+19	6.7E+19	9.0%	6.0E+18	6.0E+18
4 – 5	130 – 160	145	41000	2600	840	9.4E+21	2.8%	2.6E+20	3.3E+20	11.5%	3.0E+19	3.6E+19
5 – 6	160 – 190	175	41000	2600	840	1.2E+22	4.1%	4.9E+20	8.2E+20	13.2%	6.5E+19	1.0E+20
6 – 7	190 – 220	205	41000	2600	840	1.5E+22	4.6%	6.7E+20	1.5E+21	14.4%	9.7E+19	2.0E+20
7 – 8	220 – 250	235	41000	2600	840	1.7E+22	4.9%	8.6E+20	2.3E+21	15.4%	1.3E+20	3.3E+20
8 – 9	250 – 280	265	41000	2600	840	2.0E+22	5.2%	1.0E+21	3.4E+21	16.1%	1.7E+20	5.0E+20
9 – 10	280 – 310	295	41000	2600	840	2.3E+22	5.3%	1.2E+21	4.6E+21	16.7%	2.0E+20	7.0E+20
Total heat or electricity [J]						1.0E+23		4.6E+21			7.0E+20	
Total heat or electricity [Gigawatt-years, or GWa]						3.3E+06		1.5E+05			2.2E+04	

Of course not all of Switzerland corresponds to the average gradient assumed above, and not all has been equally surveyed or geophysically modeled. The most detailed study of Switzerland has been done by Geowatt AG, for the limited region reaching approximately from Zurich towards Geneva (Signorelli and Kohl, 2006; Baujard *et al.*, 2007), as shown in **Figure 67** below. This figure is taken from the 2006 report, and the study areas marked by black boxes were completed and reported in the 2007 publication. The study area also coincides with the areas of highest Swiss population density, which is not too important for the transmission of electricity. However if heat sales are important for initial geothermal plant economics (as this chapter discusses later), then the Geowatt study covers the areas where geothermal plants could be located within a limited heat transport distance of the most significant heat demand markets.

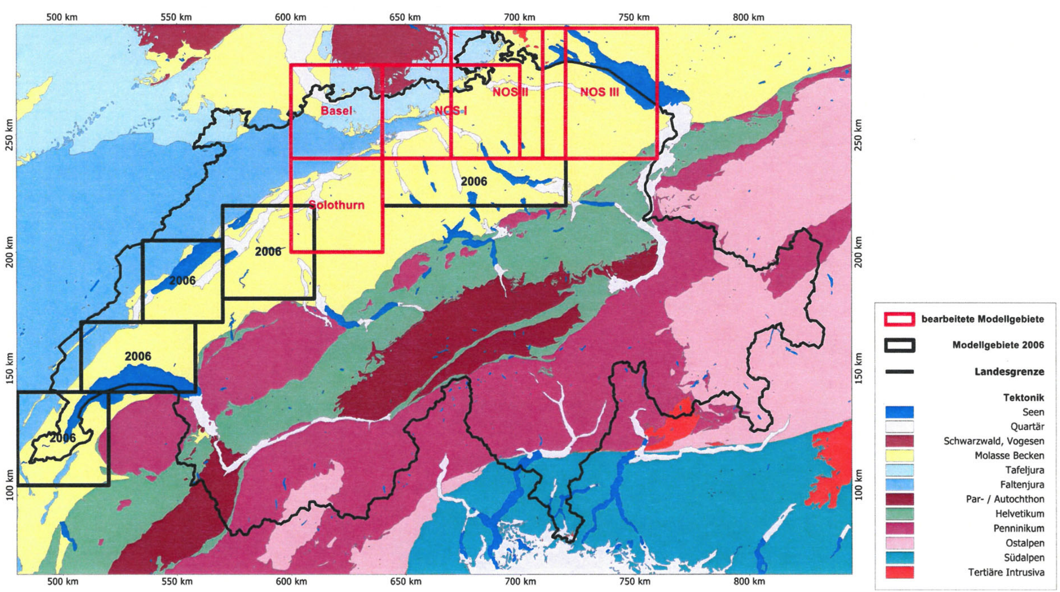

Figure 67: *Regions of Switzerland subject to geophysical modeling by Geowatt AG.*

Table 12 below summarizes the potential heat resource modeled by Geowatt AG for this limited region. The report includes more detail about different major geological strata, but the Class 3 and 4 resources of interest from 100 ˚C to 7 km deep is dominated by the crystalline basement (granite). The total potential heat resource reported for this region is much smaller, or about 32 exajoules (EJ) for the temperature range of interest for petro-thermal generation.

Table 12: *Potential heat resource modeled by Geowatt AG.*

		Upper Crystalline	Upper Muschel-kalk	Upper Malm	Upper Meeres-molasse	Total
Nord Schweiz						
Volume	km^3	4700	650	1500	1300	8150
Ave Temp	°C	105	75	80	30	
Heat in Place	EJ	969	87	209	50	1314
Ave Heat Content	EJ/km^3	0.21	0.13	0.14	0.04	
Usable - 30 yr life						
Class 2 (200m-100°C)	EJ	4.2	1.2	0.036	2.5	8
Class 3 (100°C-5km)	EJ	11.0	1.6	0.045	0.0	13
Class 4 (5-7 km)	EJ	1.8	0.1	0.001	0.0	2
Total	EJ	17.0	2.9	0.081	2.5	22
Recovery factor R		0.02	0.03	0.0004	0.05	0.02
Ost Schweiz						
Volume	km^3	2633	313	1643		4589
Ave Temp	°C	161	*143*	66		
Heat in Place	EJ	850	79	185		1114
Ave Heat Content	EJ/km^3	0.32	0.25	0.11		
Usable - 30 yr life						
Class 2 (200m-100°C)	EJ		0.3	1.8		2
Class 3 (100°C-5km)	EJ	10.7	2.4	0.5		14
Class 4 (5-7 km)	EJ	4.1				4
Total	EJ	14.8	2.7	2.3		20
Recovery factor R		0.02	0.03	0.01		0.02
Nord & Ost Schweiz						
Volume	km^3	7333	963	3143	1300	12739
Heat in Place	EJ	1819	166	394	50	2428
Usable - 30 yr life						
Class 2 (200m-100°C)	EJ	4.2	1.5	1.8	2.5	10
Class 3 (100°C-5km)	EJ	21.7	4.0	0.5	0.0	**26**
Class 4 (5-7 km)	EJ	5.9	0.1	0.0	0.0	**6**
Total	EJ	31.8	5.6	2.4	2.5	42

Source: Geothermal resource atlas for Switzerland for Swiss Geophysical Commission by Geowatt AG, 2006 and 2007 (see full references under 4.8 References).

Although the Geowatt estimates are based on detailed geophysical modeling, this is still limited by the amount of available borehole data. The average gradient can be determined over relatively large areas, but the stress and permeability of the rock that are related to developing a sufficiently large heat exchange reservoir with a low enough impedance to fluid flow are localized data that require exploratory drilling to determine. The resource is still very large but the end result is that geothermal is similar in at least one way to solar and wind power, in that it is not so much the *size* of the resource, but rather the *quality* of the resource and the resulting generation cost that is most important in determining the *economic resource* potential.

4.3 Model structure

The PSI model is a physically based, economic model that has been developed from prior modeling work done at PSI (Hirschberg, 2005), and also based upon the U.S. Department of Energy's Geothermal Electricity Technologies Evaluation Model (GETEM). The GETEM model is used by DOE to prioritize geothermal research efforts by evaluating the impacts of research in specific areas on final generation cost. It includes both binary and flash-steam (generally hydrothermal) cycles, and is very detailed in some areas that may not necessarily be justified by the necessarily rough assumptions (e.g. drilling costs) made in other areas. The PSI model uses GETEM as the base case for many physical and economic assumptions, but it has been simplified in some ways and further adapted in other ways for more extended sensitivity analysis of different cost factors. In addition, the physical model and component assumptions contained within the PSI economic model also serve as the basis for the LCA modeling that is reported in Chapter 5. The cost and LCA models are fully integrated, so that it is possible to study the cost and environmental tradeoffs inherent in different geological conditions and different plant design choices.

The basic geothermal generation system assumed in this model is a petrothermal (HDR) resource that is accessed by a single injection well with the hot geothermal fluid produced from two production wells with downwell production pumps, and used to drive a binary cycle generation plant on the surface. This basic triplet configuration is shown schematically in **Figure 68** below.

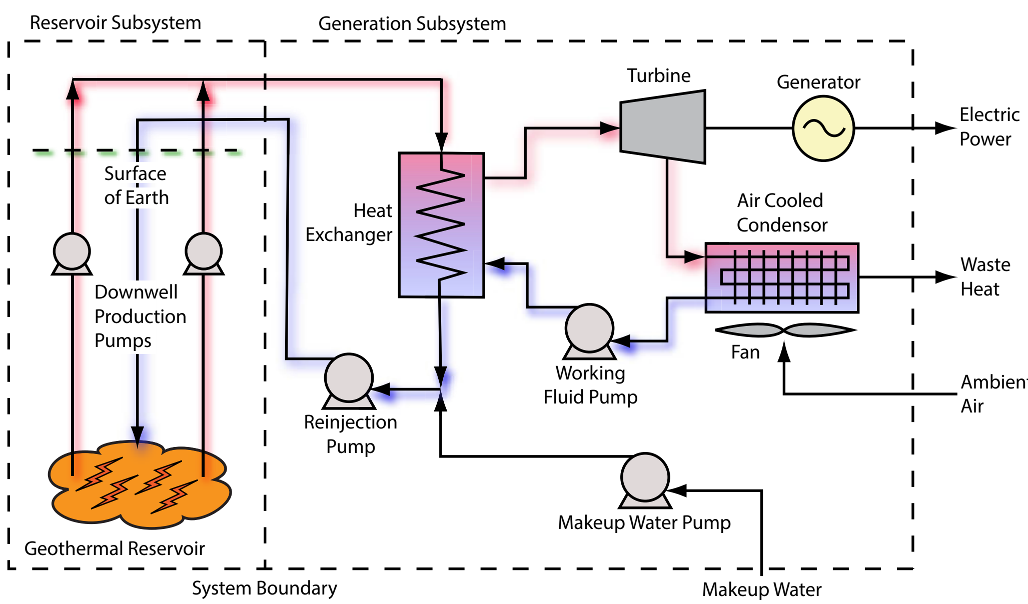

Figure 68: *Schematic diagram of binary cycle EGS system.*

The basic physical model is based on the geothermal fluid circulation. The fluid (water) is injected with a chosen pressure and flow rate (with a velocity based on well diameter). As the water goes down the well its pressure increases with depth, minus turbulent friction losses. The cool water is then heated in the EGS reservoir, with a pressure drop across the reservoir based on Darcy's Law (i.e., pressure drop is proportional to flow rate). The water also expands as it warms, and returns up the two production wells (minus reservoir losses) with changes in pressure, density, viscosity and velocity. The pressure drops further as the fluid goes up the production wells, and at some point may flash or boil into steam before reaching the surface. The downwell pumps are placed below this boiling depth by a safety factor, and pressurize the fluid so that it remains a fluid up the remainder of the well and through the generation plant until it is reinjected. Heat production is based upon the reservoir temperature (from the geothermal gradient and well depth) and the fluid flow rate. The model automatically calculates the downwell pump depth and power, thermal efficiency and gross and net plant generation. The model does not optimize the thermal cycle to conditions (e.g. Kalina cycle or others, see (Gerber and Maréchal, 2012), but the improvement in thermal efficiency is relatively small and would not affect the sensitivity to other factors.

The model uses a drilling cost curve to set well costs according to depth, and uses exponential scaling to adjust the pump and surface plant costs based on their size relative to the base reference plant. Costs are levelized based on assumed plant and reservoir lifetimes and averaged across the net generation. The model includes drilling costs, pump costs, plant costs, and operation and maintenance costs for the wells and plant. As noted above in the discussion of the economic methodology, the generation cost does not currently include taxes, depreciation, or any income credits other than for heat (e.g. no feed-in tariffs, or investment credits).

The value of the "waste" heat produced (or rejected) from the geothermal plant was initially ignored, based on the idea that in the long run widespread implementation of geothermal generation would mean that the heat produced would exceed available heat demand (e.g. there would not be enough nearby district heating networks or other heat demand). This can be seen by the fact that total district heating demand in Switzerland was about 4300 GWh in 2012, with a connected heat capacity of about 2000 MW_t (Jahresstatistik, Verband Fernwärme Schweiz, www.fernwaerme-schweiz.ch). However the heat credit can be quite important, especially for the economics of initial plants, particularly due to the low thermal efficiency and the large ratio of waste heat to electricity produced. The Begleitgruppe agreed at a project meeting that the value of heat production should be assessed, and this has been included in the results reported below.

4.4 Model inputs, cases and assumptions

The exogenous inputs to the model can roughly be divided into those that depend upon the choice of location (gradient and reservoir impedance), those that are plant design choices (well depth, fluid flow rate, reinjection temperature, etc.), and uncertainties (primarily well cost and reservoir life). The primary objectives of the model are to determine the average generation cost, the relative contribution of the different component costs to the total average cost, and the sensitivity of the average costs across the range of uncertainty for the most important component costs. This section gives the values for model inputs in both US dollars (USD), which are the original units in the GETEM model, and also in Swiss Francs (CHF), using a conversion rate of 1.1 USD/CHF.

Initial model analysis showed that the two most dominant cost factors were the drilling costs and the reservoir life. This reflects the fact that well costs include not just drilling costs, but also the number of wells in each well set (including exploratory and test wells), and well life, which determines the number of wells sets that must be drilled over the life of the surface plant and is primarily related to reservoir life. These factors were also significantly different in the base assumption for the US and Switzerland. The US GETEM model assumed lower drilling costs, at about 25 million USD (22.7 million CHF) for a 6 km well, but surprisingly also assumed only about a 5 year well life before the fluid production temperature dropped about 20 ˚C, below the binary plant's design temperature range. The initial default Swiss assumptions were much higher drilling costs (about 57 million USD, or 51.8 million CHF) for a 6 km well, based on limited historic Swiss drilling costs from the Bundesamt für Energie (BFE), but also a much longer assumed well life of about 30 years (i.e. equal to plant life). Based on these differences an initial set of four cases for analysis were chosen, i.e. 1) a US-based case that was also the reference case for model calibration, 2) a Swiss case with the higher well cost and longer well life, 3) a best-case with the lower US well costs and longer Swiss well life, and 4) a worst-case with high Swiss well costs and the much shorter US well life. The high Swiss well cost cases also included a higher plant cost, but this has a much smaller effect. These four cases were used to find the relative effects of these two major factors, and also to scope out the range of the worst to best costs that could be expected.

Feedback from Begleitgruppe members, and coordination within the project with the LCA modeling team then led to a number of changes that resulted in three Swiss reference cases, the Swiss-Base or reference case, an optimistic Swiss-Good case, and a more pessimistic Swiss-Poor case. Specific changes that were (or were not) made included the following.

Well depth – The reference well depth was reduced from 6 km to 5 km, based on expected Swiss developments.

Temperature gradient – The reference gradient was left at 35 ˚C/km for the Swiss base case, but increased to 40 and reduced to 30 for the good and poor cases, respectively.

Well cost – The drilling cost was significantly reduced to 20.9 million USD (19 million CHF) for a 5 km well, based on drilling costs from St. Gallen, which have also been used to calibrate other industry drilling cost models in Switzerland.

Well life – The well (or reservoir life) was set at an intermediate value of 20 years, between the US and prior Swiss assumptions. This was based on industry input that a project with a lower well life would not be considered. The same range as before was however kept for sensitivity analysis.

Flow rate – As noted above, the geothermal plant modeled in this work is a triplet rather than a doublet, i.e. there are two production wells rather than one. This means that the physical behavior of the circulation loop is basically the same as for a doublet with half the flow rate. Feedback from industrial partners was that the flow rate was too high at 147 l/s, and that 50 l/s would be a more appropriate level. The original triplet value was based on the GETEM model base case that is aimed at a relatively high plant power level, and is equivalent to about 75 l/s for a doublet plant. Given that the sensitivity range for this parameter goes down to 49 l/s, this is equivalent to about 25 l/s for a double or about half of the industry-suggested value. It was felt that this sensitivity range was sufficient to cover the lower suggested flow rate, and the original base value was kept to be closer to the GETEM base case. The fluid flow sensitivity range was also run quite high to explore pumping losses at high fluid velocities.

Downwell pumps – Based on industry preference for a lineshaft pump, the model was modified to automatically select this type if the pump depth is less than 700 m. Deeper pumps are kept as submersible pumps.

Reservoir impedance – The model initially assumed the GETEM value of 0.113 MPa s/l, which is relatively optimistic in view of the reservoir impedances reviewed in Chapter 3. Based on discussion with Dr. Keith Evans, a range of 0.1 to 0.5 was considered to cover the range of values from optimistic to those currently achieved but found infeasible for production purposes. The sensitivity analysis uses a base value of 0.2, and further extended the range of values down to 0.05. Initially the model also linked the fracturing cost to reservoir impedance, but after discussion with Dr. Evans, this was judged to exceed present knowledge, and impedance was left as an uncertainty for sensitivity analysis.

Reinjection temperature – The reinjection temperature is kept relatively high to reduce well scaling if fluid chemistry is unfavorable. Due to the expected chemistry for wells in the Swiss granite basement, the reinjection temperature was decreased from 75 to 60 ˚C.

Interest rate – The original GETEM interest rate was a relatively high 10%. This may be judged reasonable for high-risk projects. However Swiss geothermal planning generally includes drilling insurance (the biggest, immediate cost risk), and Swiss geothermal cost models from industry use an interest rate of 5%. This chapter uses an interest rate of 5% for the results reported for all seven cases described above.

Table 13 below shows the base values for selected key physical and economic model parameters for all the 7 analysis cases described above, and also the sensitivity ranges for the single factor sensitivity analysis that was based on the Swiss base case.

Table 13*: Selected economic model assumptions and results.*

Parameter	Units	Scoping cases (well cost, life)				Swiss reference cases			Sensitivity range
		GETEM (US)	Swiss	Best case	Worst case	CH-base	CH-good	CH-poor	
Geothermal gradient	˚C/km	35				35	40	30	20–50
Well depth	km	6				5	6	5	3–8
Reservoir temperature	˚C	225				190	255	165	
Distance between wells	km	1							
Reservoir size	10^6 m3	80							
Reservoir impedance	MPa*s/l	0.113				0.2	0.2	0.2	0.05–0.5
Flow rate (injection)	l/s	147				147	147	147	49–294
Fluid loss in reservoir		2%							
Gross plant power	MW_e	13.0				8.9	17.3	6.4	
Downwell pump depth	m	470				1350	1289	1366	
Pump power (for 2)	MW_e	1.0				3.4	2.7	3.5	
Net plant power	MW_e	12.0				5.5	14.6	2.9	
Net thermal efficiency		16%				9%	14%	6%	

Parameter	Units	Scoping cases (well cost, life)				Swiss reference cases			Sensi-tivity range
		GETEM (US)	Swiss	Best case	Worst case	CH-base	CH-good	CH-poor	
Annual net generation	GWh	100				46	122	24	
Well cost	M$/well	25.5	57.2	25.5	57.2	20.9	34.1	20.9	10–57
Well (reservoir) life	years	5	30	30	5	20	30	20	5–30
Well diameter	inches	10				10	10	10	6–16
Fracturing cost/well	M$/well	1.0							
Plant cost	$/kW$_e$	3000	4200	3000	4200	4200	4200	4200	2500–5500
Plant lifetime	years	30				30	30	20	20–45
Interest rate		10%				5%	5%	5%	2%–10%
Ave. cost	CHF/MWh$_e$	33.2	28.2	14.5	69.4	34.6	17.9	61.3	
Ave. cost w/ heat credit	CHF/MWh$_e$	22.7	17.7	4.0	58.9	14.3	5.9	31.0	

Note: blanks are equal to first column, and blanks in sensitivity column reflect constant or dependent values.

4.5 Discussion of major cost areas

Before proceeding to the cost results, it is worthwhile discussing briefly some of the key model cost inputs.

Drilling costs – Well costs are the dominant component cost for geothermal generation, with our cost results reflecting industry experience. However, total well costs are based not only on drilling costs, but also on the total number of wells required per well set and upon reservoir life.

It is expected that the high Swiss drilling costs will be based on a wide range of factors, including Swiss labor costs and rules (e.g. shift work regulations), stringent environmental regulations (e.g. for drill cutting and mud disposal), generally low Swiss drilling activity and experience, etc. The various Swiss geothermal programs carried out by Axpo, Geoenergie Suisse, St. Gallen, etc. have their own cost models, either developed in-house or adapted from German experience to Swiss conditions. These predictive models are generally confidential, although actual drilling costs are generally available after the fact. However, these industry members will state that their model has been calibrated to experience at St. Gallen, where costs were significantly lower than other deep Swiss wells (see **Figure 69** below).

Based on the GETEM model, it is assumed that there are 2 exploratory wells required (50% of base well cost each), 2 confirmation wells (120% of base well cost), 1 injection well and 2 production wells (one of which reuses a confirmation well). Total drilling costs for all wells required are therefore assumed to be 5.17 times the base well cost, which is based on a drilling cost curve. **Figure 69** below shows a range of such drilling cost curves. The lowest curve is based on the Wellcost Lite model used in the MIT report on geothermal energy (Tester *et al*, 2006), and in prior versions of the PSI model. The step-function “jumps” in the curve reflect increases in well casing diameter as well depth increases. The middle three curves are the low, medium and high exponential drilling cost curves contained in the GETEM model, and the large differences between them reflect the still large drilling cost uncertainties that exist. For the reference model well depth of 6 km, the medium GETEM cost curve gives a base well cost of about 25 million USD (22.7 million CHF). Finally, the highest drilling cost curve is based on Swiss drilling data obtained from the BFE (Siddiqi, personal communication). A polynomial cost curve was fitted to the limited amount of drilling cost data (although the fit is quite respectably good), giving a base well cost for the reference depth of 6 km equal to approximately 58 million USD (52.7 million CHF). Based on further consultation with Begleitgruppe members, and review of industry models calibrated to specific Swiss geothermal experience (Stadt St. Gallen), a final curve was added. The industry calibration point was very close to the medium GETEM curve, so this was adapted slightly to fit through the calibration point, and used as the final well cost curve. Swiss industry input was also that they would plan to drill fewer wells per set (e.g. the first exploration well would also serve as a production or reinjection well if it succeeds), which would make the drilling costs used in this work conservatively high.

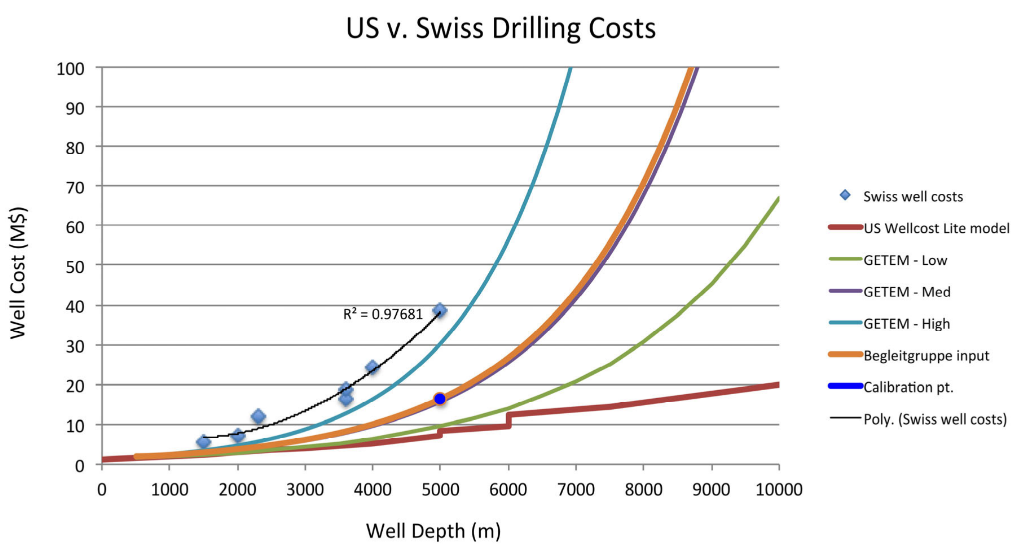

Figure 69: *Swiss and American drilling cost curve data.*

Reservoir life – The results below show that the large uncertainty in drilling costs is approximately balanced in their final effect by the also large uncertainty in well life, over the range of costs considered. Reservoir life is limited by the temperature decrease in the geothermal fluid produced, based on the design temperature range of the binary generation plant (for GETEM the design range is to 20 ˚C below initial production). The reservoir life is determined by the volume of the reservoir, how evenly the crack network accesses this volume, the heat exchange effectiveness, and the rate of fluid flow. The danger is that once a flow path is established between the injection and production well(s), the flow will be channelized to this path of least resistance. This is the basis of interest in using well blockers for sequential, parallel fracturing. Blockers currently used for oil & gas fracturing are not very suitable for the higher temperature regime of geothermal reservoirs, but there is development in progress using epoxy-fiber blockers that degrade with heat over time.

As mentioned above, although the surface generation plant is expected to have a working lifetime of 30 years, and the GETEM model assumes that well life will only be 5 years, so that a full new set of wells must be drilled (horizontal or lateral drilling is used so that the surface plant is not moved). Well life assumptions surveyed for prior PSI modeling were the same as plant life, i.e. 30 years, and other Swiss programs also assume longer well lifetimes. Based on industry inputs, a well life of less than 20 years would not be considered in Switzerland, so this was the value used for the Swiss base and poor cases. The more optimistic Swiss good case uses a well life of 30 years.

Pump costs – Although the downwell pump costs are not small (approximately 0.5 million USD, 0.45 million CHF, per pump for the reference pump size of 0.7 MW_e), they are minor in relation to well costs. However, the reliability and lifetime of such pumps can be quite uncertain based on their hostile environment (personal conversations with city of Munich). The cost to remove, refurbish and reinstall an old pump is not far from the cost of a new pump, and so it was assumed that the downwell pumps would have a service life of 5 years. The economic model automatically includes the correct number of pump replacements based on both the assumed plant life and well life.

Although the downwell pump has its impeller located down the well at the appropriate depth chosen by the model, the motor can be located either on the surface (a lineshaft pump), or down the well casing just above the pump (a submersible pump). Lineshaft pumps are less expensive, more reliable and easier to maintain, but they are limited by the length of the lineshaft. Submersible pumps are more expensive and less reliable, and they are limited by the temperature of the production fluid (i.e. by well depth and gradient, rather than pump depth). Development of higher temperature submersible pumps is an ongoing effort for geothermal research. As noted above, Begleitgruppe members communicated that some Swiss efforts are planning to use lineshaft motors, with the assistance of a surface injection pump. Based on this industry input, the geothermal model was modified so that above a depth of 700 m. a lineshaft pump was automatically chosen, while below this depth a submersible pump was chosen. Although the model automatically chooses the pump depth to prevent the fluid boiling in the well, it is possible for some sensitivity cases that the depth or temperature may exceed what could actually be achieved, and in this case the results must be treated more as a “what-if” case.

Surface generation plant costs – The surface generation plant is assumed to have a base cost of 3000 USD/kW_e (2730 CHF/kW_e) for the reference gross generation capacity of 16.3 13.0 MW_e. The cost scales with plant size using an exponential factor of 0.9. The thermal efficiency of the plant is based on the available energy due to the enthalpy and entropy differences between the production fluid and ambient environment, using the GETEM methodology, and 2nd law efficiencies that are slightly higher than the prior PSI model. The efficiency is used as the basic calibration “lever” to adjust the model to match the GETEM results for the reference case, and this was done although the GETEM efficiency does seem rather high in comparison to some figures in the literature (DiPippo, 2004).

Because the working fluid temperatures are relatively low (compared to normal thermal power plants) thermal efficiency is quite low, so even a slight increase in efficiency can significantly affect the net generation and reduce average costs (e.g. an increase from 12% to 15% efficiency is an increase of 25% in gross generation and has an even larger benefit to net generation and average cost.

4.6 Results

This section first describes the average cost results for the seven cases described, as well as the contribution of their different cost components. These results are then extended by adding the effect of having a heat credit for sales of what would otherwise be waste heat. The presentation then moves to presenting the effect of single factor sensitivity analysis for the most important cost factors, following by a combined sensitivity curve that shows their relative effect compared to each other. Finally three preliminary geothermal generation cost curves are presented, based on the three Swiss reference cases and the Geowatt estimate of the geothermal heat resource presented above.

The base assumptions in the model reflect current technology, and there are no assumptions made about how quickly the technology will evolve or improve over time. Nevertheless it is possible to see the relative contribution of different factors and their sensitivity to improvements, so that it is possible to obtain a “what-if” evaluation for the improvement of these factors.

It is worth remarking that the modeling produces some results that could at first need interpretation. The first result is that under unfavorable operating conditions (e.g. a low geothermal gradient) it is possible for the pump power required to exceed gross generation. Therefore the plant produces negative net power and the average generation cost is therefore also negative. It would be possible to assume a cost for purchased power, so that average cost would be higher instead of negative, but the negative result does emphasize the fact that unless the waste heat can be sold at a sufficient value a geothermal plant would never operate in such a regime. This discontinuity in the average costs may be observed in the sensitivity results below. Second, under some extreme circumstances the downwell pumps were either not required or were needed at a depth below the bottom of the production well. In the first case, the pump was eliminated and replaced by a pressure relief valve at the production wellhead, and the plant would not operate in the second regime.

Figure 70 below shows the results for the four cost scoping cases and the three Swiss reference cases, showing average generation costs of approximately 33, 28, 14, 69, 35, 18 and 61 Swiss cents/kWh$_e$, respectively. The results for the first four scoping cases have the same relationship as in our interim report, but are somewhat lower because the interest rate used was lowered from 10% to 5%. The first two scoping cases (33 and 28 Swiss cents/kWh$_e$) are relatively close, as the higher well costs assumed for Switzerland roughly compensate for the longer assumed well lifetimes. As can be seen, the drilling costs dominate in all four cases. Note that these four cases are physically identical in operation, and only the costs differ.

In contrast, the three Swiss reference cases (base, good and poor) differ in a number of physical conditions, including gradient, depth and plant and well life. The results show that these changes (summarized in **Table 13**) create a relatively wide range of average costs from 18 to 61 Swiss cents/kWh$_e$, even without any heat credit. These results emphasize the need to find the best location, drill as deep as possible at the lowest possible cost, and to develop the longest lasting reservoir possible.

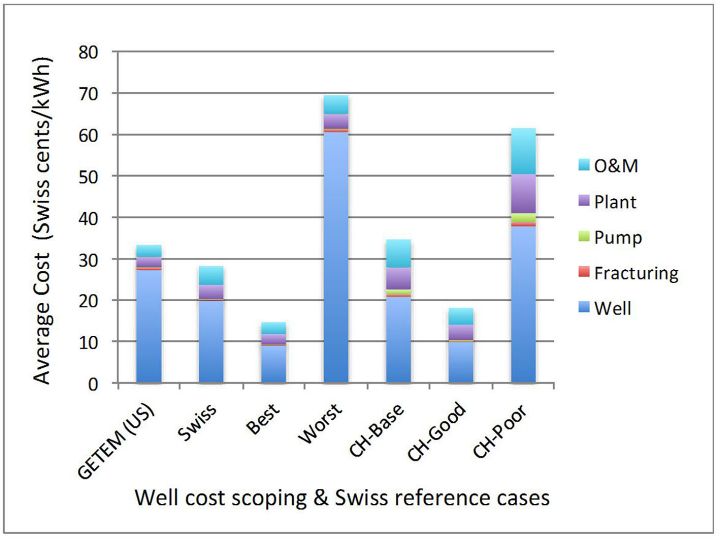

Figure 70: *Component generation costs for 7 cases analyzed.*

Heat Credit – A heat credit of 7 Swiss cents/kWh$_t$ was applied to the seven cases shown above in **Figure 70**. The major result of this analysis is that the final average cost is very sensitive to the amount of the heat credit, as shown in **Figure 71** below. It was assumed that the waste heat produced could be sold for only 2500 hours per year, producing the negative cost or credit shown by the brighter orange bar in this figure. It should be noted that the annual load factor for space heating (e.g. for a district heating company) is about 2000 hours per year, based on peak heating load in winter, basically no heating load during the summer, and low to intermediate load in spring and fall. This means that geothermal plant is delivering heat at a higher capacity factor than other heat supplied to the distribution system, and that the system requires this other supply to meet its peak heat load. In the very unlikely case that a heat customer could be found that would need *all* of the geothermal heat produced, this is shown by the lighter orange bar that shows the maximum additional credit for an additional 8760–2500, or 6260 hours/ year.

As seen, the average costs for the first four cases go from 33, 28, 14, and 69 Swiss cents/kWh$_e$ down by about 10 Swiss cents/kWh$_e$ to 23, 18, 4 and 59 Swiss cents/kWh$_e$, respectively. Note that the heat credit is equal for these four cases, since they are physically the same. The three Swiss reference cases have heat credits that increase from the good to the poor cases, decreasing the average costs from 18, 35 and 61 Swiss cents/kWh$_e$ to 6, 14 and 31 Swiss cents/ kWh$_e$, relatively.

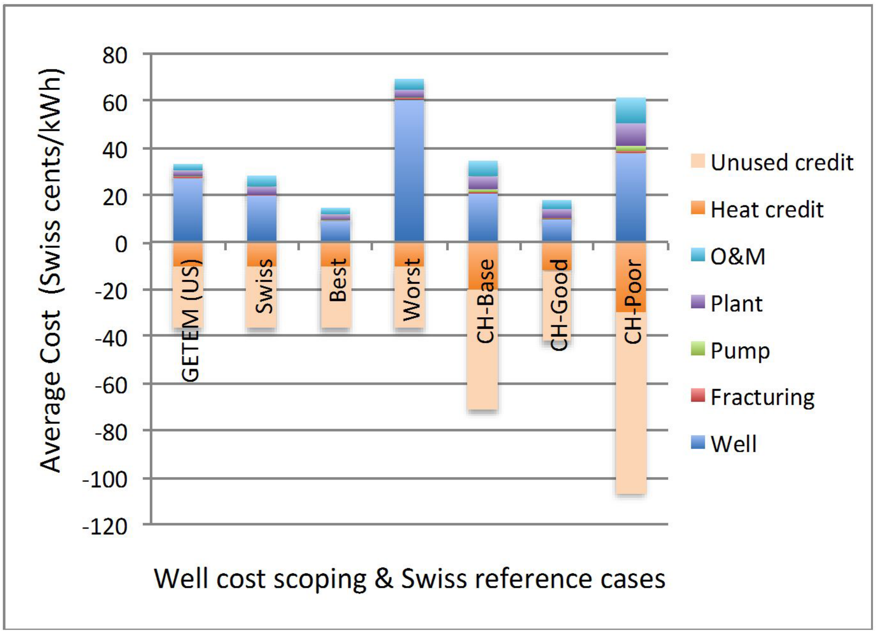

Figure 71: *Component generation costs with assumed and maximum possible heat credits.*

The reason that the heat credit has such a large impact is that the relatively low thermal efficiency means that the ratio of electricity to heat is low (about 1 to 5). Assuming that the heat can be sold, this creates a leveraged reduction in average generation cost. For the reasonable heat load factor assumed, this means that in the best case geothermal generation could actually be competitively priced relative to other generation options. In the extremely unlikely case where all the heat could be sold, this means that the cost of generation would actually be negative, i.e. the plant could pay customers to take the electricity (or operate at a loss on a purely electric basis) and still break even.

Several comments apply here. First, the analysis currently assumes that the available waste heat is the heat that comes up the well minus the heat in the reinjection fluid and the electric energy produced. This is not a very conservative assumption as there will also be some losses.

Second, in cases where the pump losses increase relative to gross generation (i.e. net generation is reduced), then the heat/electricity leverage is increased, and it will remain economically more attractive to operate the plant over a wider range of conditions.

Third, although average district heating prices for heat have increased from about 9 EUR/GJ in 1999 to 12 in 2003 and 22 in 2013 (Ecoheatcool website, 2006 and 2013), this is the price for heat sold to the customer, and not the price for heat bought by the district heating operator from the geothermal plant. The actual value of the heat credit will depend upon the temperature of the heat delivered and the negotiated price, which will also add a further siting incentive. The need for a heat credit to make geothermal economics more attractive creates a tension between the need to be close to a market for the heat produced and the desire to be farther away from a population that may be averse to the risks of induced seismicity.

Finally, the comment made above about the need for a more detailed economic analysis for any individual geothermal project is further strengthened when a heat credit is included. Based on the relative values of the electricity and heat, and the characteristics of the heat load customer, it may be possible to do better than just "selling the waste heat" and instead optimize the plant's design and operation by shifting or scheduling the energy produced between heat and electricity depending upon the season.

Because the economic benefit of the heat credit is so significant, it is interesting to compare the heat production to current and estimated future district heating demand in Switzerland. **Figure 70** below shows historic data from 2002 to 2012 reported by the Verband Fernwärme Schweiz (www.fernwaerme-schweiz.ch) for district heating heat sales, heat source capacity, electricity generation, network length and peak heat load. It is clear that annual heating demand swings are significant, but the trend of gradual growth is clear, especially in the smoother growth of the km of district heating network.

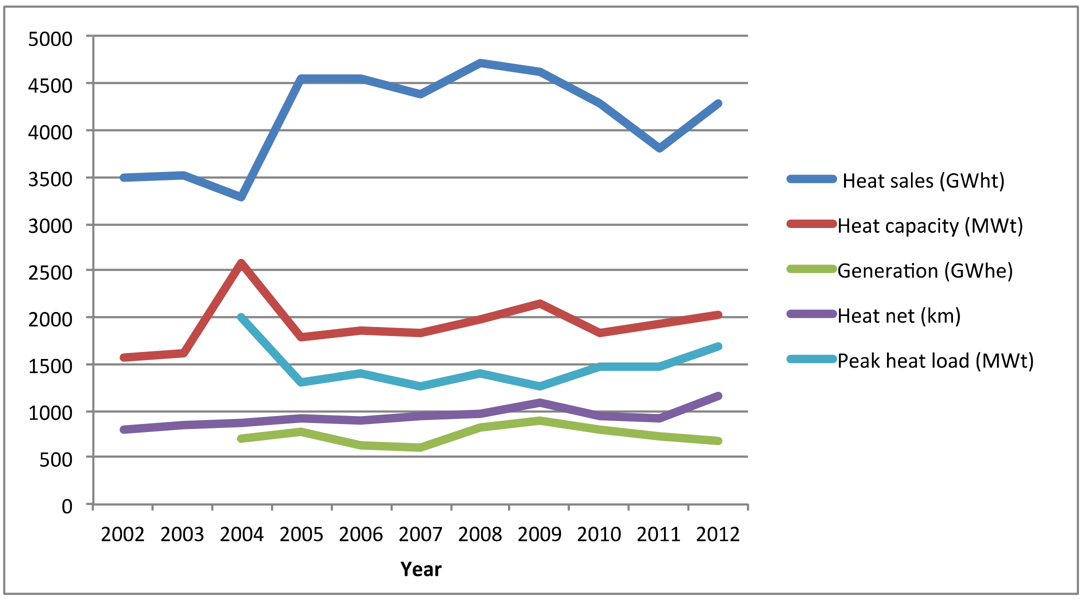

Figure 72: *Historic values for district heating heat sales, heat source capacity, electricity generation, network length and peak heat load.*

The VFS (Verband Fernwärme Schweiz; Swiss District Heating Association) has also recently published a sponsored study by Eicher and Pauli of potential future district heating demand and heat sources. This study uses a GIS-based analysis with a 100 m grid and a 2010 heat demand map to establish grid cells that have sufficient heat demand, and then uses an upper bound for the heat transport cost of 4.5 rp/kWh$_t$ to build 5500 cell clusters (and 10 megaclusters) that form the potential district heating service areas. The study assumes that total heat demand in 2010 of 85 TWh/a for water and space heating is projected to drop to 45 TWh/a by 2050, of which the study identifies 38% or 17 TWh/a that could be served by centralized district heating. The study surveys and ranks the possible heat sources to serve this demand. Geothermal heat is seen as the largest candidate source (70 TWh/a) that is widely available (and not tied to specific heat source locations), and is second only to using

Swiss lakes as heat reservoirs (97 TWh/a). Geothermal is seen by this report as the lowest ranked source of heat due to its assumed economics for power generation, but the paper does not include a heat credit in its cost calculations. The study estimates future heat market demand and heat resource supply potential, but it does not make any assumptions about the future growth rates of districting heating service into the potential heat market.

For comparison the VFS reports that the amount of heat delivered in 2012 was 4.3 TWh_t, or roughly ¼ of the projected 2050 potential heat demand. (The report does not state that currently served heat demand is deducted from its estimate of future demand). The amount of heat delivered by the geothermal plant for the CH-base case in this report is 144 GWh_t/a, which means that about 30 such plants would be required to serve all district heating demand in 2012, or about 118 plants would be necessary to serve all projected district heating demand in 2050. This many plants with a CH-base net capacity of 5.5 MW_e each would provide a total capacity of about 650 MW_e, with an annual generation of about 5.4 TWh_e, just slightly above the BFE's target contribution. It is unsure that the district heating market will achieve the VFS potential, or how much of this would realistically be geothermal heat, but at least it is possible to see that the heat market is big enough to potentially offer a heat credit for the first geothermal plants built, and the VFS study identifies the location of the heat clusters that could potentially use geothermal heat.

Component cost sensitivities – **Figure 73** through **Figure 81** below show the sensitivity of the average cost and its components to different individual cost factors, including geothermal gradient, well depth, fluid flow rate, reservoir impedance, well diameter, well life, plant life, plant cost and interest rate. The regular heat credit is still applied and shown, but the maximum possible (unused) heat credit has not been shown, simply to expand the vertical scale of the figures and to allow better understanding of the smaller component costs.

Gradient – **Figure 73** below shows the sensitivity of the average cost to the geothermal gradient. We can see that a low geothermal gradient can drive average cost extremely high, or even negative in the case of the lowest gradient. In this case the reference well depth of 5 km is maintained, so the initial production temperature is about 115 ˚C. At this temperature, the fluid heat content and the plant efficiency are both low and combine to produce gross generation that is below the pumping load. This case is worse than the similar graph in the project interim report where the base case well was 6 km and production temperature was 135 ˚C. The average heat credit decreases slightly as the gradient increases, reaching breakeven with the costs at about 45 ˚C/km.

Obviously, and all else being equal, the higher the gradient that can be found, the better. But "all else" is almost never equal, so this graph gives some indication of the location-specific sensitivity for the gradient that may be traded against either proximity to an available heat market and/or additional drilling costs.

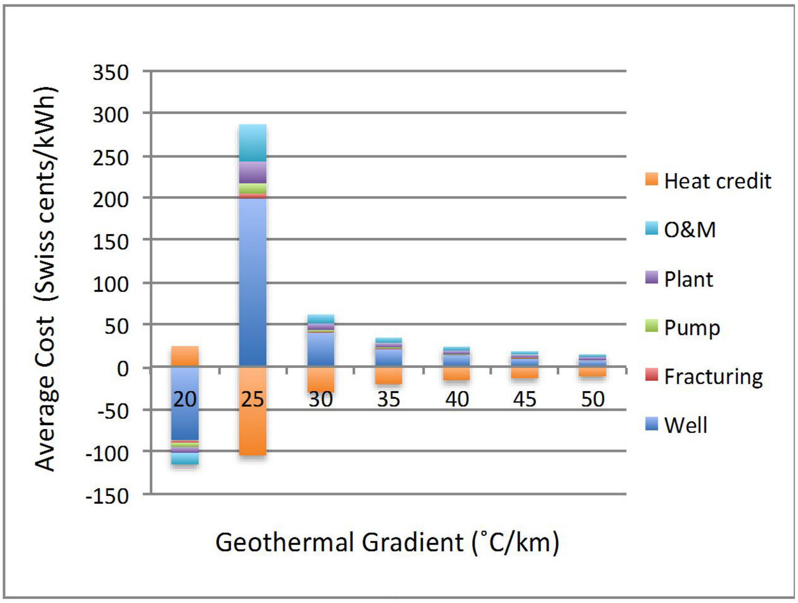

***Figure 73:** Component generation costs v. gradient.*

Well depth – **Figure 74** below shows the sensitivity of the average cost to the well depth, which of course can be chosen at any location. As with the geothermal gradient above, too shallow a well produces too low a fluid temperature, driving down heat production and plant efficiency.

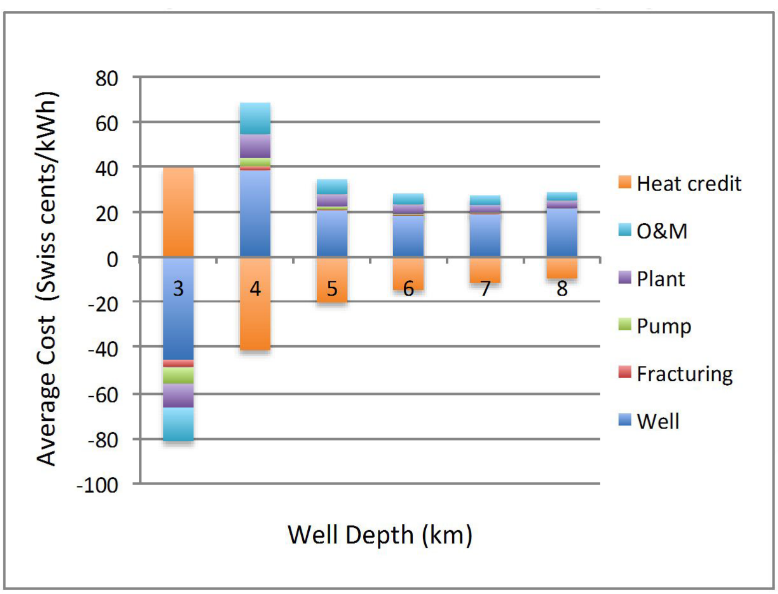

***Figure 74:** Component generation costs v. well depth.*

At a depth of only 3 km with a production temperature of 120 ˚C, these factors combine to produce gross generation below the pumping power required, driving net generation and average cost negative. It can also be seen that as the depth increases, the drilling costs increasingly dominate as a share of all other costs, even though the increase in net generation keeps the average cost from going back up too quickly. Without the heat credit, the minimum average cost is about 27 Swiss cents/kWh$_e$ at the depth of 7 km. When the total costs are combined with the heat credit, the average costs are minimized at 6 km depth with an average cost of about 14 Swiss cents/kWh$_e$. At deeper depths, the exponential increase in drilling costs increases faster than the net generation or the heat credit and the total average cost starts to rise again.

Fluid flow – **Figure 75** below shows the sensitivity of average cost to the rate of geothermal fluid flow. At the lowest flow rate of about 49 l/s, the total heat production is also low enough to drive up the average cost slightly. The average cost is minimized without the heat credit at a value of 30 Swiss cents/kWh$_e$ for a flow rate of 98 l/s, and minimized with the heat credit at about 14 Swiss cents/kWh$_e$ across a flow rate range of 98 to 196 l/s. As the flow rate is increased (and the well diameter is held constant) the fluid velocity also increases, and at the highest flow rates this increases the turbulent fluid flow resistance, driving up pressure losses, pumping power and hence the final average cost. This can also be seen in the increase of pump cost as a share of total average cost in the highest fluid flow case. However this extreme sensitivity case is unrealistic because if high flow rates were required a larger well diameter could also be chosen. Increasing production rates will also reduce the reservoir life as the heat is removed more quickly. Reservoir life has been kept constant here for the single factor sensitivity analysis, making the implicit assumption that reservoir size is rising with fluid flow, which may not be realistic.

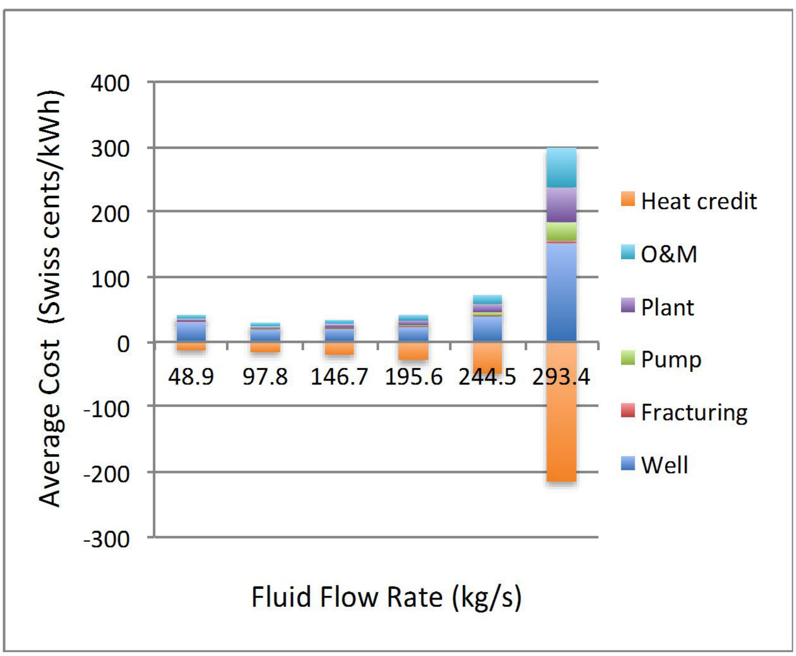

Figure 75: *Component generation costs v. fluid flow rate.*

Reservoir impedance – The challenge in creating a productive geothermal reservoir is to create a large enough reservoir with good fracturing and low impedance, but with cracks that access the whole reservoir instead of channelizing the flow to only a small part of it. If impedance is too high, then pumping losses to maintain the target flow rate will be too high, driving net power down and average cost up. This is what can be seen in **Figure 76** below. Average costs rise with reservoir impedance, until at an impedance of 0.5 MPa s/l the pumping load exceeds gross generation, and the negative net power drives the average cost negative. As with the sensitivity analysis of fluid flow rate, the increased pumping power can be seen by the increasing share of the pump cost relative to the total average cost. Although the cost is increasing due to lower net generation, the flow rate, gross heat production and heat credit are unchanged across all the sensitivity cases here.

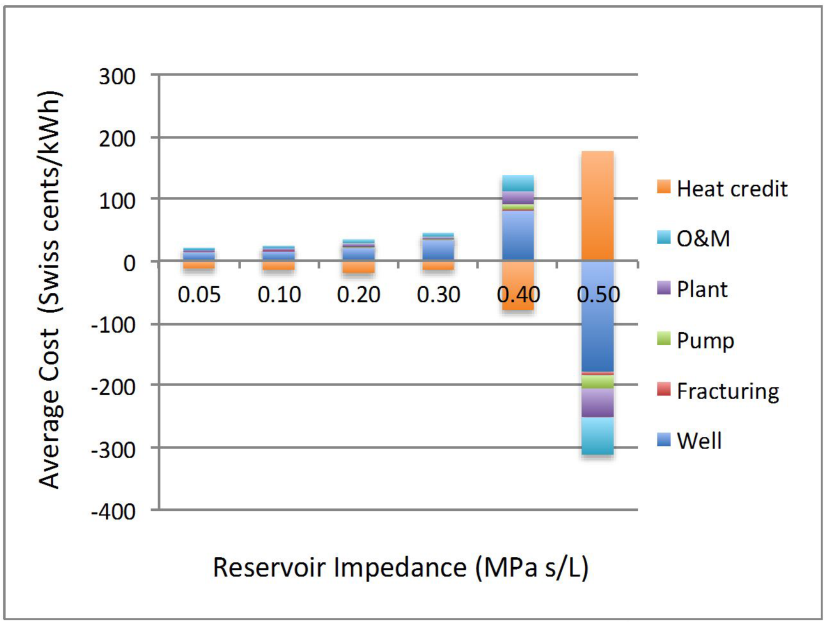

Figure 76: *Component generation costs v. reservoir impedance.*

Well diameter – The sensitivity analysis of the average cost as a function of well diameter is similar to the two preceding cases of fluid flow rate and reservoir impedance, in that all three are linked to increasing flow impedance, pressure drops and pumping losses due either to the reservoir impedance or fluid velocity. In this case however, well diameter is also linked to well cost. In the present model a rather simple exponential well cost curve based on depth alone has been used rather than a more complex well cost model. So a rather simple assumption has been made that well cost is also proportional to the volume of rock removed, and hence to the square of well diameter. This can be seen **Figure 77** below, where average cost rises with well diameter, and well costs rise as a share of total average costs. On the other hand, as the well diameter decreases toward the lowest diameter of 4 inches, the velocity of the constant fluid flow must increase until the flow becomes turbulent and the turbulent drag increases the pressure drop in both the injection and production wells. Again, this increases pump power and decreases net power and driving up average cost, although in this case the effect is not large enough to drive the net power and average cost negative. It is interesting to see that at the base fluid flow rate used, the average generation cost is minimized at a well diameter of 8 inches followed by 10 inches, both of which are common well sizes.

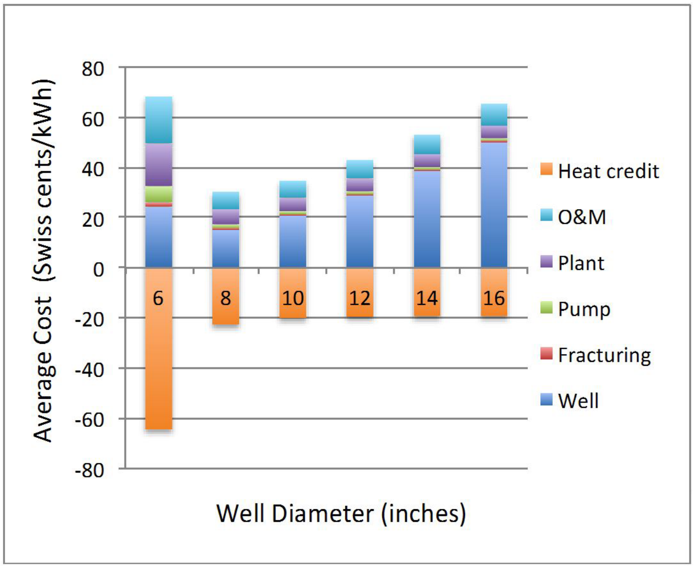

Figure 77: *Component generation costs v. well diameter.*

Well life – **Figure 78** shows the sensitivity of the average cost to the geothermal well life. This variable may also be called reservoir lifetime, since in the absence of significant well scaling the well life will be determined by the reservoir life, and its temperature drop over time. The assumption here is that if a reservoir is depleted, a new set of wells will be drilled at an angle to a new reservoir location.

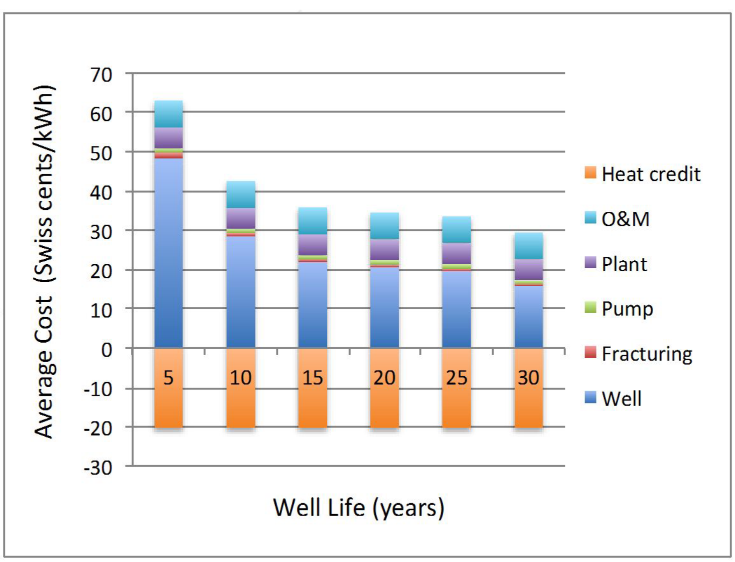

Figure 78: *Component generation costs v. well life.*

There is therefore no physical change between the different sensitivity cases, but only a financial change due to the recurring costs of the new wells. The figure shows that as the well life drops below the plant life of 30 years there is a cost increase due to the need for a second well set. The cost is almost constant until the well life drops from 15 to 10 years, requiring a third well set, and then another larger increase as well life drops to 5 years, requiring six well sets. The cases with well lives of 15, 20 and 25 years are almost equal, but with slight differences due to the number of pump replacements required. All the other cost components and the heat credit remain constant. Well lifetime depends on reservoir size and fluid flow rate, so this sensitivity is related to the fluid flow sensitivity also discussed above.

Plant lifetime – The sensitivity analysis for average cost as a function of plant life is shown in **Figure 79** below. There are basically two effects here which combine to produce this rather crooked and seemingly inconclusive series of results from a plant life of 20 to 45 years.

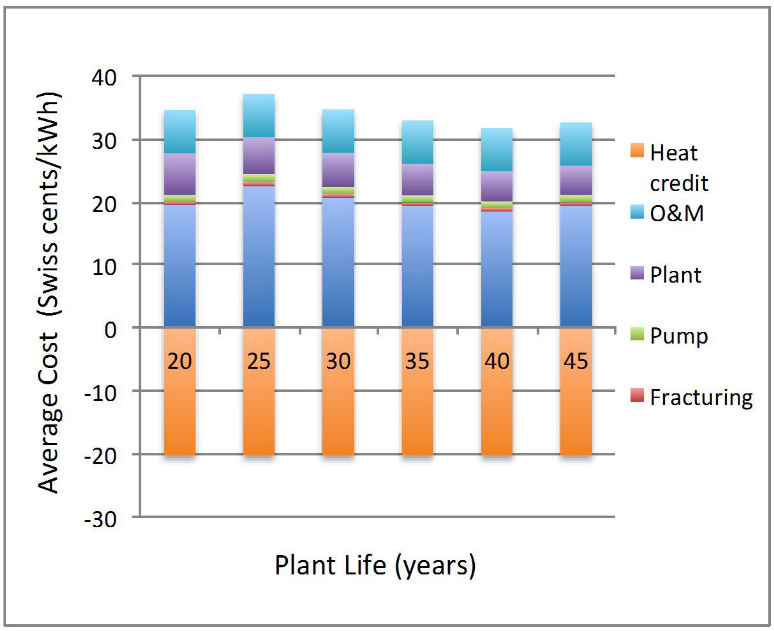

Figure 79: *Component generation costs v. plant life.*

First, the fixed surface plant costs are amortized forward over the plant life, so the longer the plant life the lower the average cost. Second, the base plant life is 30 years, compared to the base well life of 20 years. As the plant life is increased from 20 to 25 years a second set of wells is required, and as the plant life increases from 40 to 45 years a third set of wells is required. These step functions upward as well costs increase with longer plant life combine with the smoother decline in average surface plant costs as the plant life increases. All other costs and the heat credit remain constant as the physical model parameters are constant.

Plant cost – The sensitivity analysis for average cost as a function of plant cost is shown below in **Figure 80**. This is perhaps one of the less interesting sensitivity analyses, as there are no physical interactions, and the plant cost is less dominant than the well cost or well life. It behaves exactly as might be expected, as the components for the surface plant capital cost and annual plant O&M (which is a percentage of the capital cost) both increase smoothly. The only non-linearity in the progression is solely due to the fact that the base case value of 4200 USD/kW_e (3820 CHF/kW_e) has been inserted into the normal interval from 4000 to 4500 USD/kW_e (3640 to 4090 CHF/kW_e).

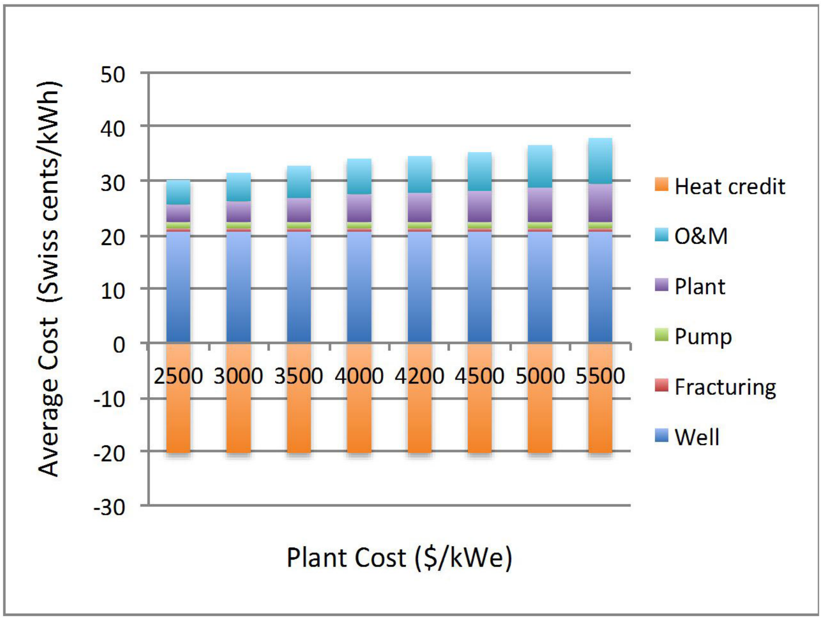

Figure 80: *Component generation costs v. plant cost.*

Interest rate – **Figure 81** below shows the sensitivity of the average costs to the interest rate that is applied to the LCOE analysis within the geothermal model. As described the LCOE methodology brings all construction costs forward to t = 0 (and all operating costs back to t = 0), before amortizing the present value at t = 0 forward over the plant life. The effect of the interest rate on the individual components of the total average cost therefore depends on how these cost components are distributed over time. The one-time capital costs (i.e. the surface plant costs) increase smoothly with the interest rate, the annual costs (the O&M costs and the heat credit) are amortized backwards and forwards by equally for all interest rates, so they show as constant over the range of interest rates, and finally the more irregularly recurring costs (well and pump costs) are effected in an intermediate way depending upon their exact timing.

Quantitatively, the most interesting observations are the constancy of the heat credit at 20 Swiss cents/kWh, and the increase in the total of the other costs from 29 to 46 Swiss cents/kWh_e.

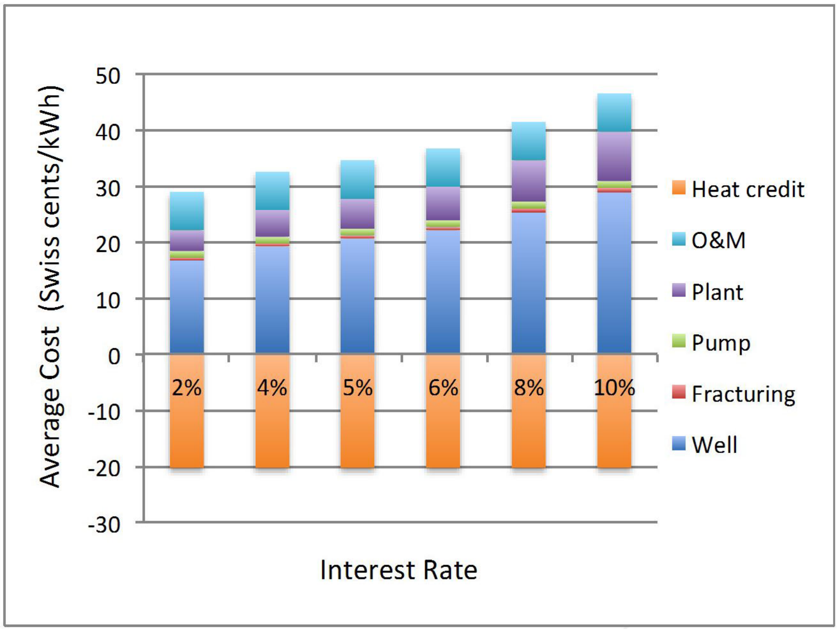

Figure 81: *Component generation costs v. interest rate.*

Relative scale of single factor sensitivities – **Figure 82** below shows the total average costs (including the heat credit) for all the individual sensitivity cases plotted together, varying from about 25% to 200% of their base values. The base value for each factor can be seen in the graph legend to the right.

We see that, based on the steepness near the base values, the geothermal gradient, well depth, well diameter, and reservoir impedance have the greatest effect, followed by well cost and interest rate. The factors of fluid flow and well life can produce steep sensitivities at their more extreme values, while plant life and plant cost have the lowest effects.

Also interesting is the fact that while most of the factors have monotonic effects, the cost factors of well depth and fluid flow have minima at or near their base values, and the generation cost increases in either direction from these base values.

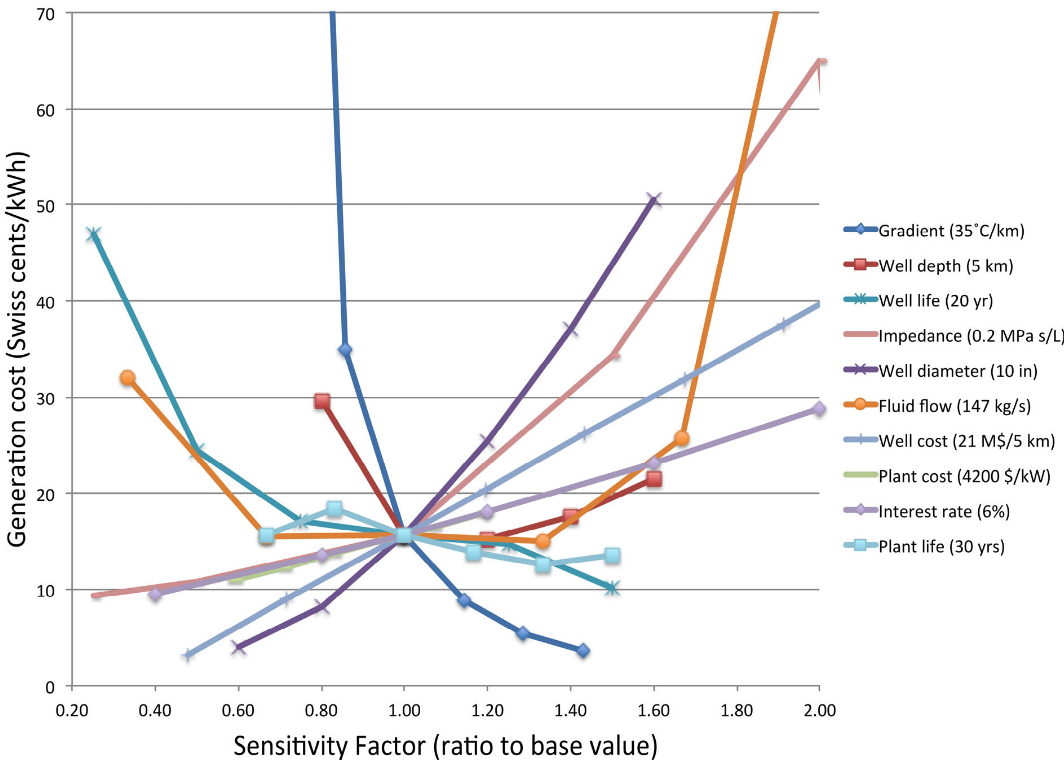

Figure 82: *Sensitivity of geothermal average generation costs to model factors.*

Cost supply curves – Based on the cost model developed, it is now possible to construct geothermal cost supply curves for the three Swiss reference cases described above, with and without the heat credit assumed. As can be seen in **Figure 83**, the amount of cumulative generation increases rapidly below a generation cost of about 100 Swiss cents/kWh$_e$, and flattens out above this. In all six cases, the maximum amount of generation available is about 800 TWh$_e$, based upon the Geowatt survey of potential heat shown in **Table 12** above for the region reaching approximately from Zurich to Geneva. The cumulative generation is therefore much more conservative than if the simpler but larger resource base given in **Table 11**. The amount of potential electricity has also been reduced by omitting very uneconomic cases where net generation was, and hence average cost, was negative, as explained in the sensitivity analyses above.

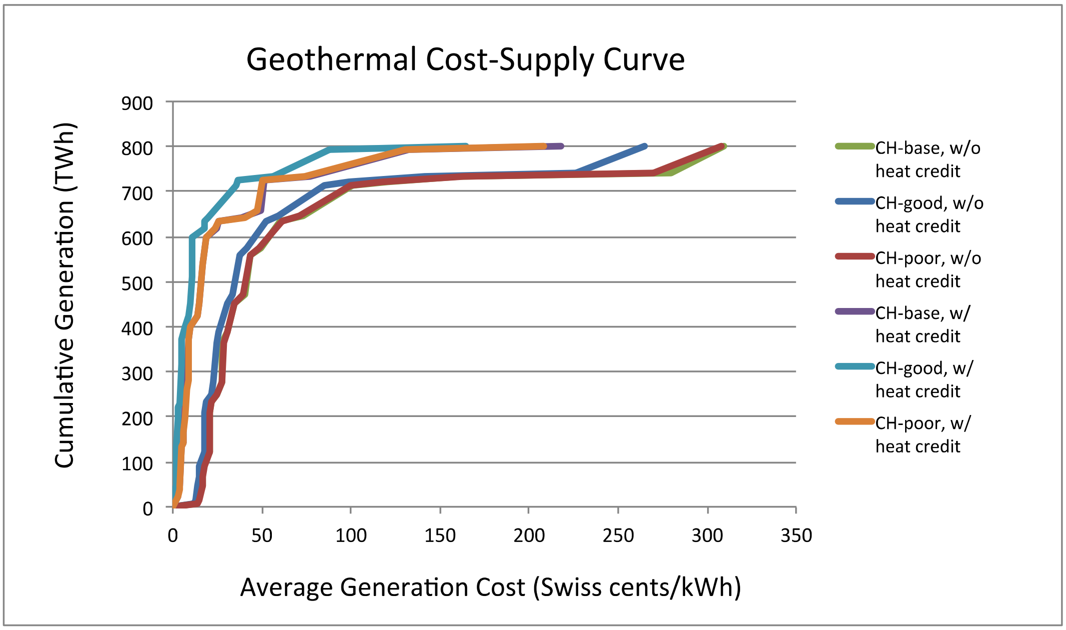

Figure 83: *Cost supply curves for 3 Swiss reference cases (with and without heat credit).*

It is more interesting to concentrate on the leftmost part of the figure, so this has been done in **Figure 84** below by reducing the horizontal scale to a maximum of 150 Swiss cents/kWh$_e$.

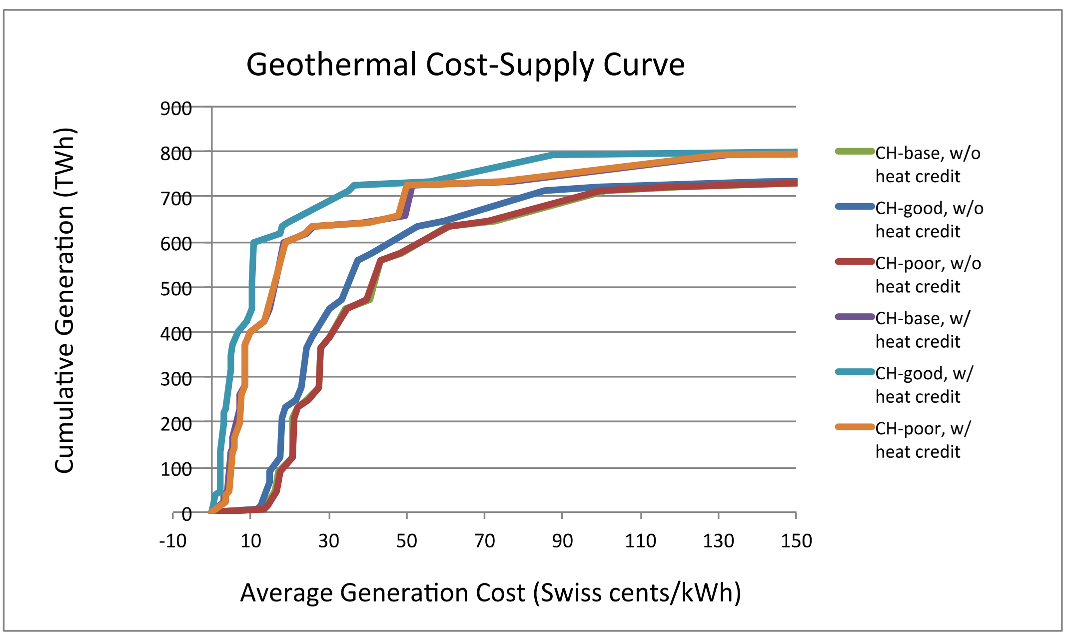

Figure 84: *Cost supply curves for 3 Swiss reference cases (expanded scale).*

Here we can see that the CH-good case with the heat credit is best (farthest to the left) as expected. It is, followed by the CH-base and CH-poor cases with the heat credit, which lie parallel or overlapping. This is because the main cost differences between these two cases are in their well depths and gradients, and the supply curve sums across a range of both these variables to find the total available generation at different costs. The cases without the heat credit follow to the right, with the CH-good case again followed by the parallel CH-base and CH-poor cases.

These geothermal generation cost supply curves must be viewed and used with some cautions. The results of the cost model for each curve are created using only the depth and gradient information associated with the amounts of heat contained in the Geowatt survey. The other results of this chapter show that many other factors have large impacts on average cost, including reservoir size, impedance and life that depend in turn upon geological properties like stress and permeability that can only be based on drilling. These cost curve results must therefore be viewed as a first, and rather basic attempt to create Swiss geothermal cost curves that should be improved as resource distribution data become available that includes more factors that are relevant to a more accurate assessment of geothermal costs.

4.7 Conclusions

Based on the economic geothermal modeling work that has been performed, we can draw the following conclusions.

- The geothermal economy model that has been developed and adapted to Swiss case conditions, including integration with the linked LCA model, has proven very useful in understanding the relative contributions of the various components to the overall average cost, and also the relative impacts of the many factors that influence these costs.
- The changes that have been made over the course of the project have improved the model significantly for modelling Swiss conditions, included implementation of the heat credit, a reduction in drilling costs and an increase in well life based on industry inputs, the use of lineshaft pumps above a minimum depth, and an increase in the range of reservoir impedances analyzed.
- Although the cost of electricity from geothermal energy is currently high, it could be possible for geothermal generation to make a significant contribution to the future Swiss energy mix if quite significant cost reductions can be achieved by research and development, standardisation and simplification. The geothermal cost model developed can evaluate the effect of improved cost factors on the final average cost, but this report does not forecast if or when such improvements may actually take place. There are still significant data uncertainties for many important cost factors. So the results are more conclusive regarding the relative scale of the various cost contributions and sensitivities than they are for the absolute results.
- Well cost still dominate, but less than they did before due to the reduction in assumed Swiss drilling costs based on industry models calibrated to the experience in St. Gallen.

- Life cycle well costs include not only drilling costs, but also the number of wells and the well (or reservoir life). There are three major ways to decrease well costs, i.e. fewer wells, lower drilling costs and longer reservoir life, with the last two regarded as having the most potential for long term improvement.
- The lower cost of reservoir development compared to well drilling, and their relative benefits on average generation cost suggest that there is significant economic leverage and incentive for effective fracturing to increase reservoir life and reduce impedance. Improvements in drilling may reduce overall costs more, but more effective reservoir creation is likely to have a greater payback.
- The heat credit also has a large economic leverage based on the relative shares of the electricity and heat produced, so there is a significant incentive to find heat customers, particularly for initial geothermal plants where costs have not yet decreased due to improved technology and learning.
- The economic benefit of heat sales can lead to a tension between the need for proximity to heat customers, and the proximity to a population that may be sensitive to induced seismicity.
- The whole chain of losses and efficiencies (reservoir impedance, pumping load, generation efficiency, etc.) can be quite important, as average cost is not only sensitive to the numerator of total cost, but also sensitive to the denominator of net generation.
- Site-related model parameters are more important than design choices, in the sense that it is likely harder to find the right location with good gradient and reservoir potential than it to choose the best depth, flow rate, etc. for that site.
- The generation cost curves are interesting and illustrative results, but limited in their conclusiveness, as it has been shown that the gradient and depth are important, but these are only two of the factors that influence average cost. There is significant potential to improve the generation cost curves when additional and more detailed geologic data becomes available.
- It is already possible and interesting to envision a GIS database that would include improved resource data, environmental standards, local regulation and related costs, the availability of local heat demand, etc., which would make it possible to calculate a map of average generation cost that would show the best locations to drill for geothermal projects.

4.8 References

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5 WP4: Environment

Karin Treyer, Hiroki Oshikawa, Christian Bauer, Marco Miotti (PSI)

This work package evaluates the environmental burdens and potential impacts as a consequence of "normal operation" of geothermal systems for electricity (and heat) generation by means of Life Cycle Assessment (LCA). With this methodology, the environmental burdens per unit of electricity (and heat) generated under various conditions in Switzerland can be quantified over the complete life cycle of deep geothermal systems. Environmental impacts from power from future deep geothermal plants in Switzerland are then compared with other energy technologies used in Switzerland today and probably in the future in Chapter 9.

5.1 Methodology: Life Cycle Assessment (LCA)

LCA is a standardized methodology and allows for a comprehensive and comparative assessment of the environmental burdens and potential impacts of products and services (ISO, 2006a; b). Therefore, it is the methodology to be used when comparing the environmental performance (strengths and weaknesses) of different energy technologies, among them geothermal systems.

The idea behind a life cycle perspective in the context of power generation is that the environmental impacts of electricity are not only due to the power production process itself, but also originate from the production chains of installed components, materials used, energy carriers, and necessary services. Through an LCA analysis, a product is investigated throughout the entire life cycle ("cradle-to-grave"). In the context of geothermal power generation, construction, operation and end-of-life of a geothermal power plant with its different subsystems need to be included (**Figure 85**). On the one hand, geothermal power plants do not consume any fuel and show no direct emissions during the operation period. But, on the other hand, the construction of geothermal power plants requires large amounts of energy and material. Hence, the question is if such plants are also environmentally promising from a cradle-to-grave point of view. By using the LCA methodology, a comprehensive set of potential environmental impacts (i.e. impacts on human health and ecosystem quality as well as resource consumption) derived from the whole life cycle of geothermal power plants can be analyzed. The range of environmental burdens includes emissions to air, soil and water, land use, and consumption of energy and non-energy resources.

According to the international LCA standards ISO 14040/44 (ISO, 2006a; b), an LCA is carried out in four steps: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact analysis, 4) Interpretation.

5.1.1 Goal and scope

Goal and scope of the LCA within this project is the quantification of environmental burdens during the complete life cycle of deep geothermal systems per unit of electricity (and heat) generated under various conditions in Switzerland. In Switzerland, geological research suggests the possibility of exploiting medium-temperature (90−180 °C) geothermal resources by drilling deep wells (3000–6000 m). Among all types of geothermal systems, the focus is on both deep hydrothermal and petrothermal (Enhanced Geothermal Systems, or EGS) geothermal energy systems, primarily for electricity production. **Figure 85** shows the **system boundaries** of the system under research. The system can also be imagined as divided into the surface system with the power generating unit and the subsurface system with the wells, the stimulation process, and the downhole pump.

The **functional unit** of the LCA carried out is the production of 1 kWh net electricity with a deep geothermal power plant (petrothermal or hydrothermal), with parameters adapted to Swiss specific conditions.

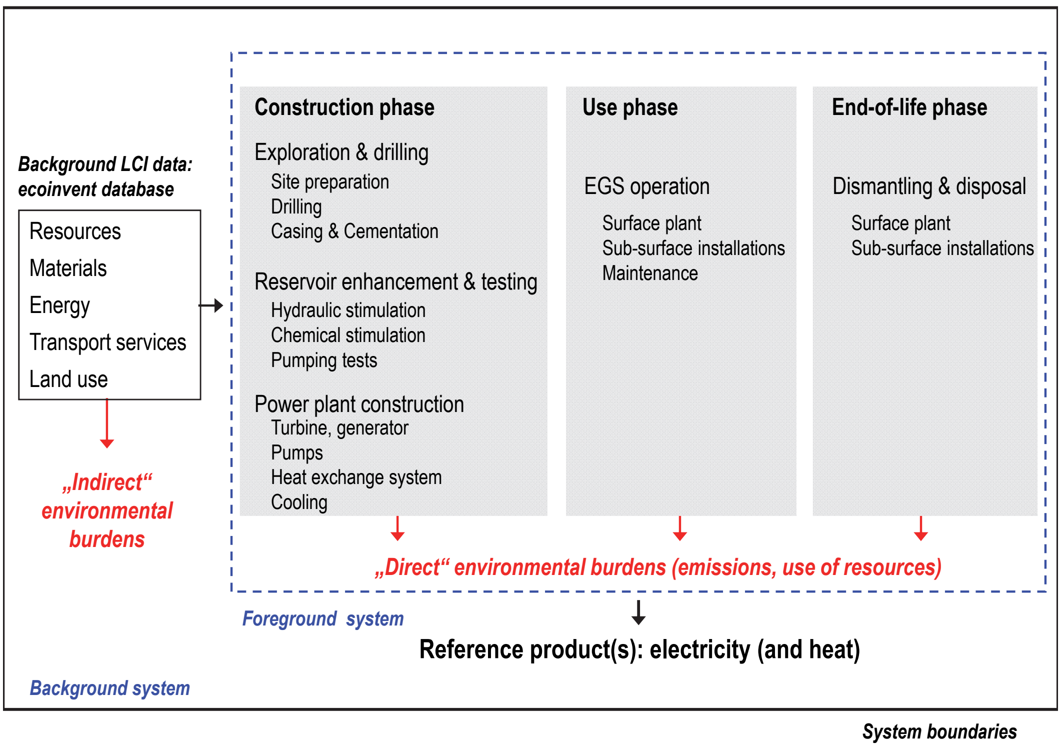

Figure 85: *System boundaries for the LCA of deep geothermal power generation.*

5.1.2 Inventory analysis

The **inventory analysis** accounts for all energy and material inputs, land transformation and occupation, emissions of substances to air, water and soil as well as extraction of energy and non-energy resources in the processes of the foreground system. Background data are taken from the worldwide leading LCI database "ecoinvent" (ecoinvent, 2013); the complete set of life-cycle-inventory (LCI) data is compiled according to the data format and quality guidelines of ecoinvent. This procedure and the possible subsequent submission of the new LCI data will allow for a) consistency with the latest data format and quality guidelines for LCI data, and b) external peer-review of the data.

5.1.3 Burdens and impacts

Burdens and impacts related to human health as well as to ecosystem and resource quality that are directly or indirectly caused during the construction, use and end-of-life phase of geothermal systems are quantified. For this, SimaPro 7.3.3 with ecoinvent version 2.2 is used. In order to ensure comparability with existing datasets and studies for electricity production in Switzerland, the calculations have not been made with the most recent version 3.0 of ecoinvent. The Life Cycle Impact Assessment (LCIA) method chosen is ReCiPe (H) (Goedkoop *et al.*, 2009).

5.1.4 LCA results

The **LCA results** of geothermal power generation are used for a comparative evaluation of the environmental performance of geothermal systems against alternative power and heat generation technologies in Switzerland. The alternatives (renewables, fossil, nuclear) are based on previous work of the Technology Assessment group at PSI (Bauer *et al.*, 2008; Roth *et al.*, 2009; Schenler *et al.*, 2009).

5.2 Literature review: Life Cycle Assessment of deep geothermal energy

Currently, a number of deep geothermal systems are operated all over the world – mainly hydrothermal plants. The environmental performances of deep hydrothermal and petrothermal (EGS) geothermal energy systems have been evaluated by only a few LCA studies. **Table 14** compares some features and impacts according to the LCA studies of geothermal system presented in the following sections.

Bauer *et al.* (2008)

For the modelling of a deep geothermal system in Switzerland, LCI data were compiled based on the planned Hot-Dry-Rock plant in Basel, Switzerland (Haering, 2003), a doctoral thesis (Rogge, 2004), and (Bauer, 2007; Jungbluth, 2007). The data were implemented into ecoinvent version 3.

Argonne National Laboratory (USA)

The Argonne National Laboratory in the USA published four reports on life cycle assessment of geothermal plants (Clark *et al.*, 2011a; Clark *et al.*, 2011c; Sullivan *et al.*, 2010; 2011).

(Sullivan *et al.*, 2010; 2011) present a process-based life cycle energy and greenhouse gas emissions analysis. They model plants according to four scenarios in the south-western United States: Two EGS scenarios referring to the work previously performed by MIT in 2006 (Tester *et al.*, 2006), and two hydrothermal scenarios referring to data from the "Raft River" site in Idaho. The "GREET" (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) LCA model was used as the basis for the analysis (Argonne, 2013a; b). A comparative evaluation was carried out between geothermal and other existing power generation systems.

The report by Clark *et al*. (2011b) presents a comprehensive and comparative life-cycle based analysis of water consumption for large-scale geothermal power plant systems. Four reference plants are modelled using different scenarios, equivalent to those defined by (Sullivan *et al.*, 2010; 2011). This report summarizes not only the water quantity required in geothermal systems, but also aspects of water quality derived from the whole life cycle of the geothermal system. Total water requirements (gallon/kWh) of the whole life cycle are compared for four scenarios for geothermal plants, conventional combustion energy systems, and renewable energy systems. For all processes from construction to the end of the operation of geothermal system, the operational make-up water requirement was found to consume the largest quantity of water. In addition, the authors present a statistical analysis of geo-fluid compositions. To determine the water quality of typical geo-fluids in the USA, over 3100 data points from all over the USA are used for this analysis. Based on this statistical analysis, the water pollution potential and the risk of scale formation and corrosion are discussed.

Frick *et al.* (2010)

Frick *et al*. (2010) made a comprehensive LCA of geothermal power production from EGS with a focus on the geological conditions in Germany. Data are based on internal research in the Helmholtz centre Potsdam, data from the drilling company "Mi-SWACO", and data from the Umweltbundesamt (UBA). The environmental impacts are calculated for several scenarios. Further, sensitivities of different parameters were calculated, along with a contribution analysis. In conclusion, the authors identified four key parameters to keep environmental impacts low, which are: (a) material and energy inputs for the drilling process, (b) reservoir productivity, (c) auxiliary power for cooling, and (d) the amount of district heating demand.

Gerber and Maréchal (2012)

Gerber and Maréchal (2012) developed a multi-objective optimization approach based on economic, environmental and thermodynamic criteria focusing on the geological conditions in Switzerland. The inventory data of Frick *et al*. (2010) and the ecoinvent v2 database were used as the main inputs to the environmental part. The computational model identifies the optimal EGS design based on well depth, heat to power conversion technology, and district heating demand. The results show that all the optimal economic configurations also have a beneficial environmental balance. In conclusion, the authors specify the optimal geothermal design in Switzerland: EGS with 5500−6000 m well, Kalina conversion system, and with 20−35 MW district heating capacity.

Lacirignola and Blanc (2013)

Lacirignola and Blanc (2013) expanded the LCA of Frick *et al.* (2010) with different scenarios, in order to reflect realistic design alternatives based on lessons learned from current EGS test installations. The study reflects geological conditions in central Europe. The inventory data (LCI) are mainly based on a technical survey of the pilot EGS plant in Soultz-sous-Forêts (France) and on ecoinvent v2 data. Ten scenarios are described by combinations of the number of wells, well depth, geothermal fluid temperature, production flow rate, and seismicity risk. The results of the LCIA are shown for five impact categories: Human health, ecosystem quality, climate change, resources, and seismicity risk. Seismicity risk was analyzed qualitatively.

Bayer *et al.* (2013)

Bayer *et al.* (2013) have made a review of existing literature on environmental impacts of geothermal power. They find that "only few studies provide quantitative estimates of both direct and indirect environmental consequences".

Table 14: *Literature review on existing life cycle assessments of electricity production with deep geothermal power plants. In general, the studies model EGS or HT plants as they could be built today or in near future. EGS = Enhanced geothermal system; HT = Hydrothermal; CH = Switzerland, US = United States, DE = Germany.*

Reference	Region	Geothermal type	Impact Indicator	Impacts per kWh	General remarks
Pehnt (2006)		Hot Dry Rock	a) Global warming b) Acidification c) Eutrophication	a) 41 g CO_2eq b) 190 mg SO_2eq c) 24.8 mg PO_4^{3-}	Comparison of future (2010) power systems and heating systems for selected renewable sources. The LCI is based on various sources. The LCI and the properties of the geothermal plant are not described in detail.
Bauer *et al.* (2008)	CH	EGS	Eco-indicator 99 (H,A) with ten impact categories	Amongst other impact categories: Greenhouse gas emissions 27 g CO_2eq	Evolutionary technology development was assumed between 2000 and 2030 for a selected set of power technologies, including a deep geothermal power plant with a capacity of 3 MW of electric power.
Clark *et al.* (2011a); Clark *et al.* (2011b)	US	HT, flash system and binary system; EGS	Water use	Ca. 1.9 l	Quantification of the water use for construction and operation of deep geothermal power plants with capacities of 20 MW and 50 MW. Air cooling is assumed. The appendix of 2011a presents a detailed inventory of water consumption for each life cycle stage.
Sullivan *et al.* (2010; 2011)	US	EGS, HT	Energy consumption and GHG per kWh output	Energy use: ca. 0.2 kWh_{in}/kWh_{out} Greenhouse gas emissions: Ca. 20 g CO_2eq	LCA of deep geothermal systems in comparison with other power production technologies. The reports provide details of the modelled plants and material use for the different plant parts. The modelled plants have capacities of 20 MW and 50 MW for EGS, and 10 MW and 50 MW for HT plants.
Frick *et al.* (2010)	DE	EGS	a) Greenhouse gas emissions b) Acidification potential c) Cumulated energy demand d) Eutrophication	a) Ca. 50–60 g CO_2eq b) Ca. 400 mg SO_2eq c) Ca. 600–750 kJ d) Ca. 50–60 mg PO_4^{3-}	Study providing detailed parameter data for 12 case study plants with capacities between 0.46 and 11.1 MW. The base case for which the results are noted here has an installed power capacity of 1.75 MW.
Gerber and Maréchal (2012)	CH	EGS	Global warming potential 100a, Ecoindicator 99	No data for impacts per kWh produced, but only for the functional unit “EGS construction, operation and dismantling”.	This study seeks the optimal configuration of future EGS systems in Switzerland in terms of environmental impacts and economy.

Reference	Region	Geothermal type	Impact Indicator	Impacts per kWh	General remarks
Lacirignola and Blanc (2013)	Central Europe	EGS	a) Greenhouse gas emissions b) Acidification potential c) Cumulated energy demand d) Eutrophication	a) Ca. 17–58 g CO_2eq b) Ca.300–600 mg SO_2eq c) Ca. 800–900 kJ d) Ca. 40–80 mg PO_4^{3-}	Data for 10 case study plants with capacities between 0.8 and 3 MW, based on data from Soultz-Sous-Forêts and compared with (Frick *et al.*, 2010).
Bayer *et al.* (2013)			Qualitative discussion of topics like land use, geological hazards, waste heat, atmospheric emissions, or water consumption	For a case of a binary plant, 10MW, capacity factor >90%, 5 wells, closed circles, air cooling, heat use, little land use, the authors assume that "Life cycle GHG emission will be in the range of a few tens of CO_2 equivalents per kWh."	Review of life cycle environmental effects of high-enthalpy geothermal power plants and construction of a literature-based life cycle inventory.

5.3 Modelling of petrothermal and hydrothermal plants in this LCA chapter

Hydrothermal plants take their hot fluid from a geologic layer with a natural presence of (hot) water. Petrothermal plants are built in hot granite rock by stimulating fracturing between two or more wells. But even within these two categories, a variety of well and plant designs and geological conditions can be imagined. In general, differences between petrothermal and hydrothermal plants lie in the stimulation phase and the number and depth of wells (see Sullivan *et al.*, 2010). Hydrothermal plants stimulate – if at all – with small amounts of acid, whereas petrothermal plants depend on the fracturing of the underground rock with significant amounts of water using high pressure pumping equipment (and hence expend non-negligible energy). Additionally, wells for hydrothermal plants tend to be shallower than wells for petrothermal plants and therefore require less drilling energy and casing material. Normally, a well doublet is used for hydrothermal power, whereas petrothermal plants for electricity production are often designed as a triplet.

Different plants designs and geological conditions − mainly the number and depth of wells and the lifetime achieved by the wells − have a higher influence on environmental impacts than the differences between petrothermal and hydrothermal per se. It is therefore not possible to determine "the" typical hydrothermal plant case and "the" typical petrothermal plant case. As a result, it was decided not to explicitly model the results for both of these types, but rather for a specific set of the key parameters. Sensitivity analyses will show the influence of these on the environmental performance.

5.4 Coupling of the cost model with the life cycle analysis

Work package 3 on costs in this research project is based on a physical model that uses extensive physical parameters to define the geothermal power plant. This physical model was coupled to the present life cycle assessment, so that the results of the cost model are comparable with the LCA model and enable a consistent environmental/economic evaluation. Please see Section 4.3 and Section 4.4 for a detailed description of this model and the reasoning for the sets of parameters chosen that are important for the cost model. **Figure 86** presents the resulting structure with key aspects of each model. The model is based on plant design choices and key geological parameters depending on the choice of the plant location. The plant design can be chosen, while the key geological parameters are rather inherent properties found according to the geological conditions. Further, uncertainties such as the reservoir lifetime influence the outcomes of the model. The production flow rate is an important parameter that must be balanced over the lifetime of a geothermal power plant in order to ensure sustainable use of the underground heat and a long production life.

The key parameters listed in the box "plant model" have been subjected to a sensitivity analysis for both the cost (WP 3, Chapter 4) and the environmental assessment (Section 5.6.3).

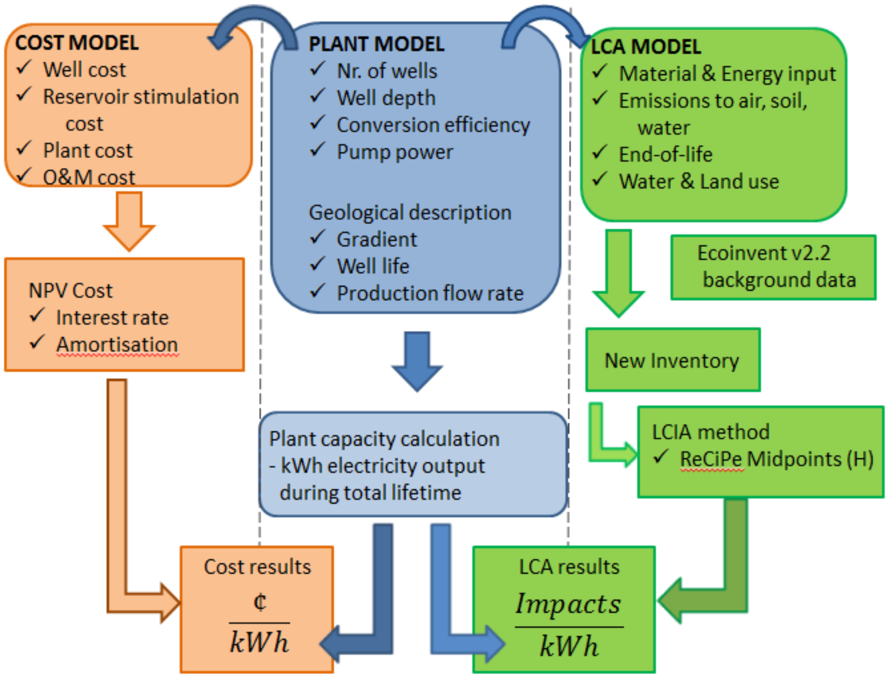

Figure 86: *Coupling of the physical model with the cost and the LCA model.*

Table 15: *Key physical parameters of the base cases for deep geothermal plants.*

	Medium capacity (Base case)	**High capacity**	**Low capacity**
Net plant power	5.5 MW_e	14.6 MW_e	2.9 MW_e
Downwell pump power (for 2 pumps)	3.4 MW_e	2.7 MW_e	3.5 MW_e
Geothermal gradient	35 °C/km	40 °C/km	30 °C/km
Well depth	5 km	6 km	5 km
Number of wells	6 (2 well triplets during total lifetime)	3 (1 well triplet during total lifetime)	3 (1 well triplet during total lifetime)
Surface plant life time	30 a	30 a	20 a
Well (reservoir) life time	20 a	30 a	20 a
Pipe inside diameter	10 inches (25.4 cm)	10 inches (25.4 cm)	10 inches (25.4 cm)
Production flow rate	147 l/s (2*73.5)	147 l/s (2*73.5)	147 l/s (2*73.5)
Electrical efficiency	14%	17%	13%
Rig power source	Electricity		
Rock stimulation	Yes	Yes	Yes
Surface system	organic Rankine cycle (ORC) with benzene as working fluid		
Cooling system	Air cooling		
Heat and power cogeneration	No		

Reasoning for the choices of well depth, geothermal gradient, well life, reservoir impedance and reinjection temperature can be found in Section 4.4.

The **plant net capacity** shows the capacity of the plant after subtraction of all auxiliary energy needs for pumping, cooling, circulation of the working fluid and similar. One of the major internal energy uses is to pump the brine fluid in order to avoid boiling in the well. Whereas this downwell pump capacity is explicitly calculated in the physical plant model, the remaining auxiliary energy use is accounted for implicitly in the physical model and cannot be quantified in this study. It would be interesting in a future project to separate this energy use for i.e. cooling and working fluid pumping.

A **well triplet design** was chosen to ensure a flow rate high enough to give a plant generation capacity that was reasonably high for electricity production.

The **lifetime** of a well is primarily determined by the geological conditions and by the amount of heat extracted over time. The base case assumes that after ca. 15 to 20 years, a new well set (triplet must be drilled for a total lifetime of 30 years for the plant. In reality, the productivity and quality of the well will determine whether a new well set will be drilled at the same place, and if the plant's lifetime will be extended over 30 years by gradual refurbishment of parts of the power plant.

The **well's production diameter** is in general larger than for oil or natural gas wells. For plants in Switzerland, diameters between approximately 6 to 10 inches are being discussed; 10 inches was chosen for the present modelling.

The **production flow rate** is a crucial factor for the well lifetime and must be carefully chosen during operation. According to (Meier and Zingg, 2013; Sonderegger, 2013; Thumann, 2013), a minimal lifetime of 30 years should be achieved for cost-effectiveness. It must be considered that the productivity of the geothermal reservoir might decrease over time, which is not modelled in the present study. Sanyal (2005) defines the sustainable capacity of a geothermal reservoir as the capacity that can be economically maintained over the life of a power plant. For sustainability, geothermal resource degradation (pressure drop down/ reservoir cooling) must be compensated by taking practical steps. Research has shown that by keeping energy extraction below a certain limit, shallow hydrothermal reservoirs can be productive over long periods of time (around 100 years) (Axelsson *et al.*, 2005; Bromley *et al.*, 2006). Fox *et al.* (2013) conducted numerical analysis to estimate how renewable EGS reservoirs might be. They use a simple model using rectangulars to evaluate heat transfer during alternating periods of extraction and recovery. The values given here are for a well triplet with two production wells.

Expression of the **efficiency** of a geothermal power plant is subject to discussions, as it cannot be determined in the same straight forward way as for i.e. fossil fuel plants. Different publications suggest either the first or the second Law of thermodynamics, i.e. (DiPippo, 2004; Qureshi and Zubair, 2007). The physical model used here shows both the first and the second law efficiency. The efficiency presented in the table is the ratio between the gross thermal output of the plant (determined by the production and injection temperatures, the fluid flow and fluid's heat capacity) and the actual gross electricity generation, based on the mass flow and the specific exergy of the fluid.

Rock stimulation is assumed in all three cases. This phase does not completely correspond to hydrothermal plants. See Section 5.6.1 for comments.

The **surface plant** is modelled with an organic Rankine cycle using benzene as the working fluid (see Section 5.5.3). Air cooling is assumed. In the base case, no use of the excess heat is modelled (see Section 5.6.2).

5.5 Life cycle inventories

This section shows the LCI established for this project. The LCI work is based on the datasets on geothermal power in ecoinvent provided by (Treyer and Bauer, 2012), literature data, information from plant operators or planners, and the physical model. **Figure 87** shows the modules (unit processes) of the LCI for this project.

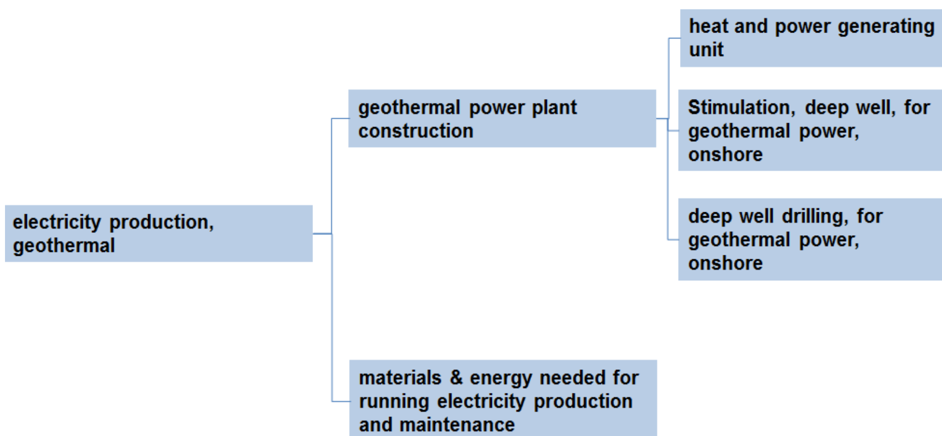

Figure 87: *Modules (datasets) of the life cycle inventory made for the modeling of the geothermal system as defined by Figure 85.*

No module for prospecting activities such as comprehensive measurements of seismic activity in a specific region and related transport or material use is considered, as these impacts would be minor when calculated for the production of 1 kWh of electricity.

The following subsections present the life cycle inventory and underlying sources, estimations and calculations with the following structure:

a) Short introduction to the module.

b) Included and excluded issues related to the module, i.e. discussion of completeness and shortcomings of the inventory.

c) Table showing the inventory with ecoinvent unit process names, figures valid for the base case (medium capacity), short comments and main sources.

d) Detailed description of the inventory.

5.5.1 Deep well drilling

Previous LCA studies (see Section 5.2) show that the drilling of the deep wells is the most important process in the life cycle of a geothermal power plant in terms of material and energy use and corresponding impacts. For details on the drilling process see work package 2, Section 3.3 "Drilling and completion." Geothermal drilling profits from the experience gained in onshore oil and natural gas drilling, but not all facts can be carried over for the case of deep geothermal power, especially not for drilling for petrothermal plants, as these take place in hard rock (granite) and operate with larger boreholes.

This inventory includes the following elements:

- **Drilling energy use**. In Switzerland, the energy source is electricity from the grid. Diesel is only used as a stand-by and for activities on or related to the drill site.
- Material and energy use for the **casing** (steel, cement) of the borehole. Losses of cement during the cementation phase are accounted for.
- **Drilling fluid** composition and treatment
- **Drilling cuttings** transport and treatment
- **Transport** of the drilling infrastructure, casing material, and drilling fluid ingredients
- **End-of-Life** of the borehole, i.e. **abandoning** with cement bridges
- Extra drilling for **exploratory** wells

The inventory does not include the following elements:

- Energy use for **pumping tests,** which can be considered as negligible compared to the energy use for drilling
- **Possible emissions of natural gas** from the ground during the drilling. In practice, natural gas will not be vented to the atmosphere but – as is operational practice – diverted to a flare stack and for the most part burned with CO_2 as a product. Geothermal drilling is done in rock that is assumed to not be host to much natural gas. However, as the events in St. Gallen have shown, unforeseen reservoirs can be opened during drilling. In spite of this, with current knowledge it is not assumed that this will be the regular case so that an LCA referring to "normal operation" should consider it. If future work shows that regular natural gas emissions occur while drilling deep wells for geothermal power in Switzerland, then estimates of CO_2 as a flare product should be included. Such estimates are available for natural gas and oil exploration drilling, where rock formations are chosen with a high likelihood of natural gas presence – which is not considered to be comparable to locations chosen in Switzerland for deep geothermal power.
- **Possible radioactivity of drill cuttings** and the corresponding necessary treatment of such cuttings. Naturally occurring radioactive materials (NORMs) may be expected and must be treated in line with regulatory requirements. Please consult the chapter on work package 5 "Risks" for a discussion of possible radioactivity related to deep geothermal power. According to Sonderegger (2013), the drill cuttings in St. Gallen have been measured regularly for radioactivity. The same type of monitoring will be implemented in future projects according to Meier and Zingg (2013) and is considered standard practice.

- Possible radioactive emissions. Based on currently available literature probable, emissions of Radon are very low (GtV 2013) − but no measurements for deep geothermal power plants are available.
- Possible special **additives to the cement of class G** used for the casing of geothermal wells, as no such data were available.
- **Extra drilling** needed to account for unsuccessful wells. Future experience will tell what percentage of wells will result to successfully run plants; the topic is dealt with in Section 5.6.3.
- **Extra amounts of drilling fluid** due to "lost circulation" (losses of large amounts of drilling fluid through fractures in the rock), as no estimates were available.

Table 16: *Inventory for the process "deep well drilling, for deep geothermal power". All amounts refer to the reference flow "deep well, drilled, 1 meter". As the discussion in Section 5.5.1.2 shows, some parameters are not generally valid for 1 meter of drilling, but change with changing depth of the well. This inventory reflects the conditions for a 5000 m well.*

Category	Ecoinvent unit process name	Unit	Amount	Comment	Source(s)
Reference product	Deep well, drilled, for geothermal power	m	1		
Energy consump-tion	Diesel, burned in diesel-electric generating set/GLO	MJ	111	Rather pessimistic assumption of diesel use for - different applications at the drilling site (i.e. staplers), based on St. Gallen - backup in case of electrical power outage, based on Basel.	Haering (2003); Sonderegger (2013)
	Electricity, medium voltage, at grid/CH	kWh	3932	Electricity use for the drilling process (including tripping time), calculated as a function of well depth, well volume and installed machine capacity.	Haering (2003); Legarth and Saadat (2005); Sonderegger (2013)
Casing	Portland cement, strength class Z 52.5, at plant/CH	kg	213	Cement use calculated for a given well design with an inner pipe diameter of 10 inches (0.254 m). A loss factor of 1.5 is assumed. No dataset for class G cement exists in ecoinvent, so that this dataset is taken as a proxy. No data for special additives were available.	

Category	Ecoinvent unit process name	Unit	Amount	Comment	Source(s)
	Reinforcing steel, at plant/RER U	kg	309	Steel use calculated for a given well design with an inner pipe diameter of 10 inches (0.254 m).	
	Transport, lorry 20–28t, fleet average/CH U	tkm	20	Transport of casing material (steel and cement). Default transport distances are taken from Frischknecht *et al.* (2002)	Frischknecht *et al.* (2002)
	Transport, freight, rail/CH U	tkm	207		
Infra-structure	Steel, low-alloyed, at plant/RER U	kg	0.5	Estimation for the material use of the drilling bit. The chosen material in the ecoinvent database could also be brass.	
	Transport, lorry 16–32t, EURO4/RER U	tkm	213	Transport of drilling infrastructure. Drilling infrastructure for Swiss drillings most probably comes from North Germany. Assumption of 100 basic transports before the start of the drilling and 5 transports per week during the drilling phase.	Sonderegger (2013), estimation
	Transformation, from agriculture	m^2	0.6	A drill site area of 18’000m^2 is assumed, including the actual drilling rig area, storage area, etc.	Information from different drillings.
	Transformation, to industrial area	m^2	0.6	See above	
	Occupation, industrial area	m^2a	7.5E-5	It is assumed that the actual drilling time amounts to 6 months for 5000 m, and that the preparation and closing time of the drill site amounts to 4 months.	Estimations.
Drilling fluid	Water, well, in ground	m^3	0.5	The amount for the use of water per m is a rather rough estimation.	
	Bentonite, at processing/DE U	kg	20	Amounts for the drilling fluid components are rough estimations.	Kaiser and Fäs (2004); Sonderegger (2013) estimations.

	Potassium carbonate, at plant/GLO U	**kg**	**15**		
	Cellulose fibre, inclusive blowing in, at plant/CH U	kg	18		
	Barite, at plant/RER U	kg	20		
	Sodium hydroxide, 50% in H_2O, production mix, at plant/RER U	kg	1		
	Chemicals organic, at plant/GLO U	kg	20		
	Transport, lorry 20–28t, fleet average/CH U	tkm	5	Transport of drilling fluid ingredients). Default transport distances are taken from Frischknecht *et al.* (2002).	Frischknecht *et al.* (2002)
	Transport, freight, rail/CH U	tkm	56		
	Treatment, sewage, to wastewater treatment, class 3/CH U	m3	0.6	It is assumed that the total volume of water used for the drilling fluid is treated, in addition to an estimated 0.1 m^3 of meteoric water.	
Drilling cuttings	Disposal, drilling waste, 71.5% water, to residual material landfill/CH U	kg	466	Calculated from the volume of the borehole.	
	Transport, freight, lorry 3.5–7.5 metric tons, EURO 5	tkm	23	The cuttings are assumed to be transported over 50 km to disposal.	Assumption

5.5.1.1 Infrastructure

Infrastructure on the drill site includes the following items:

- Drilling rig: mast, drawworks, rig power system, mud pumps with noise protection, top drive, blowout equipment, mud tank system, solids control equipment
- Silos
- Reservoirs for the hot water from pumping tests
- Containers for the workers
- Transformer station

The material use for the mentioned infrastructure is neglected in the present inventory. Solid parts such as the drill rig components are usable for the drilling of many kilometers, so that the material use per kWh electricity produced would not influence the LCA results.

The LCI therefore only accounts for land use and for transportation of the drilling rig components. The infrastructure for the drilling rig is provided by companies specializing in oil drilling. Such companies likely to drill in Switzerland are often located in northern Germany. In this inventory, 100 basic transports over a distance of 800 km are assumed, plus additional 5 transports per week of drilling over the same distance (Sonderegger, 2013).

5.5.1.2 Drilling energy consumption

Ecoinvent provides datasets for onshore and offshore drilling according to (Jungbluth, 2007). However, they are specific for oil drilling. As described in WP2 Section 3.3.1.8 “Differences between oil-gas and geothermal drilling,” there exist substantial differences between oil-gas and geothermal drilling, which are mainly (a) drilling in hard fractured, crystalline rocks and (b) larger borehole diameters, which require more powerful rig equipment and lead to a higher energy need. Drilling energy consumption does not follow a linear curve, but is rather an exponential function of the well depth, the well diameter, the drilling mud used and – as a result of all these parameters − the capacity of the drilling rig (Bello and Teodoriu, 2012; Legarth and Saadat, 2005). The latter two are especially dependent on different geological conditions. Therefore, data from one borehole cannot just be taken over for the modelling of a borehole at another location. Further, it can be assumed that drilling for hydrothermal plants might in general need less rig capacity, as they are often less deep and are drilled in sedimentary rock, as opposed to drilling for petrothermal plants in granite rock.

The main energy consumers during the drilling are the top rig drive, the mud pumps, the draw works and the casing process (Bello and Teodoriu, 2012; Chemwotei, 2010; Legarth and Saadat, 2005). Literature values for energy consumption per meter drilled vary over a large range and are mostly valid for oil and natural gas drilling (Jungbluth, 2007; Teuber *et al.*, 1999). Estimates for geothermal drilling energy consumption are shown in **Table 17**. The high variation is possibly due to very different rock conditions, technology and equipment, and actual progress of the drilling process.

Table 17: *Energy consumption for drilling according to various studies. All previous studies assumed diesel for energy use, whereas in Switzerland electricity is used. Consider that the values for diesel are valid for the input of diesel, whereas the electricity stands for the actual energy used.*

Energy consumption for drilling of deep boreholes	**GJ/m**		**Diameter [cm]**	**Depth [m]**
	Diesel input	Electricity use		
Jungbluth (2004; 2007) ; oil production	9		15 – 70	n.s. (<3000)
Rogge (2004); EGS	5		n.s.	> 3000
Dones *et al.* (2009); test drilling for nuclear repository	1.5		n.s.	2000
Kayser (1999); EGS	2.1		n.s.	1300 – 2500
Teuber *et al.* (1999); oil production	4.9		n.s.	3010
Treyer and Bauer (2012); EGS	7		20–40	5500
Frick *et al.* (2010); Léda Gerber and Maréchal (2012); EGS	7.5		n.s.	n.s.
Lacirignola and Blanc (2013) ; EGS	4.0.		n.s.	n.s.
This study (varying with depth & diameter)		8.5/11.3/14.1	25.4 (smallest diameter)	3000/4000/5000

In previous LCA studies, diesel-electric generators are assumed to be used in well drilling activities. (Frick *et al*., 2010) and (Gerber *et al*., 2012) estimate 7492 MJ of diesel consumption per 1 m of drilling. In ecoinvent v3 (Treyer and Bauer, 2012), 7000 MJ/m is assumed, and (Lacirignola and Blanc, 2013) assume 4000 MJ/m. In diverse LCA studies, process contribution analysis shows that diesel consumption of the drilling rig has one of the biggest impacts on the environment (Frick *et al.*, 2010; Gerber and Marechal, 2012; Lacirignola and Blanc, 2013). (Lacirignola and Blanc, 2013) included one scenario with power for rig operation supplied by the French electricity grid. In this scenario, some categories of environmental impacts are largely mitigated. For the specification of the drilling rig power system in this project, further investigation is needed for the amount of fuel consumption, which depends on the machine capacity used at each site. Appropriate amounts of energy consumption per meter of drilling in Switzerland should be estimated based on empirical drilling data in Switzerland. In Switzerland, the energy source is electricity from grid, with diesel only acting as backup.

This project searched for new estimates of the drilling energy use for geothermal wells in order to be able to respond to different well designs and geological conditions. A paper by (Legarth and Saadat, 2005) was found to be suitable to make a first step in the right direction, presenting different methods to estimate the energy consumption of geothermal drilling. A first method assumes only a relation between the energy use and the well depth and diameter, whereas the second method takes into account that different rock types, drilling fluids and borehole diameters need different rig capacities. This latter method is taken to calculate the energy consumption in this LCA, following the formula:

$$EC = E_n * z * V_b * P_r \text{ (1)}$$

EC Energy Consumption [kWh_e]

E_n Empirical factor presented in the paper [$kWh\ m^{-1}\ m^{-3}\ MW_e^{-1}$]

z depth of the well

V_b Volume of the well

P_r Machine average capacity (rig capacity)

For future research, it is necessary to collect empirical data from (preferably) geothermal drilling in Switzerland or comparable geological conditions in order to compare the calculated data with actual experience. As there are still significant uncertainties, the influence of the energy consumption on environmental impacts is subject to sensitivity analysis (see Section 5.6.3).

5.5.1.3 Casing material use: steel and cement

See also WP2, Section 3.3.1.3 "Casing and cementing" for detailed information and a sketch of a possible wellbore design.

The casing is normally made from steel and cement and has several important functions, which are mainly:

- Stabilisation of the borehole
- Definition of the production zone
- Control of the flow rate and fluid pressure
- Protection of the environment such as aquifers over the whole length of the well from the geothermal fluid pumped up or down.

Steel and cement use are a function of well depth and diameter as well as the design of the casing, i.e. which length the different sections are. The **drilling and casing schemes** assumed in this analysis are based on schemes considered for St. Gallen, Basel and Sauerlach (BFE, 2009; Kaiser and Fäs, 2004; Pletl *et al.*, 2010). The borehole diameters (well design scheme) amount to 28'' – 21½'' – $16^1/_8$'' – 12½'' and casing diameters to 24'' – 18'' – $13^5/_8$ –11'' (1 inch = 0.0254 m)[26]. An open-hole completion is assumed for the lowest 300 meters of the well.

Geothermal **cements** should tie well casing to the rock formation, be impermeable, hydraulically isolate the well from geological strata other than those related to production and injection, and resist attack by substances present in geothermal reservoirs. It is normally a cement of low density (light-weight), mainly Portland cement class G with a density of around 1800kg/m^3) (Bett, 2010; Finger and Blankenship, 2010; Sonderegger, 2013). In order to account for additional cement use due to loss zones encountered in the geological surroundings of the borehole, a factor of 1.5 was applied on the calculated cement use amount. Cement and steel use were calculated according to casing schemes based on Basel

[26] Consider the terminology and different types of diameters: (a) well diameter, (b) casing diameter, (c) pipe diameter (in decreasing order). The pipe diameter for this design is 10''.

and St. Gallen (BFE, 2009; Haering, 2003). An open hole in the production zone was considered for a distance of 300 m. The resulting behavior of cement and steel amounts with rising borehole depth is shown in **Figure 88** and **Figure 89** for the casing design presented above.

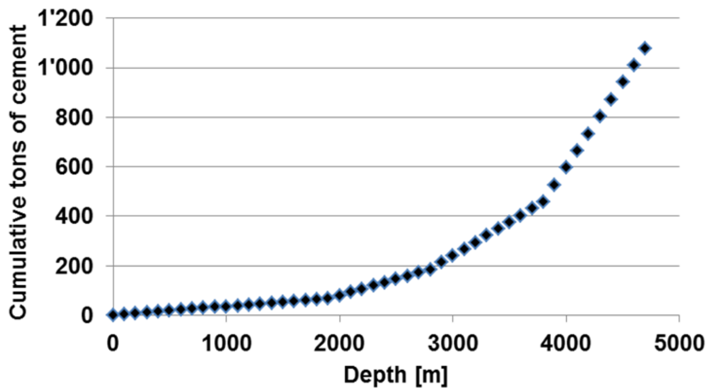

Figure 88: *Cumulative use of cement for the casing according to the model used in this project.*

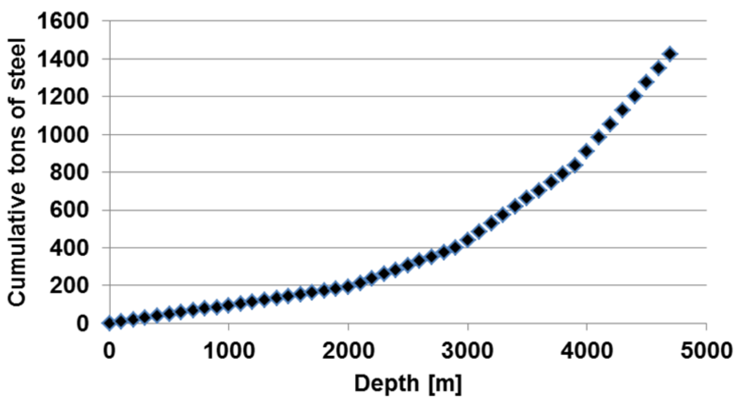

Figure 89: *Cumulative use of steel for the casing according to the model used in this project.*

5.5.1.4 Drilling fluid

See also in WP2, Section 3.3.1.2 "Drilling Fluids" and WP5, Section 6.1.2.2 "Drilling Mud" for more information. Drilling fluids used for geothermal drilling are in general "a simple mixture of water and bentonite clay, possibly with polymer additives" (Chemwotei, 2010; Finger and Blankenship, 2010). They should fill all the functions of drilling fluids, such as cleaning the hole of cuttings, lubricating the drill string, maintaining the stability of the borehole, and others. There exist pure bentonite muds, polymer muds or a mixture of these two.

In St. Gallen, mixtures of bentonite and polymers, potassium carbonate and chalk were used (Sonderegger, 2013). Data for Basel are similar to those found in the environmental impact assessment report by (Kaiser and Fäs, 2004). In general, the exact composition of a drilling mud depends a lot on the actual drilling conditions.

The information on the amount of drilling fluid used varies between different sources. St. Gallen indicates a use of 2600 m^3 of fluid for one borehole, whereas the environmental impact assessment report from Basel mentions a use of 600 m^3 to 1000 m^3 of water per well. It should be taken into account that the amount of circulation losses[27] can differ greatly between different wells in different geological conditions. Additionally, drilling mud can be recycled to a certain extent.

In general, all wastewater from the drilling phase must be treated in a wastewater treatment plant, including the drilling fluid. Only water treated to standards imposed by the regulator is allowed to flow into surface water bodies. The wastewater from the drill site is partly first stored in place and used for laboratory testing. All wastewater goes then to a public wastewater treatment plant. Use of specific drilling fluid components should therefore be discussed with the owner of the intended wastewater treatment plant in order to ensure complete treatment.

The inventory data for the drilling fluid are assumptions based on (Chemwotei, 2010; Kaiser and Fäs, 2004; Sonderegger, 2013) and cover the main substances used in terms of amounts, as detailed compositions of drilling fluids are normally confidential and are generally available in drilling reports (which in turn are usually submitted to the regulator as proof of compliance with regulations). It should be considered that the inventory covers several types of possible substances that could be added to the water but that would not be combined in reality. For example, bentonite cannot be used in the presence of chloride. The drilling fluid is assumed to be treated in a common wastewater treatment plant, thereby adding some meteoric water to be treated. Remaining emissions to surface water bodies, such as total organic carbon, are accounted for in the dataset chosen for the wastewater treatment.

5.5.2 Stimulation, deep well

The aim of the stimulation step is to improve the connectivity of two or more boreholes with the reservoir. To open up a fracture network between the production and injection wells, EGS systems require hydraulic stimulation, often augmented by chemical stimulation. In the EGS project in Basel, ***hydraulic stimulation*** was conducted (Ladner and Häring, 2009). During the hydraulic stimulation, fresh water is pumped down with high pressure. In addition to the hydraulic stimulation, several types of ***chemical stimulation*** were examined in the EGS pilot plant at Soultz-sous-Forêts (Portier *et al.*, 2009). Chemical stimulation utilizes acids that react and remove mineral phases restricting fluid flow. Depending on the geology, stimulation with hydrochloric acid is often used for hydrothermal plants if necessary. The stimulation step for deep wells can be carried out on very different levels: from no stimulation needed to simple chemical stimulation with hydrochloric acid to hydraulic stimulation using water at high pressure. Unlike in the oil and gas industry, complex chemical mixtures are usually not used for stimulation of geothermal wells for cost reasons (see also WP5, Chapter 6 on risks). Various literature exists on stimulation techniques and tests for geothermal power plants (Chabora *et al.*, 2012; Garcia *et al.*, 2012; GtV; Pfeil, 2012; Portier *et al.*, 2009; Tischner *et al.*, 2012). Literature data from shale gas fracturing should be regarded with care, as both the techniques and the geological conditions might not be comparable with petrothermal systems stimulating in granite. A risk related to hydraulic

[27] "Loss of drilling fluid to pores or fracture in the rock formations being drilled" (Chemwotei, 2010).

fracturing is induced seismicity that may cause harm to people and damage property and the environment, which is covered in other work packages of this study. The LCA part considers the energy, water and chemical use due to stimulation of a deep well.

This inventory includes the following exchanges:

- Energy use
- Water use

The inventory does not consider the following issues:

- Use of chemicals, such as hydrochloric acid. This should be added as a result of further research.
- Possible greenhouse gas emissions due to the flaring of natural gas from the ground during the stimulation are not considered for the same reasons as mentioned in the section on the drilling inventory (please refer to page 194 for more details).

Table 18: *Inventory for the process "stimulation, deep well, for geothermal power". All amounts refer to the reference flow "stimulation, with 1 m³ water".*

Category	Ecoinvent unit process name	Unit	Amount	Comment	
Reference product	Stimulation, deep well	m^3	1		
	Tap water, at user/CH U	m^3	1		
	Electricity, high voltage, at grid/CH U	kWh	100	Rough estimation needing further research	see Table 19 and Table 20

5.5.2.1 *Stimulation for hydrothermal plants*

For hydrothermal plants, it is assumed that no or a simple stimulation with hydrochloric acid is carried out. In St. Gallen, only small amounts of hydrochloric acid were used (2*75 m^3, Sonderegger, 2013). In a normal operation case, no acid reaches a groundwater layer, as regulations are very strict with regards to groundwater protection. Due to these reasons, the inventory neglects data for stimulation for hydrothermal plants in Switzerland.

5.5.2.2 *Stimulation for petrothermal plants*

For petrothermal plants, hydraulic stimulation is a key step in developing the reservoir (underground heat exchanger). According to (Meier and Zingg, 2013), planned EGS projects in Switzerland will apply a multifracture method (Zimmermann *et al.*, 2010) instead of a one-step method as used in Basel (Ladner and Häring, 2009). Two (or more) parallel wells follow a highly inclined or even horizontal direction from a certain depth and are connected in an overlapping manner to the reservoir with several stimulation events. Those single stimulation events are designed to work with lower injection volumes than the method in Basel, which is expected to reduce the likelihood of a seismic event. According to (Meier and Zingg 2013), neither the horizontal drilling nor the use of the multifracture method are expected to have a significant influence on energy use for the drilling or the stimulation, so that no special cases for the single or multifracture method are modelled.

A first estimate of energy and water use for the hydraulic stimulation was made based on Basel (Ladner and Häring, 2009) as shown in **Table 19**, which results in an **electricity use** of approximately 11 kWh per m^3 of water used.

IEAGHG (2013) indicates a minimum, mean and maximum diesel consumption of 3.6, 7.2 and 10.8 litres per m^3 of fracking fluid used. This corresponds to approximately 171, 342 and 513 kWh/m^3, calculating with a heating value of 40MJ/l and an efficiency of 30% for the generators. Sullivan *et al.* (2010) give a value of 188.5 m^3 fuel used per stimulation. Combination with another report by the same authors on water consumption (Clark *et al.*, 2011), the electricity use amounts to 102−133 kWh/m^3. In contrast, calculations from Frick *et al.* (2010) show again a quite low energy use of only 14 kWh/m^3. *This study assumes an energy consumption of 100 kWh/m^3*.

***Table 19:** Estimation of energy and water use during the hydraulic stimulation of the well in Basel according to (Ladner and Häring, 2009).*

Basel hydrologic stimulation	**Pressure**	**Injection rate**	**Duration**	**Energy consumption**	**Water consumption**
	bar	L/min	hours	kWh	m^3
1st step	120	500	33	3280	984
2nd step	180	900	12	3321	664
3rd step	240	1700	21	13940	2091
4th step	260	2500	21	22208	3075
5th step	290	3000	16	23780	2952
6th step	250	1900	6	4750	684
Total				**118799**	**10450**

This energy and water use was compared with different sources as the compilation in **Table 20** shows.

***Table 20:** Water and energy use for stimulation of petrothermal systems – compilation of literature values.*

	Water use	**Energy use**	**Energy use/Water use**
	m^3/stimulation	kWh/stimulation	kWh/m^3 water
Ladner and Häring (2009)	10’450	118’799	11
IEAGHG (2013)	nd	nd	171−513
Sullivan *et al.* (2010)	42’200−55’400 (from Clark *et al.* (2011))	5’631’120 (based on: fuel use of 118.5 m^3 per stimulation)	102−133
Frick *et al.* (2010)	260’000	3’564’000	14
This study	**40’000**	**4’000’000**	**100**

The used amount of **water** cannot be determined as a fixed value, but depends on the geological conditions and therefore on the success during the stimulation. In contrast to the water consumption shown in **Table 19**, (Kaiser and Fäs, 2004) propose a water use of 50’000 m^3 for the stimulation of the well in Basel. (Clark *et al.* 2011) also try to estimate the required water volume for all stimulation activities, i.e. they differ between the following phases: prestimulation test, main stimulation, post stimulation, short-term circulation, long-term circulation. They come up with figures between 42’200 to 55’400 m^3 per well, and additionally quantified a literature average of 27’000 m^3 per well. *A first assumption of 40’000 m^3 of water used is made*, which is certainly subject to the conditions at each individual site and might be higher or lower. It is assumed that no water is reused.

This is a topic that needs further research in future projects.

5.5.3 Heat and power generating unit

Deep geothermal power plants in Switzerland will operate with rather low fluid temperatures compared to other plants on the world, which can for example even be driven directly by pressurized geothermal steam at 150 °C or more in the case of dry steam power plants. Binary systems have the highest conversion efficiency for medium-temperature geothermal resources and will therefore be used in Switzerland. **Figure 90** shows a schematic drawing of such a binary system. Binary systems can be divided into **Organic Rankine cycle (ORC)** systems with various organic working fluids and **Kalina cycle** systems with ammonia and water as working fluid. This study assumes the use of an ORC system. DiPippo (2013) or ASUE (2011) give a good overview of binary cycle power plants and the functional principles of ORC and Kalina cycle systems.

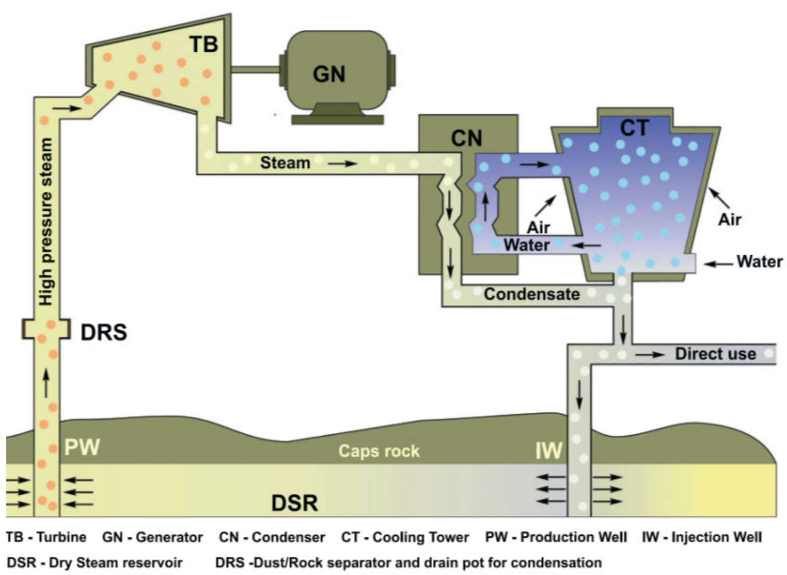

Figure 90: *Schematic drawing of a surface binary system used for geothermal plants with medium-temperature brine (Guzović et al., 2012).*

This inventory includes the following elements:

- Land use for the building and other space needed
- Material use for the turbine and generator
- End-of-life of the heat and power co-generation unit
- Benzene as working fluid
- Transport of the input materials
- The inventory includes in an implicit way the energy use for the surface plant operation, such as pumping the working fluid or the cooling.

The inventory does not consider the following issues:

- Material use for the air cooling facility
- This dataset does not take into account the possible need for regular maintenance to clean or even replace pipes due to **scaling/deposits** from mineral precipitation of the geothermal fluid. Further, it does not take into account the possibility of **scaling** of NORMs, which would lead to special disposal of certain components of the power generating unit (heat exchangers, pipework, valves, etc.) at their end-of-life. HGN *et al.* (2003) and the information given in the WP5, Chapter 6 “Risks” indicate that this topic needs further research. Sonney and Vuataz (2008) give an overview on a database called BDFGeotherm with information on geological, hydrogeological and geothermal conditions of different locations in Switzerland, which might also give hints on possible scaling.

Table 21: *Inventory for the process “heat and power cogeneration unit, 1 MW electrical, 6.4 MW thermal”. All amounts refer to the reference flow “heat and power cogeneration unit, 1 MW electric, 6.4 MW$_t$”. The inventory for the heat and power generating unit is basically taken from (Bauer, 2007).*

Category	Ecoinvent unit process name	Unit	Amount	Comment	Sources
Reference product	Heat and power cogeneration unit, organic Rankine cycle, 1 MW$_e$, 6.4 MW$_t$	unit	1		
Diverse	Building, hall/CH/I U	m2	250		Bauer (2007)
	Concrete, sole plate and foundation, at plant/CH U	m3	14	Literature value/calculated value. The original value of 34’000 kg concrete for the foundation was divided by a density of 2380 kg/m^3	Bauer (2007)
	Aluminium, production mix, at plant/RER U	kg	320		Bauer (2007)
	Rock wool, at plant/CH U	kg	90		Bauer (2007)
	Copper, at regional storage/RER U	kg	320		Bauer (2007)

Category	Ecoinvent unit process name	Unit	Amount	Comment	Sources
	Polyethylene, HDPE, granulate, at plant/RER U	kg	340		Bauer (2007)
	Chromium steel 18/8, at plant/RER U	kg	460		Bauer (2007)
ORC components	Steel, low-alloyed, at plant/RER U	kg	39000	Literature value/estimation. The amount of the steel mass is estimated based on a 1 MW plant in (Rogge, 2004). Weights of the different ORC components: Evaporator (11 t), boiler (4 t), turbine (3 t), generator (4 t), pump for working fluid (1 t), condenser of the organic circulating fluid (16 t)	Rogge (2004)
Conditioning	Sheet rolling, aluminium/RER U	kg	320		
	Wire drawing, copper/ RER U	kg	320		
	Sheet rolling, chromium steel/RER U	kg	460		
	Sheet rolling, steel/RER U	kg	39000		
Working fluid	Benzene, at plant/RER U	kg	436	Calculated from an input of 300 kg Perfluoropentane (Density 1.664 g/ml) and a density of 0.874 g/ml for Benzene	Rogge (2004)
Transport	Transport, lorry 20–28 t, fleet average/CH U	tkm	2048	Transport of ORC component materials and working fluid. Default transport distances are taken from Frischknecht *et al.* (2002).	Frischknecht *et al.* (2002)
	Transport, freight, rail/CH U	tkim	24248		
Energy use	Electricity mix, CH	kWh	2400		Bauer (2007)
	Heat, light fuel oil, at boiler 100 kW condensing, non-modulating/CH U	MJ	300		Bauer (2007)
End-of-life	Disposal, solvents mixture, 16.5% water, to hazardous waste incineration/CH U	kg	436	Proxy dataset for the disposal of the Benzene	
	Disposal, steel, 0% water, to inert material landfill/CH U	kg	39000		

Category	Ecoinvent unit process name	Unit	Amount	Comment	Sources
	Disposal, copper, 0% water, to municipal incineration/CH U	kg	320		
	Disposal, aluminium, 0% water, to municipal incineration/CH U	kg	320		
	Disposal, building, mineral wool, to final disposal/ CH U	kg	90		
	Disposal, building, polyethylene/polypropylene products, to final disposal/CH U	kg	340		
	Disposal, building, concrete, not reinforced, to final disposal/CH U	kg	14		

5.5.3.1 Working fluids

The ***Kalina cycle*** uses ammonia and water as the working fluid. The selection of the appropriate working fluid for an ***organic Rankine cycle system*** depends on "the thermodynamic and physical properties, stability, environmental impacts, safety and compatibility, availability and cost" aspects (Chen *et al.*, 2010). (Bao and Zhao, 2013; Franco and Villani, 2009; Guzović *et al.*, 2012; Saleh *et al.*, 2007; Victor *et al.*, 2013; Minder, 2007) are examples of the literature for the discussion on how to find the optimal working fluid and the effect of the working fluid choice on the power plant's efficiency. Saleh *et al*. (2007) discuss possible working fluids for the ORC. Some of these can be excluded in the Swiss case, as the use of working fluids are subject to the "Chemical Risk Reduction Ordinance" (ChemRRV, 2005). According to this regulation, ozone-depleting refrigerants must not be used (Annex 2.10, Art.2.1, Abs.1 lit.a). Stationary systems containing refrigerants stable in the atmosphere and containing more than 3 kg of refrigerant are subject to authorisation. Authorisation is only granted if no substitute products or processes are available, and if state-of-the-art mesures have been taken to prevent emissions (Annex 2.10, Art.3.3, Abs.2 lit.a,b). Substances falling under this regulation which might be considered to be used in a geothermal ORC are e.g. the single-substance refrigerants R134a, R125, and R143a. Instead, natural refrigerants must be used if available, e.g. single-substance refrigerants such as R717 (NH_3), R744 (CO_2), R600a (Iso-butane), or blends such as R290/R600a (Propane/Iso-butane) (BAFU, 2009). According to (Meier and Zingg, 2013), benzene or toluene are likely ORC working fluids. Other working fluids which might be chosen in Switzerland are mentioned in Minder (2007), amongst which are n-Pentane, different forms of butane, or methane. It is also possible that deep Swiss geothermal power plants might be run with the Kalina Cycle and therefore with ammonia (NH_3). Chen *et al.* (2010) present properties of different fluids, such as molecular weight or latent heat. It will be shown later that the working fluids do not contribute to a remarkable portion of environmental impacts of electricity from deep geothermal power. Calculations with ecoinvent (2013) show that the environmental impacts of the production of potential organic working fluids are in the same range, whereas ammonia causes higher impacts.

The base case of this study is modelled with **benzene** with average environmental impacts per kg of substance produced as representative for possible working fluids for the ORC. As the Kalina cycle is less mature and not yet often used in geothermal plants, the ORC is chosen as base case. The effect of the choice of the working fluid on the efficiency of the plant is neglected in this study.

5.5.3.2 Cooling

The **cooling system** is another key issue for binary plants in order to improve the conversion efficiency. There are three different types of cooling systems: a) surface water (once-through systems), b) wet cooling towers, or c) dry cooling towers. (Mendrinos *et al.*,2006; Minder, 2007) state that a water-cooling system is the most efficient, and air-cooling is the worst among these three. However, water cooling systems require large amounts of surface water during the whole operation phase. Wet type cooling towers consume less surface water, and also improve the thermal energy conversion efficiency (Kutscher, 2002). In running hydrothermal plants in South Germany, air cooling is often used. Further, dry cooling avoids site restrictions based on water availability, and accounts for 78% of geothermal capacity according to (Mishra *et al.*, 2011), so this type of cooling is assumed in this project.

5.5.3.3 Extrapolation of the dataset

The data are valid for a heat and power cogeneration unit with a capacity of 6.4 MW thermal and an estimated capacity of 1 MW electrical. For extrapolation of the inputs and outputs of this 1 MW unit to higher capacity power plants, an extrapolation factor based on (Heck *et al.*, 2009) is applied according to the following formula:

$$m_{extrapolated} = m_{1MW} * 10^{0.67}$$

Unfortunately, the ecoinvent background database does not provide detailed data on chemicals used for working fluids in organic Rankine cycles. Future research projects should aim to fill this gap in the inventory. For the moment, the refrigerant R134 is used as a proxy for all possible working fluids used in ORC units.

5.5.4 Geothermal power plant

This dataset collects all the different parts necessary to build a geothermal power plant: deep well drilling, stimulation, and surface power generator. It further includes the implementation of a downhole pump connected with the power generator. It is assumed that the power plant is built directly at the top of the borehole, so that no long pipes are needed for transport of the brine fluid.

This inventory includes the following elements:

- The following modules described in the previous sections: wells, stimulation, the power generator

- Land use
- Material use and transports for the downhole pump

Table 22: *Inventory for the process "geothermal power plant". All amounts refer to the reference flow of "1 geothermal power plant with a capacity of 5.5 MW_e".*

Category	Ecoinvent unit process name	Unit	Amount	Comment	Source(s)
Reference product	Geothermal power plant, 5.5 MW_e	Unit	1		
Land use	Occupation, industrial area	m^2a	240000	Lifetime of 30 years.	
	Transformation, from pasture and meadow	m^2	8000	Estimation. The ORC unit has an area of $500m^2$; additional space is needed for the surroundings.	
	Transformation, to industrial area	m^2	8000	See above	
Downhole pump and rising pipes	Steel, low-alloyed, at plant/RER U	kg	223'132	One pump in each of the two production wells with a lifetime of 5 years – see also describing text below.	Pletl (2010); Sonderegger (2013)
	Transport, lorry 20–28t, fleet average/CH U	tkm	11'157	Transport of the steel for the pump. Default transport distances are taken from Frischknecht *et al.* (2002).	Frischknecht *et al.* (2002)
	Transport, freight, rail/CH U	tkm	133'879		
Other	heat and power cogeneration unit, organic Rankine cycle, $1MW_e$	p	5.05	Extrapolation according to Section 5.5.3	
	deep well drilling, for geothermal power, onshore	m	32000	2*3 wells of 5000 m plus an exploration well of 2000 m	
	stimulation, for geothermal power	m^3	40000	Rough assumption that needs further sensitivity analysis, see Section 5.5.2.	

Downhole pump: Pumping or pressurization is often necessary in order to bring the geothermal fluid up to surface. Line shaft pump and electrical submersible pumps are the two common technologies that are widely used in geothermal application (Lobianco and Wardani, 2010; Qi *et al.*, 2012). The motor of the pump consumes electricity during the whole well operation. Electricity consumption and certain amounts of material input should be considered. In this project, the type and the depth of the pump is determined by the physical model. In the base case, a submersible pump must be placed at a depth of 1350 m, which is rather deep. The pump is assumed to have a weight of 650 kg and its motor is to have a weight of 1700 kg (Pletl, 2010). It is connected through a rising pipe made of steel to the surface. No extrapolation of the values for the pump and the motor are made for higher or lower pump capacities.

5.5.5 Electricity production, geothermal, deep

This dataset collects all parts necessary to produce electricity from geothermal power: The geothermal power plant on the one side and substances for maintenance on the other side.

This inventory includes the following elements:

- Yearly losses of the working fluid of 8% are taken into account
- “Amount” of geothermal plant needed per 1 kWh calculated from the cumulative lifetime electricity production

The inventory does not consider the following issues:

- Transport of the benzene is neglected
- Possibility of leakage of geofluid to an aquifer layer. This is not considered to be normal operation (see WP5 “Risks”, Section 6.1.2.6 “Geofluids”).

Table 23: *Inventory for the process “electricity production, geothermal, deep”. All amounts refer to the reference flow of “1 kWh electricity, high voltage”.*

Category	Ecoinvent unit process name	Unit	Amount	Comment
Reference product	Electricity, high voltage	1	kWh	
Infrastructure	Geothermal power plant, 5.5 MW_e	unit	6.72E-10	= 1 / (annual electricity production * lifetime) = 1/(5.77E7 kWh/year * 30 years)
Working fluid	Benzene	kg	3.05E-06	Yearly loss of 8% of refrigerant
Emission to air	Benzene	kg	3.05E-06	

The production of electricity at a deep geothermal power plant needs energy for the pumping of the brine and energy at the surface plant, such as for the working fluid pump, the makeup water pump, the cooling, and other requirements. While the energy for the pump is taken from the geothermal power itself, the energy needs for the surface plant might also be covered by electricity taken from the grid.

In this study, all the energy use is assumed to be covered internally and is accounted for in the calculation of the net capacity of the plant in the physical model that is the basis for the cost and the environmental analysis.

5.6 Life Cycle Impact Assessment results

The Life Cycle Impact Assessment (LCIA) was performed using the method "ReCiPe (H) Midpoints, Europe" (Goedkoop *et al.*, 2009) with the common LCA software SimaPro 7.3.3 and ecoinvent v2.2.

The midpoint indicators in LCA correspond to different impact categories, in which all emissions, material use, water or land use with the same "damage mechanism" are aggregated. Equivalence factors (relative to one substance in each category) are used for aggregated quantification. For example, all greenhouse gas emissions from the total life cycle are compiled in the category "climate change", calculated as CO_2 equivalents according to their individual global warming potentials based on CO_2 as the reference substance. **Table 24** shows all ReCiPe midpoint categories and their reference units. The calculations have been made for all of them, but not all of these categories are shown in the following results section for the sake of readability and oversight. Results will be presented in the main part of this section for the categories marked in bold. The complete results are listed in **Table 26** in the appendix. The selection was made based on the relevance of the single categories in the context of power generation and based on expert knowledge of which categories have higher influence on the overall environmental performance of power generation than others.

Table 24: *Midpoints categories in ReCiPe (Goedkoop et al., 2009).*

Impact category	Unit (equivalents)
Climate change	**kg CO_2 eq to air**
Ozone depletion	kg CFC-11 eq to air
Terrestrial acidification	kg SO_2 eq to air
Freshwater eutrophication	kg P eq to freshwater
Marine eutrophication	kg N eq to freshwater
Human toxicity	**kg 1.4-DCB eq to urban air**
Photochemical oxidant formation	kg NMVOC eq to air
Particulate matter formation	**kg PM10 eq to air**
Terrestrial ecotoxicity	kg 1.4-DCB eq to industrial soil
Freshwater ecotoxicity	kg 1.4-DCB eq to freshwater
Marine ecotoxicity	kg 1.4-DCB eq to marine water
Ionising radiation	**kg U235 eq to air**
Agricultural land occupation	m^2*yr (agricultural land)
Urban land occupation	m^2*yr (urban land)
Natural land transformation	m^2 (natural land)
Water depletion[28]	**m^3 (water)**

[28] The impact category "water depletion" must be used with care, as the modelling of the water use in the underlying life cycle inventories in ecoinvent v2 is not completely consistent over all technologies and over the whole life cycle chains. As the water use for deep geothermal power is an often discussed topic, the corresponding impact category is nevertheless included in the presentation of the results for this TA-SWISS project. It must be considered that the actual impact on the environment from the water depletion depends greatly on the water scarcity in the region where the water is withdrawn.

Impact category	Unit (equivalents)
Mineral resource depletion	**kg Fe eq**
Fossil resource depletion	kg oil eq

The impact of the production of one kWh electricity with deep geothermal power depends largely on the capacity of the power plant, i.e. how efficiently the wells can be used and how much electricity can be produced over the lifetime of both the power plant and wells. Therefore, the results for the average, low and medium capacity cases presented can be interpreted as representing the absolute range of impacts. These cases also show the relative importance of individual elements in the life cycle of the geothermal electricity production (Section 5.6.2). The sensitivity analysis in Section 5.6.3 represents the variation of key parameters such as the well depth, number of wells, flow rate, gradient and their influence on the environmental impacts. The next sections compare the impacts calculated in this study with other studies and compare the LCA results of deep geothermal power with other electricity production technologies in Switzerland.

5.6.1 Life Cycle Impact Assessment for three different cases

Figure 91 compares climate change impacts of the three different deep geothermal power plants with capacities of 5.5 MW_e (average), 14.6 MW_e (high) and 2.9 MW_e (low) (see **Table 15** and **Table 13**). The chosen impact category for this result example is climate change as one of the most well known LCA impact categories. However, the pattern is practically the same for all other impact categories. The life cycle components as shown in **Figure 87** are the drilling phase, the stimulation phase, the cogeneration unit and the category "Others" summarizing land use, working fluid loss refill, and steel use for the downhole pump.

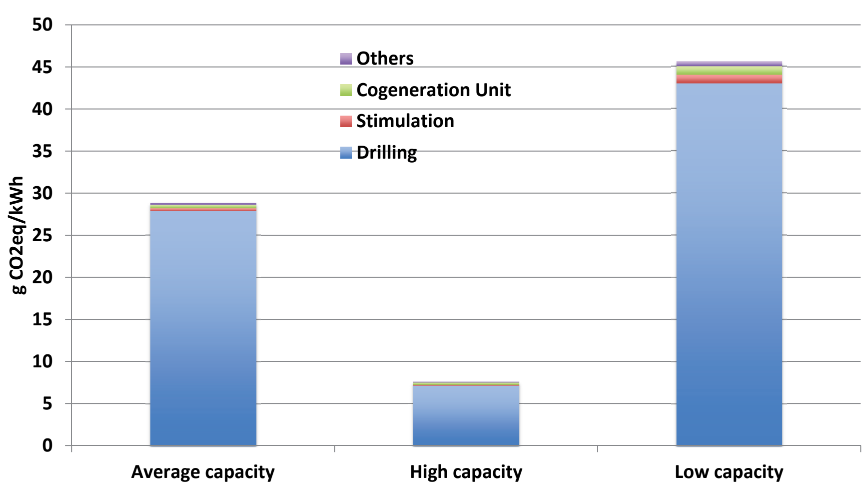

Figure 91: *Climate change results for the three deep geothermal plants (average, high and low capacity) modelled in this study. The category "Others" contains land use of the plant, working fluid loss refill, and steel transport and use for the downhole pump.*

The cumulative CO_2-equivalent emissions per kWh over the whole life cycle of the power plant vary between approximately 8 and 46 g CO_2 eq/kWh; the plant with the lowest capacity shows the highest impacts. This is due to the much lower output of electricity over its whole life, while impacts from the dominating drilling phase are not lower for this plant. Consider that for both the high and low capacity case the drilling of one well set (triplet) is assumed only, whereas in the average case two well sets must be drilled over the plant's lifetime. For all cases, the drilling phase clearly dominates the climate change impacts. **Figure 92** evaluates if this finding holds true also for five other impact categories for the average case, and **Table 26** in the annex proves the same for all remaining impact categories.

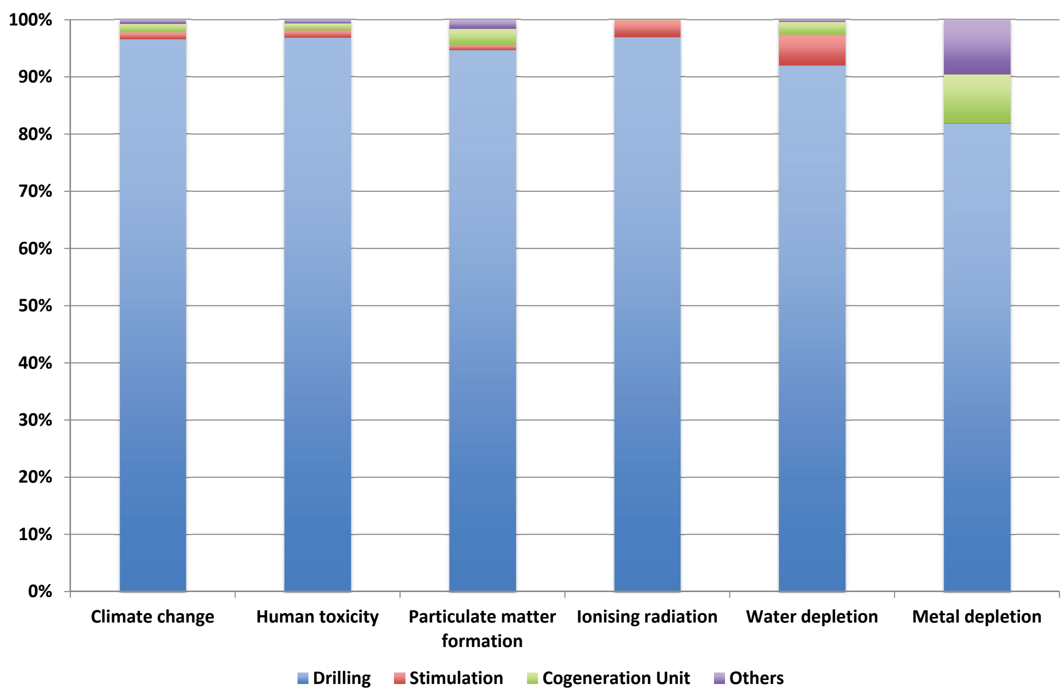

Figure 92: *Influence of the different life cycle components on six selected impact categories for the "average capacity" plant case. The category "Others" contains land use of the plant, working fluid loss refill, and steel transport and use for the downhole pump.*

The stimulation with water and energy, the generation unit and other inputs play a very minor role. Within the generation unit the construction of the building and the related steel use are dominant, whereas the choice of the working fluid plays only a marginal role. For the dominating drilling phase, **Figure 93** shows the split into different materials and services for six selected impact categories.

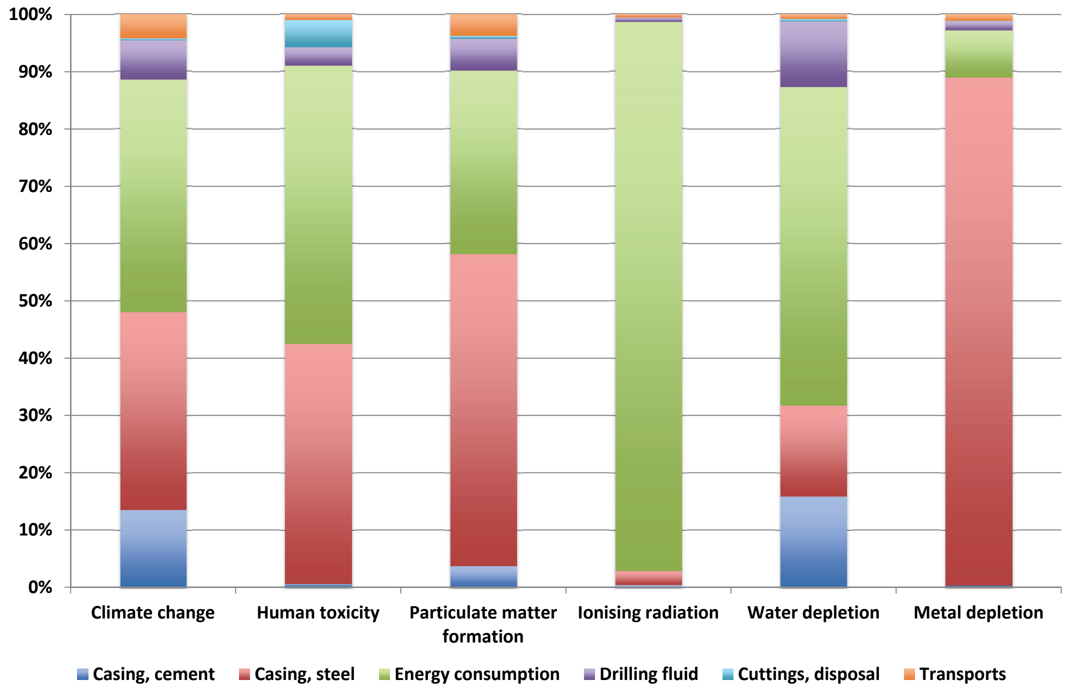

Figure 93: *Contribution of materials and services to the impact of the drilling phase for six selected impact categories, shown for a well depth of 5000 m. Cement and steel are used for running casing. Energy consumption contains mainly electricity from the grid and a small amount of diesel used on the well site for moving goods. Transport includes transportation of infrastructure, casing and related materials, drilling fluid ingredients, and cuttings.*

Clearly, energy consumption and the use of steel for the casing dominate the impact of drilling wells – even with electricity as the energy source. Data on drilling fluids are still somewhat uncertain. They may have a higher or lower influence. The choice of the working fluid does not influence the results in a significant manner.

5.6.2 Heat and power cogeneration

As the list of geothermal plants in Germany suggests, geothermal plant design includes district heating supply in most of the cases, mainly due to economic reasons. If a deep geothermal power plant is constructed near an existing district heating network, the use of heat is likely. However, in most of the cities without such an existing network, pipeline construction might be too expensive to maintain economic viability of a geothermal project.

The cogeneration of heat and electricity is a so-called "multi-output process" in LCA, which can be dealt with by allocating the total environmental impacts to the different outputs or by expanding the system. Using allocation, geothermal systems with both electricity and heat as useful products require splitting the environmental burdens between the two products. In the case of heat and power cogeneration, all inputs and outputs of the system and therefore the environmental impacts are partitioned between (or "allocated to") electricity and heat produced. According to (ISO, 2006a; b), allocation should be avoided by system subdivision as first choice. If this is not possible, allocation should be made according to physical, monetary or other properties. Various possibilities for allocation according to these requirements for combined heat and power systems are discussed in (Heck, 2007). The often used exergy allocation is not considered to be the first choice in the case of geothermal power, as both the electrical and thermal efficiency of the system are not easy to define. Price allocation would be a possibility for this project, based on the physical model coupling cost and the environmental assessment in this study. The relation of the output of usable (net) heat to (net) electricity is around 55 MW_t: 5.5 MW_e = 10:1. The cost of the heat and electricity are taken from work package 3. The sales price of heat amounts to 77 $/$MW_t$, which equals ca. 8 Swiss cents/kWh. The average generation costs of electricity are calculated to amount to ca. 35 Swiss cents/kWh. This results in a relation of ca. 1:4.5 between the heat and the electricity.

Given the resource constraints of the present project, the following assumptions are made:

- No changes in the system boundaries for the case of additional heat use were introduced, such as the flows related to the building of a district-heating network.
- The heat is present anyway and is used in the CHP case “for free”, i.e. it does not lead to a decrease in the electrical efficiency of the plant.
- Considering that the system remains unchanged, the only difference is that “superfluous” heat can be used without accounting for any additional burdens. The resulting impacts per kWh electricity are lower compared to the results presented before for the case of allocation, as a part of the impacts are allocated to the production of heat. If system expansion were chosen, the production of both electricity and heat would be compared with plants producing either of these products.

5.6.3 Sensitivity analysis

As discussed above and as in the cost assessment, a sensitivity analysis of key parameters is carried out and presented for six impact categories (**Table 25** and **Figure 94**). **Table 25** shows all parameters used in the sensitivity analysis. In each analysis, only one parameter is changed actively, with the physical model calculating the impact on other parameters. The most important change is reflected by the change in the plant’s capacity. Negative values going towards infinite can be observed in specific cases where the conditions become so unfavorable that the plant’s own use is higher than the actual possible production. Blank cells in the table indicate that no change was made or occurred in comparison to the base case.

Table 25: *Ranges of sensitivity tests on different parameters and their influence on the other parameters. In most cases, the plant net capacity is the only parameter showing changes.*

	Medium capacity (Base case)	**Gradient**	**Well depth**	**Pipe inside diameter**	**Well life-time**	**Fluid flow rate**	**Energy consump-tion, drilling**	**Rock stimu-lation**
Plant net capacity	5.5 MW_e	(-1.64) – 20	(-1.21) – 29	(-224) – 7.3	5.5	3.6-6.6 – 1.3	5.5	5.5
Gradient	35 °C/km	**20–50**	35	35	35	35	35	35
Well depth	5 km	5	**3–8**	5	5	5	5	5
Number of wells	6	6	6	6	**18–3**	6	6	6
Surface plant life time	30 a	30	30	30	30	30	30	30
Well life time	20 a	20	20	20	**5–50**	20	20	20
Pipe inside diameter	10 inches (25.4 cm)	10	10	**3.3–20**	10	10	10	10
Fluid flow rate	147 l/s (2*73.5)	147	147	147	147	**49–294**	147	147
Energy use, drilling	3932 kWh/m	3932	3932	3932	3932	3932	**1750–11650**	3932
Rock stimulation	40’000 m^3	40’000	40’000	40’000	40’000	40’000	40’000	**10’000 – 200’000**

One can frequently observe that the environmental impacts are close to each other for a certain range of capacities, and then at a certain threshold capacity increase rapidly (**Figure 94**).

The label “higher value of range” indicates the use of higher values than the default value. In the present case, this often leads to higher power plant capacities and therefore lower environmental impacts per kWh of electricity. The “lower value of range” indicates the use of lower values than the default value. Impacts cannot drop more than 100%, as otherwise they would even indicate a benefit for the environment, which is not possible in the present system. The label “range of net capacity” shows how much the net capacity changes with the variation of each parameter. This means that the well depth has the highest influence on the net plant capacity. The sensitivity analyses, however, for well life, energy consumed for drilling operations and stimulation are based on constant capacities. In the case of the pipe inside diameter and the fluid flow rate, the base case corresponds to the optimal net capacity, and both increasing and decreasing of these parameters leads to lower capacities. The ranges are of very different sizes, with the following factors between minimum and maximum value: gradient (2.5), well depth (2.7), well life (10), pipe inside diameter (6), fluid flow rate (6), drilling energy consumption (6.7) and rock stimulation (20). Parameter values leading to negative plant capacities have been excluded from **Figure 94**.

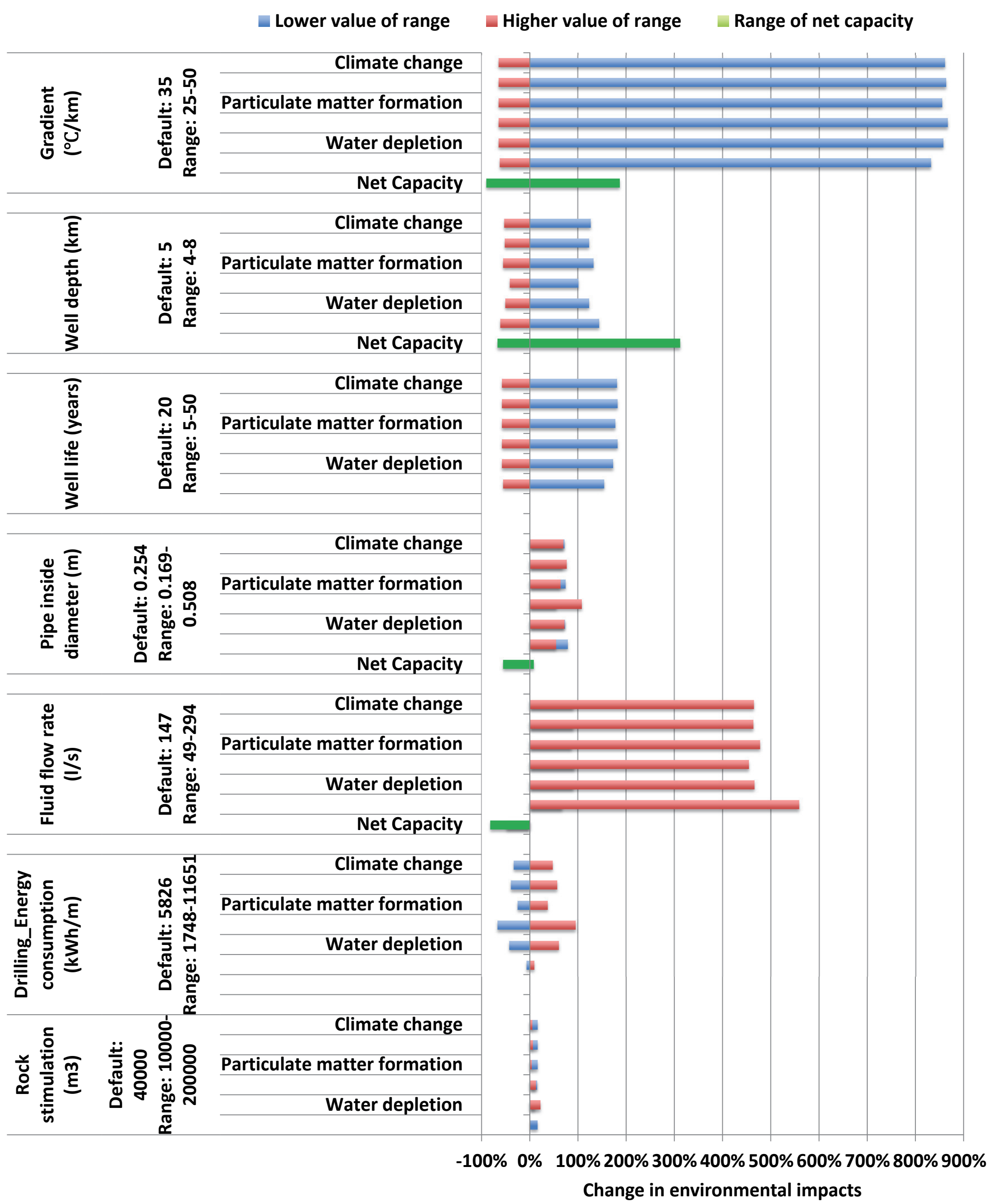

Figure 94: *Sensitivity analysis of six key parameters determining the capacity of a deep geothermal power plant, shown for six impact categories. Impacts cannot drop more than 100%, as otherwise they would indicate a benefit for the environment, which is not possible in the present system.*

In general, patterns are similar for the six impact categories:

- The lower the gradient, the higher the environmental impacts. Analyses show that this is especially true for gradients lower than 30 °C/km. For example, the results for climate change jump from 48 g CO_2 eq/kWh (30 °C/km) to 240 g CO_2 eq/kWh (25 °C/km), and go towards infinity for a gradient of 20 °C/km due to the resulting negative plant capacity. The same can be observed in the other impact categories.

- Greater well depth leads to higher energy consumption per meter drilled and higher material needs for the casing. However, capacity also increases. Deeper wells seem to be beneficial for environmental impacts. This might not be directly applicable to hydrothermal plants.
- Decreasing well life with constant plant lifetime leads to the necessity of drilling more wells and, assuming constant lifetime electricity production, to correspondingly higher impacts. A well life of 5 instead of 30 years leads to environmental impacts about 3 times higher per kWh.
- The well diameter and hence casing diameter do not show the same behavior as the above parameters, but are optimal for a diameter of 10 cm. Higher and lower diameters lead to higher impacts. This is due to the influence of energy consumption for drilling operations and the amount of fluid that can be pumped through the pipe with a certain pump capacity. Doubling the pipe diameter from 25.4 cm to 50.8 cm leads to environmental impacts which are around 1.7 times higher per kWh.
- Also for the production rate, an optimum can be observed at 147 l/s. Higher flow rates lead to higher pump energy use, whereas lower flow rates correlate with lower gross capacities, but also lower pump capacity. Increasing the flow rate to 294 l/s leads to environmental impacts which are around six times higher per kWh.
- Varying the energy consumption per meter of borehole by a factor of 6 leads e.g. to changes in the climate change from 20 g CO_2 eq/kWh (1750 kWh/m) to 44 g CO_2 eq/kWh (11'650 kWh/m) for the base case with 5000 m deep wells. In general, the environmental impacts increase by around a factor of two.

Varying the water and corresponding energy consumption for the rock stimulation by a factor of 20 leads e.g. to changes in the climate change from 25 g CO_2 eq/kWh (use of 10'000 m^3 water per plant) to 26 g CO_2 eq/kWh (200'000 m^3). Also in all other impact categories, the influence of the water and energy consumption for the stimulation on the impacts per kWh is very marginal (factor of around 1.05). This underlines once more the finding that the influence of the stimulation phase on the environmental impacts is very low.

5.7 Conclusions

The LCA study in this project has established a life cycle inventory based on Swiss data, literature data and data from a physical model, making it possible to study the environmental impacts for future deep geothermal plants over a wide range of possible physical conditions and design choices.

The life cycle inventory shows major improvements compared to earlier studies, mainly for the drilling phase. Instead of relying on data from oil and gas drilling, this study bases the assumptions for energy consumption on specific literature for geothermal drilling as well as on measurements in Switzerland. Further, the physical model and the LCI are adjusted to Swiss specific conditions by using electricity as the energy source, assuming transport distances reasonable for Switzerland, and excluding ozone depleting working fluids.

It was found that the physical parameters related to the reservoir properties and the plant design determine the power plant's capacity and lifetime, and therefore are crucial for the final results for environmental impacts. Differences between hydrothermal and petrothermal plants are mostly based on such design choices and inherent reservoir properties. Further, the influence of the stimulation phase is very small, so that the separate modelling of these two plant types was not pursued. Three cases for an average, an optimum and a low capacity power plant give an impression of the range of environmental impacts of electricity from deep geothermal power. The model makes it therefore possible to provide a first answer to the effect of the great uncertainties related to the physical conditions in the underground and their influence on the environmental impacts.

The environmental impacts of deep geothermal plants in Switzerland have been calculated by means of Life Cycle Assessment. This method covers only normal operation, i.e. it does not consider any accident cases. Groundwater pollution due to faulty drilling operations as well as induced seismicity due to stimulation or fluid reinjection are therefore not represented in the results. Further, issues with great uncertainties due to lack of experience have not been incorporated. Examples of such factors include the number of unsuccessful wells, methane leakage during drilling and deposits in the pipes from the geo-fluid.

In accordance with literature, the drilling phase has the highest influence on environmental impacts. The surface plant, the choice of the working fluid and the stimulation play minor roles. Sensitivity analyses show that a bad choice of certain parameters would lead to negative plant capacities. Besides this, the environmental impacts per kWh of electricity produced vary by a maximum of a factor of six within the sensitivity ranges shown in this project. Worst cases with related high environmental impacts would not be economically feasible, even when accounting for a heat credit. The co-production case was only roughly modelled in this study and leads to decreased environmental impacts per kWh of electricity as well as to a cost improvement.

The results of this LCA on deep geothermal power are compared to other environmental impacts of other power producing technologies in Switzerland in Section 9.1.1.

Future research should investigate the following topics in more detail:

- Verification of drilling energy use with field data from Switzerland.
- Filling data gaps and uncertainties, mainly:
  - Accounting for unsuccessful wells
  - Accounting for possible greenhouse gas emissions from the well during the drilling and stimulation phases
  - Accounting for possible radioactive drill cuttings or scaling in the pipes and surface plant, as well as potential radioactive emissions based on measured data if available
  - Energy and water use in the stimulation phase
  - Drilling fluid composition and the amount needed during drilling
  - Maintenance work related to possible deposits from the geo-fluid in the pipes
- Combinations of parameters for further sensitivity analyses
- Explicit representation of the auxiliary energy use for the surface plant, as done for the downwell pump energy use in this study, so that different electricity sources can be considered

From the point of view of environmental impacts, deep geothermal power is worthwhile to consider as a potential part of the future electricity mix, as it exhibits a comparable or even better performance level than typical for other supply technologies used in Switzerland today or of interest for the future.

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5.9 Appendix

Table 26: *Results of the Life Cycle Impact Assessment, calculated with ReCiPe Midpoints (H) for a medium (5.5 MW_e), an high (14.6 MW_e) and a low (2.9 MW_e) capacity case.*

		Base case (medium capacity)	**Optimal case (high capacity)**	**Pessimistic case (low capacity)**
Climate change	g CO_2 eq/kWh	28.8	7.55	45.6
Ozone depletion	kg CFC-11 eq/kWh	2.57E-09	6.95E-10	4.07E-09
Terrestrial acidification	kg SO_2 eq/kWh	1.04E-04	2.79E-05	1.65E-04
Freshwater eutrophication	kg P eq/kWh	1.76E-05	4.68E-06	2.76E-05
Marine eutrophication	kg N eq/kWh	6.27E-06	1.67E-06	9.95E-06
Human toxicity	kg 1.4-DB eq/kWh	1.74E-02	4.62E-03	2.74E-02
Photochemical oxidant formation	kg NMVOC/kWh	8.66E-05	2.24E-05	1.38E-04
Particulate matter formation	kg PM10 eq/kWh	5.91E-05	1.55E-05	9.44E-05
Terrestrial ecotoxicity	kg 1.4-DB eq/kWh	3.47E-06	9.33E-07	5.54E-06
Freshwater ecotoxicity	kg 1.4-DB eq/kWh	3.36E-04	9.05E-05	5.38E-04
Marine ecotoxicity	kg 1.4-DB eq/kWh	3.42E-04	9.20E-05	5.47E-04
Ionising radiation	kg U235 eq/kWh	6.40E-02	1.82E-02	1.01E-01
Agricultural land occupation	m^2a/kWh	8.18E-04	2.44E-04	1.37E-03
Urban land occupation	m^2a/kWh	4.17E-04	1.29E-04	8.86E-04
Natural land transformation	m^2/kWh	4.71E-06	1.23E-06	7.52E-06
Water depletion	dm^3/kWh	7.97E-04	2.20E-04	1.31E-03
Metal depletion	g Fe eq/kWh	8.35	2.36	14.5
Fossil depletion	g oil eq/kWh	8.15	2.13	12.9

6 WP5: Risks

This chapter on risks consists of four distinct parts. First, an overview of various risk aspects potentially leading to accidents is presented, followed by an analysis of selected hazardous substances and blowouts with regard to their consequences on human health and the environment. In the second part, seismic risk is evaluated in detail. Third, a brief summary of risk management approaches as applied by industry is given. Last, risk perception issues are addressed combining a literature review with a content analysis of newspaper articles.

6.1 Accident risk

Matteo Spada & Peter Burgherr (PSI)

6.1.1 Introduction

Comparative assessment of accident risks is a key factor in a comprehensive evaluation of energy technologies with respect to sustainability and energy security concerns. For this purpose the Paul Scherrer Institut has developed and established a methodological framework, which since its initial formulation in the early 1990s has been continuously updated and extended to keep up with the current state-of-the-art and to cover newly emerging needs (e.g. Hirschberg et al., 1998; Burgherr, 2011; Burgherr et al., 2013; Burgherr and Hirschberg, in press). PSI's Energy-related Severe Accident Database (ENSAD) is the central element and quantitative foundation to provide a consistent and unbiased evaluation of a broad portfolio of current and future energy technologies (e.g. Hirschberg et al., 1998; Burgherr et al., 2004; Burgherr et al., 2008; Burgherr et al., 2011)

Historically, comparative risk assessment has mainly addressed large centralized technologies such as fossil energy carriers, hydro and nuclear power because of their dominant role in the energy system. However, more recently the evaluation of new renewable technologies has received a strong focus due to new policies aiming at a more sustainable energy supply. Although decentralized technologies may partially be less prone to severe accidents, they need to be adequately considered because generally no energy technology is completely risk free (Burgherr, 2011).

In the context of Switzerland's new energy policy, deep geothermal energy is supposed to make a substantial contribution. Therefore, a comprehensive assessment of geothermal accident risks and their associated consequences is needed, including a comparison of risk indicators with other technologies (see Chapter 9).

Usually, the public discussion of risks from deep geothermal energy is centered on induced seismicity. Although this is clearly a key aspect and deserves in-depth treatment (Section 6.2), the variety of other potential accident risks should not be ignored or played down. For example, the goal of existing regulations and standard operating practices is to prevent or at least successfully mitigate the risk of hazards such as gas kicks that could develop into borehole blowouts. Another area of concern is groundwater contamination due to surface leaks of geothermal brine or stimulation fluids as well as internal well blowouts. Finally, it is essential to consider both the drilling and operational phases of a deep geothermal system because accidents can occur in both stages.

In this first part of work package 5 (Section 6.1), various risk aspects of deep geothermal energy systems are identified, characterized and to the extent possible quantitatively analyzed with regard to their potential consequences for human health and the environment. It is important to note that in contrast to methods typically used by industry (Tixier et al., 2002), comparative risk assessment (CRA) uses a different approach. Historical data on accidental events are collected from a broad range of information sources, and subsequently analyzed. In this way, CRA can be seen as a more generic, top-down approach useful for sustainability evaluation and technology comparisons that complements the detailed, bottom-up evaluations carried out by industry for specific facilities and sites. Furthermore, CRA can provide valuable inputs to decision-making and policy formulation processes. Finally, CRA with its focus on technological accidents is closely coordinated with research efforts evaluating seismic risk (Section 6.2) and risk perception (Section 6.3)

The comparative risk assessment of deep geothermal systems performed in this study can be separated into two distinct tasks. First a literature review is undertaken to identify and characterize the potential sources of accident risks (except seismic risk that is treated in Section 6.2). Second, risk indicators relevant for accidents causing damage to human health and the environment are defined and quantified. Third, special attention is given to blowout accidents, and to hazardous substances used either as additives in the drilling mud or as working fluid in the operational phase (see **Table 27**). Finally, fatality rate was used as the risk indicator in the comparative analysis of selected new renewable technologies and the limited-scope MCDA carried out in Chapter 9.

6.1.2 Accident risks of deep geothermal systems

Induced seismicity is often the dominant topic in current discussions about risks of deep geothermal systems, although a comprehensive assessment should consider other risk aspects too. In recent years, several overviews of potential geothermal risks and their associated consequences have been published (e.g. Tester et al., 2006; DiPippo, 2012; Kagel et al., 2007). Additionally, studies on specific risk factors such as groundwater contamination (e.g. Aksoy et al., 2009; Clark et al., 2011; Navarro et al., 2011) or natural radionuclides (e.g. Eggeling et al., 2013) have been conducted. **Table 27** provides an overview of the various accident risks of deep geothermal systems. It is important to note that in comparative risk assessment a full-chain approach (Hirschberg et al., 1998; Burgherr and Hirschberg, 2008a) is used because accidents can occur at all stages of an energy chain, i.e. both the drilling and operational phases need to be taken into account. Since deep geothermal systems have not yet been installed at many sites, historical experience in terms of accidents is rather limited, particularly if one compares it for example to fossil energy chains. Therefore, the estimation of risk indicators for blowouts and hazardous substances is based on historical experience that can be considered a meaningful proxy for deep geothermal systems. Chosen risk indicators address human health (e.g. fatalities, injuries, evacuees) and environmental impacts (e.g. spills).

Table 27: *Issues and risks related to a particular phase in Deep Geothermal Systems.*

Phase	Issue	Risk
Drilling	Drilling Muds	Risk related to the use of hazardous substances
Stimulation	Stimulation	Risk related to the use of hazardous substances
Drilling and Operational	Blowout	Risk related to blowout accidents
	Landslides	Risk related to landslide hazard
	Induced Seismicity (see Section 6.2)	Risk related to induced seismicity hazard
Operational	Geofluids	Risk related to the hazardous substances brought to the surface by the circulation of the geofluids
	Cooling System	Risk related to the use of hazardous substances
	Working Fluids	Risk related to the use of hazardous substances

Although this study is principally aimed for Switzerland, the overarching methodological approach is generic enough so that it should be applicable to other countries or regions. A key factor to be taken into account is the basement's geology in the region of interest. In fact, the local geological conditions can completely change even inside a country. This is an important step in the siting process of deep geothermal systems. Moreover, it may determine the type of power plant (Kalina or organic Rankine cycle) that is suitable for a given location.

The following sections discuss the various risk aspects listed in **Table 27**.

6.1.2.1 Blowouts

A blowout is defined as an uncontrolled flow of formation fluid or working fluid into the wellbore, and sometimes catastrophically to the surface. Therefore, in the latter case blowouts could potentially be the source of consequences to human health and the environment. Well blowouts may occur both during work on a well (e.g. drilling), and during well operation. Blowouts during these operations usually are the result of loss of well control, possibly caused by inadequate prevention or mitigation measures to keep or regain well control, and failure of barrier systems (e.g. the blowout preventer) during escalation of a kick (e.g. Grace, 2003). Blowouts can also happen during other types of well operation such as production or injection or in wells that are shut-in/idle or abandoned. These blowouts typically occur due to the failure of some well component, either as a result of aging (e.g. well-casing corrosion or an improperly plugged well).

Few studies have assessed the risk for the drilling phase in deep geothermal systems. For example, blowout risks were estimated by PSI using an approximate approach in the European Union (EU) project SECURE (Burgherr et al., 2011), and for the IPCC special report on renewable energy sources (Burgherr 2011). Geothermal drilling generally relies on the same kind of technology used in the oil and natural gas (O&G) industry, modified for high temperature applications and larger well diameters (Finger and Blankenship, 2010). The key differences between drilling for deep geothermal systems and O&G can be summarized as follows (e.g. Tester et al., 2006):

- Temperature is higher in deep geothermal systems
- Production pressure is lower in deep geothermal systems
- Production rates are higher for deep geothermal systems

Due to the lack of data for geothermal energy, the risk assessment of the drilling phase for deep geothermal systems could roughly be approximated from the corresponding risks in oil and gas energy chains. In this study, however, only natural gas accidents are considered to constitute a valid proxy, since natural gas has been extracted in small quantities in Switzerland. For example in Finsterwald (canton of Lucerne) a total volume of 73 million cubic metres was produced between 1985 and 1994, which corresponds to about 3% of Switzerland's current annual natural gas consumption (BFE, 2007). Other studies reported probabilities for a blowout accident in the order of 10^{-4} (blowouts/drilled well) for both natural gas and oil exploration (e.g. OGP, 2010; Andersen, 1998).

6.1.2.2 Drilling mud

In the drilling phase another important aspect to take into account in a comprehensive risk assessment is the mud used for the drilling. The mud in deep geothermal systems and geothermal systems in general, is a composition of water and some additives, such as barite (see WP3, Section 3.3.1.2). The additives are added to the fresh water in order to increase the viscosity, the weight and to control the pH. Thus, the concentration of the additives and the type of mixture strongly depends on the geology of the area.

Fresh water and active and inert solids are mixed to obtain a mud with certain desired properties, primarily to increase the viscosity. Active solids, clays (bentonite) and polymers are added to the water to produce a colloidal suspension. They determine the viscosity of the mud and are known as viscosifiers. Inert solids are those added to the mud either by drilling (formation particles) or by using barite (barium sulphate) as a weighting material. These solids increase the density of the mud without significantly affecting the viscosity (e.g. Chemwotei, 2011). In addition, the alkalinity of the fluid is important for corrosion control, rheological properties in bentonitic mud, and for its reaction with certain formation constituents; normal pH is 9.5 to 10.5, but higher values are not uncommon (e.g. Finger and Blankenship, 2010).

Water-based drilling mud (spud mud) commonly consists of bentonite clay (gel) accounting for around 10% of the mixture, with additives such as barium sulfate (barite), calcium carbonate (chalk) or hematite (e.g. HSL, 2000). In some cases (natural bentonite mud), caustic soda (ca. 1% of the mud mass) is added to water and bentonite (ca. 9% of the mud mass) in order to stabilize the pH between 9.5 and 10.5.

Another common type of water mud consists of polymers. These types of muds are commonly used for geothermal wells (1) to clean the hole and keep the cuttings suspended, (2) while adding a drill pipe, and (3) when there is a total loss of circulation and water is the drilling fluid (e.g. EPA, 2004). They consist of both natural (guar gum) and water soluble synthetic organic polymers. Although the cost of most polymer additives is about 10–40 times higher[29] than the cost of bentonite, the lubricating quality of many polymer muds is excellent and can noticeably reduce bit and drill-string wear. Furthermore, polymer mud often has a lower solid content compared to bentonite mud. Although polymer mud may lack the gel strength, which is required to suspend particles or to form a satisfactory filter cake like bentonite mud, polymer mud can be pumped at much higher viscosities (e.g. Chemwotei, 2011).

Thus, the water-based mud can generally be considered an "environmental and human friendly" mixture (WP2 personal communication), meaning that most of the chemical additives are not dangerous for the environment and human health. However, in the case of caustic soda (or Sodium hydroxide, NaOH) this statement is not true. In fact, caustic soda is a highly caustic metallic base and alkali salt and it is extremely corrosive for humans (as well as metals). Therefore, it could cause fatalities primarily in case of ingestion (e.g. ATSDR, 2002).

According to health, safety, and environmental (HSE) policies, the packaging, transport, and storage of drilling-fluid additives and/or premixed fluid systems are closely scrutinized regarding HSE issues. In addition, personnel who handle drilling fluid and its components are required to wear personal protective equipment (PPE) to prevent inhalation or other direct contact with potentially hazardous materials. The application of these safety regulations has contributed to the fact that only very few accidents (see Section 6.1.5.3) related to the drilling mud have been documented in the last 23 years.

6.1.2.3 Chemical, matrix, thermal and hydraulic Stimulation

In most instances geothermal wells and reservoirs are stimulated, either chemically or hydraulically, near the wellbore or further into the reservoir or, sometimes referred to as the matrix. The purpose is to improve the hydraulic communication across the well-formation interface, and between the near well-bore and the reservoir. This practice is common for both injection and production wells.

The main technique for stimulation generally used in Enhanced Geothermal Systems (EGS) is the "hydraulic stimulation" using water as the injection fluid (Section 2.3).

While hydraulic stimulation is still often done exclusively with water (freshwater, brackish or geothermal brine) without any kind of additives (e.g. Dumas and Angelino, 2013), several other studies highlight the usefulness of chemicals for various stimulation techniques, even in the case of EGS (e.g. Grant and Bixley, 2011; Chabora et al., 2012; Breede et al., 2013 ; Clark et al., 2013). However, in present practice large-scale hydraulic stimulation operations are only complemented with additives for specific purposes because they are very expensive.

While gel and proppants have been developed and largely used in the O&G industry, their use in geothermal wells have been only observed in few cases (e.g. Zimmermann and Reinicke, 2010; Clark et al., 2013). For example utilization of gels and proppants has been reported for several geothermal wells such as the Groß Schönebeck (e.g. Zimmermann and Reinicke, 2010) and Bad Urach (e.g. INL, 2006) sites in Germany, the Baca site in the USA (e.g.

[29] http://www.georgiaunderground.net/all–products/hdd–directional–drilling–products/hdd–bentonite–and–drilling–fluids.html

Morris and Bunyak, 1981; Portier et al., 2007), and the Fjällbacka site in Sweden (e.g. INL, 2006).

Geothermal wells are commonly treated chemically with the aim to remove or avoid flow obstructions into the wells or from fractures close to the well (e.g. Portier et al., 2007; Kalfayan, 2008; Schulte et al., 2010; Clark et al., 2013). In most of the documented cases of chemical stimulation, the acidization involves – depending on the prevailing geological conditions – solutions of hydrochloric acid (HCl), hydrogen fluoride (HF), potassium chloride (KCl) or ammonium chloride (NH_4Cl), with concentrations of around 0.1% to 15%, injected in three main steps (e.g. Sarda, 1977; Jaimes-Maldonado and Sánchez-Velasco, 2003; Nami et al., 2008; Schulte et al., 2010; Clark et al., 2013).

Chemical (sometimes acid) treatments also occur in standard production and injection operations, as additives for corrosion and scale inhibition (e.g. Portier et al., 2007), (e.g. Schulte et al., 2010). Here small dosages are injected usually downhole to counter adverse effects of geothermal brines.

Therefore, even though the concentrations of the diverse chemical substances mixed with water and injected into the wells seem to be low or negligible in some cases due to the dilution factor, the final volume of these substances delivered to the underground must be determined to estimate if there could be potential effects on the surrounding environment. All these activities are regulated activities, requiring permits, regulatory oversight and filings, which are complemented by accepted industry standards.

6.1.2.4 Working Fluids used in the Power Plants

After the drilling and testing phase, the operational phase for a deep geothermal system starts. In the operational phase it has been shown (Gerber and Maréchal, 2012) that for deep geothermal systems in Switzerland, the binary cycle power plant type is more efficient and has lower costs. It can be divided in two power plant types, namely the Kalina cycle, and the organic Rankine cycles. These types of power plants are commonly used in low-temperature environments (≤ 120˚C). In the binary process, geothermal water is used to heat another liquid, such as benzene, which boils at a lower temperature than water. The two liquids are kept completely separate through the use of a heat exchanger, which transfers the heat energy from the geothermal water to a secondary fluid (also known as the "working fluid"). The secondary fluid vaporizes into gaseous vapor and the force of the expanding vapor turns the turbines that power the generators. Finally, the fluid is air cooled or condensed with water. In the meantime, the geothermal fluid is re-injected into the borehole (e.g. Goldstein et al., 2011).

In the Kalina cycle, the working fluid is a composition of water and ammonia (NH3). Ammonia is commonly used as a fertilizer, but there are other applications, e.g. as a precursor to nitrogenous compounds or as a cleaner. Although in wide use, ammonia is toxic and corrosive for humans, and in general is dangerous for the environment (e.g. Roy et al., 2011; Lewis, 1996). In this context, the transportation of the chemical and its use in the power plant poses a potential threat.

In the ORC cycle, the working fluid differs, based on the working temperature (e.g. Saleh et al., 2007). Following Gerber and Maréchal (2012), we considered in the current analysis the most common organic fluids used in ORC cycles. These fluids are n-pentane, iso-butane, iso-pentane, benzene, toluene, n-butane and R134a (see also WP4, Section 5.5.3.1 “Working Fluids”). These fluids are highly inflammable (iso-butane, iso-pentane, benzene, toluene, n-butane), toxic (R134a, iso-pentane) and can impact the environment (iso-pentane). In the EGS context, accidents with these chemicals pose a potential danger to human health and the environment during transportation and their use in the power plant

In this study, the risk of accidents due to the use of hazardous chemicals is considered only for the ORC binary cycle. In fact, the ORC binary cycle is the traditional binary cycle technology while the Kalina cycle technology is relatively recent with only a few plants worldwide operating. For this reason, Switzerland’s potential operators prefer established technologies (Michael Sonderegger and GeoEnergy Suisse, personal communication).

6.1.2.5 Dry and Wet cooling systems

In a geothermal power plant cooling is necessary in order to condense the vapor driving the turbine, lower the heat rejection temperature, raise power output and increase heat to power conversion efficiency (e.g. Mendrinos et al., 2006). The process of cooling can be based on air (dry cooling) or water (wet cooling). Dry cooling is most commonly adopted in geothermal energy systems, having a share of ca. 80% (e.g. Mishra et al., 2011). In a binary cycle power plant the cooling of the working fluid is accomplished by using a second heat exchanger (e.g. Kutscher and Costenaro, 2002). Thus, the fluids never make contact with the atmosphere (air-cooling) or the water (wet-cooling) (e.g. Bahadori et al., 2013). However, a catastrophic accident cannot be completely excluded. For example, a failure of the pipeline that transports the working fluid into the secondary heat exchanger could produce contact between the water/air and the former. As a consequence, based on the working fluids commonly used (Section 6.1.2.4), the environment and the human health could be severely affected.

6.1.2.6 Geofluids

In both the drilling and operational phases a potential risk is connected to the chemical composition of the geofluids and, in particular, to the fluid losses (brine) along the whole geofluids cycle. Geothermal brine is a mixture of saline solution, various chemicals and gases. It can be extremely difficult to handle in geothermal operations due to its high temperature, among other factors (e.g. Stapleton, 2004). Furthermore, severe scaling and corrosion effects of geothermal brines can cause corrosion in wells, lines and equipment. As scaling can strongly limit the performance of the system by decreasing heat transfer, some attempts to mitigate scale formation imply the use of chelating agents or acids with lower corrosion rates (e.g. Clark et al., 2011). Thus, if not handled responsibly, geofluids are a potential source of water and soil contamination due to the presence of toxic minerals (e.g. arsenic, barium, antimony), and elevated dissolved solid elements (e.g. sodium chloride, bicarbonate, sulfate, silica, calcium, potassium, and naturally occurred radioactive materials (NORMs), e.g. Aksoy et al., 2009; Clark et al., 2011).

Proper well drilling, design and engineering controls of the power plant are extremely important for minimizing the risk of accidents, such as pipeline leakage that could spread the brine into the environment, and thus be dangerous to both the environment and human health (e.g. Tester et al., 2006). From recent studies of the underground, it has been shown that freshwater contamination by geofluids is one of the most common impacts of geofluids (e.g. Stapleton, 2004; Aksoy et al., 2009; Clark et al., 2011; Navarro et al., 2011). Other principal pollution elements found in these studies strongly depended on the regional geology. For the U.S. significant concentrations of antimony were found in addition to arsenic (Clark et al., 2011; Stapleton, 2004). The same elements including also boron were found in the groundwater close to the Balcova (Turkey) geothermal field (Aksoy et al., 2009). Finally, Navarro et al. (2011) reported in addition to the arsenic, concentrations of lithium and rubidium in the groundwater close to the La Selva (Girona, Spain) geothermal system. Based on these studies, arsenic can be considered as the most common toxic element possibly present in the geofluid brine. Arsenic is highly toxic for the environment and human health; thus it could be a serious danger in case of its release through geofluids (e.g. due to pipeline leakage).

Finally, radionuclides could also be part of the brine (e.g. Köhler and Degering, 2010; Cuenot et al., 2013; Eggeling et al., 2013). They commonly occur in geothermal fluid samples. The most frequently detected radionuclides are ^{238}U, ^{232}Th, ^{40}K and ^{226}Ra (Parmaksiz, 2013). The accumulation of radionuclides can occur in the inner parts of the drilling equipment, in pipes, valves, tanks, or in cooling systems. Therefore, it can represent, at first, a risk for the workers at a deep geothermal system site. However, in order to avoid and prevent such problems in geothermal installations, measurements of radiation levels on site are constantly performed. Thus, they can lead to the organization of several radioprotection measures for workers and the public (e.g. in France, Cuenot et al., 2013). Furthermore, studies carried out in the USA (EPA, 2013) and Germany (Gellermann et al., 2001; Köhler and Degering, 2010) show that the total expected quantity of radioactive material at geothermal power plants waste is not harmful to human health, unless water samples are used as drinking water. Actually, the radioactive exposure level is expected to satisfy the limit of 1 mSv/yr valid for the population (e.g. EPA, 2013; Gellermann et al., 2001; Köhler and Degering, 2010), while the limit for workers is higher, 20 mSv/yr, with which the results of these studies seem to comply. The latter is achieved, since employers who work with materials that contain small but, from a radiation protection perspective, significant amounts of naturally occurring radioactive substances are required to take action to restrict the radiation exposure of their employees and other persons who may be affected by their work with such materials according, for example, with the Ionising Radiations Regulations 1999 (IRR99) of the NORMs of the UK's Health and Safety Executive.

6.1.2.7 Induced Landslides

In the past, landslides have occurred close to shallow geothermal system sites, but the cause of them is often unclear (e.g. Tester et al., 2006). Many geothermal fields are in rugged terrain that is prone to natural landslides, and some fields actually have been developed atop ancient landslides (e.g. DiPippo, 2012). Badly sited wells, particularly shallow injection wells, may interact with faults and cause slippage. Under these circumstances, it is possible for a section of a slope to give way initiating a landslide. However, proper geological characterization of the field, by analyzing inherent characteristics of the material and the site and the factors which produce an increase in shear stress, and those which reduce shear strength, should eliminate the possibility of such a catastrophe (e.g. Voight, 1992).

6.1.3 Comparative risk assessment of energy technologies

The importance of performing comparative risk assessment of accidents in the energy sector has been repeatedly emphasized in the past (e.g. Rasmussen, 1981, Fritzsche, 1989, Inhaber, 2004). Nowadays, it is considered a well-established discipline, and in the past decades a number of important advancements have been achieved (e.g. Greenberg et al., 2012).

The Paul Scherrer Institut (PSI) initiated a long-term research activity in the early 1990s, building upon extensive historical experience complemented by Probabilistic Safety Assessment (PSA), at the core of which is the Energy-related Severe Accident Database (ENSAD) (Hirschberg et al., 1998). For an up-to-date overview several recent publications and references therein can be consulted (Burgherr et al., 2013, Burgherr et al., 2014, Burgherr and Hirschberg, 2014).

For fossil energy carriers and hydropower (supplemented by site-specific assessments) extensive historical experience is available, whereas for nuclear a site-specific simplified level-3 PSA is required. In the case of new renewables the limited experience needs to be complemented by expert judgment, approximations and analogies, and chain-specific modeling where feasible. Chain-specific results are essential in several respects, i.e. to:

- detect weak points in the energy infrastructure
- calculate a broad range of risk indicators
- compare risks among various energy chains
- evaluate regional differences within and between energy chains
- identify temporal trends

In general, there is no agreed definition of the term risk; however in engineering and natural sciences, risk is commonly decomposed into the product of frequency and severity (e.g. CCPS, 2010):

$$R = f * S$$

The number of accidents per year gives the frequency, while severity measures the extent of the consequences of each accident. The frequency distribution is influenced by temporal trends, while the severity distribution is influenced by a number of parameters such as the material involved in the accident or the different products and the amount of material present, or the number of people in the vicinity of an accident.

Risk is expressed by means of risk indicators using the standard method of aggregated indicators (e.g. Burgherr et al., 2013). In this way it provides a direct measure of accident consequences (e.g. fatalities) per unit of electricity produced (e.g. Gigawatt-electric-year, GWeyr), suitable for comparisons between, for example, hazardous substances.

In the current study, the above described PSI framework approach for risk assessment has been used. The following sections provide an overview of how the risks of hazardous substances and blowouts were assessed for geothermal systems.

6.1.4 Hazardous substances

Risks related to hazardous substances can occur in both the drilling and operational phases.

In the **drilling phase**, the mud is based mainly on water with a low percentage of chemical additives. In general, these additives are considered an "environment and human friendly" mixture (see Section 6.4.1.2), meaning that most of them are not dangerous for the environment and human health. However, in some cases chemicals, such as caustic soda (Michael Sonderegger personal communication), are used in order to affect the pH.

Caustic soda or Sodium hydroxide (NaOH) is an alkaline compound that is used in manufacture of chemicals and soaps as well as in petroleum refining. It is a very corrosive chemical and irritating in all exposure routes. Exposure to low levels of NaOH produces irritation of skin, eyes, nose, and throat. In case of higher-level exposures, NaOH causes severe burns that can result in permanent damage to all tissue it contacts (OEHHA, 2003). Acute exposure by inhalation causes severe burns, swelling of the voice box, lung edema and irreversible obstructive pulmonary disease. Skin exposure can cause painful burns with deep ulcerations. In contact with the eyes opacification of the cornea may occur. Ingestion can produce severe injury to the mouth, esophagus, and stomach (OEHHA, 2003).

In the **operational phase**, the ORC binary cycle is used in the analysis, since it is considered more suitable than the Kalina cycle in Switzerland (Michael Sonderegger and GeoEnergy Suisse personal communication). The most common substances used in ORC cycle are n-pentane, isobutane, isopentane, benzene, toluene, n-butane and R134a. These chemicals are highly toxic and inflammable, meaning that they pose a potential danger for human health and the environment. Among all the substances listed above, the risks related to the use of benzene and toluene are taken into account in this study. In fact, these are the substances most likely to be used in ORC binary cycle in Switzerland (GeoEnergy Suisse personal communication), since in this case the working fluids are subject to the "Chemical Risk Reduction Ordinance" (ChemRRV, 2005).

Benzene is a component of products derived from coal and petroleum and is found in gasoline and other fuels. It is used in the manufacture of plastics, detergents, pesticides, and other chemicals. Benzene is a chemical that is a colorless or light yellow liquid at room temperature. It has a sweet odor and is highly flammable. Benzene evaporates into the air very quickly. Its vapor is heavier than air and may sink into low-lying areas. Benzene dissolves only slightly in water and will float on top of water (OEHHA, 2001a). With exposures from less than five years to more than 30 years, individuals have developed, and died from, leukemia. Long-term exposure may affect bone marrow and blood production. Short-term exposure to high levels of benzene can cause drowsiness, dizziness, unconsciousness, and death (OEHHA, 2001a).

Toluene is a component of products derived from the process of making gasoline and other fuels from crude oil and making coke from coal. It is used in making paints, paint thinners, fingernail polish, lacquers, adhesives, and rubber and in some printing and leather tanning processes. Toluene is a clear, colorless liquid, which becomes a vapor when exposed to air at room temperature. Toluene vapor has a sharp or sweet odor, which is a sign of exposure (OEHHA, 2001b). Toluene can cause irritated eyes, nose, and throat; dry or cracked skin; headache, dizziness, a feeling of being drunk, confusion and anxiety. Symptoms worsen as exposure increases, and long term exposure may lead to tiredness, slow reactions, difficulty sleeping, numbness in the hands or feet, or female reproductive system damage and pregnancy loss. If swallowed, toluene can cause liver and kidney damage (OEHHA, 2001b).

6.1.4.1 Methodological approach

Direct estimation of accident risks due to the use of hazardous substances in geothermal systems is currently not possible, since the available historical experience is very limited. Therefore, this study attempts to provide a justifiable and understandable approximation by using data of accidents in which the three hazardous substances described above were involved, and which occurred during activities that are relevant for the full geothermal energy chain. For example, well, transport and storage accidents have a certain relevance for geothermal, whereas accidents that happened, for example, in a shoe manufacturing cannot be used as a proxy for geothermal.

In total, five databases were queried for accidents involving caustic soda, benzene and toluene. The raw accident information retrieved from the various databases was then further processed to generate the final dataset for analysis:

1. accident records were verified, cross-checked and homogenized
2. accidents not considered relevant for geothermal were removed manually
3. accident subsets for different types of consequences were prepared

The following sections provide detailed information on various aspects of the proposed risk assessment approach for hazardous substances. First, a brief description of the scope and boundary conditions is given to put the analysis into context. Second, the coverage and characteristics of the five databases are presented. Third, it is explained how risk indicators were normalized to ensure that results allow direct comparison among hazardous substances, but also with blowout results.

6.1.4.1.1 Scope and boundary conditions

The current TA-SWISS study has a clear focus on Switzerland, and thus risk assessment results should also be representative for the Swiss situation. It is clear that there are not enough data available to perform a distinct evaluation for the Swiss case. Therefore, a key assumption of this risk assessment is that accidents that occurred in highly-developed countries of the Organisation for Economic Co-operation (OECD) can be considered adequate to provide a valid proxy for Switzerland because the regulatory frameworks and safety procedures are generally more advanced, and more strictly controlled and adhered to, compared to non-OECD member states (e.g. Hirschberg et al., 1998, Burgherr and Hirschberg 2008b; Burgherr et al., 2012).

6.1.4.1.2 Databases

Since the various databases cover different time periods, it was decided to include the years 1990−2012. In this way it can be assumed that the reporting levels are more homogenous than if accidents further back to the 1980s or even 1970s were included. At the same time one should keep in mind that deep geothermal applications are still a relatively new technology when compared to large centralized generation options, and thus taking into account accidents too far back is not so representative for the current situation.

Emergency Response Notification System (ERNS)

http://rtknet.ombwatch.org/db/erns/

The Emergency Response Notification System (ERNS) also called The Spills and Accidents database is a database of incidents reported to the National Response Center (NRC) of the USA. The general public can report to the NRC all kinds of accidents in which hazardous materials are involved. The reports of the NRC, though extensive and useful to study, are known to be partially incomplete and even inaccurate in few cases, since the reported events are generally not confirmed. Additionally, some accidents can be reported twice in the database. However, these shortcomings did not provide a major obstacle for the current analysis because only a small part of the database was queried (three substances), and because query results from the various databases were cross-checked to find potential inconsistencies. There are three different search parameters that are particularly useful to find specific data in the ERNS database: Area search helps finding accidents that occurred in a specific geographic area; Discharger search helps to find all accidents produced by a particular suspected responsible such as a company; Material search allows searching for accidents related to a specific substance.

Major Hazard Incident Data Service (MHIDAS)

OSH-ROM (Occupational Safety and Health on CD-ROM); discontinued in 2006

The Major Hazard Incident Data Service (MHIDAS) was developed on behalf of the Major Hazards Assessment Unit of the United Kingdom Health and Safety Executive. MHIDAS contains information on more than 10’000 accidents from 95 countries around the world, especially the USA, the UK, Canada, Germany, France and India. The accidents registered involve hazardous substances, and resulted in or had the potential to produce an offsite impact. However, nuclear incidents and events associated with the extraction of the materials are not included in this database. MHIDAS has been discontinued in 2006, but is partially continued by OSH Update (see below).

OSH Update

http://oshupdate.com

OSH Update is a collection of 19 databases with worldwide coverage and from authoritative sources. It contains information on occupational health and safety issues. In this study two out of the 19 databases, namely HSELINE and MHAID (Major Hazards Accidents and Incidents), are used.

The database HSELINE is a product of the UK Health and Safety Executive (HSE) Information Services, which since 1977 has collected references to documents relevant to health and safety at work. This includes references to HSE and also the Health and Safety Commission (HSC) publications, together with references to worldwide documents, conference proceedings, journal articles, research reports and legislation in a wide range of manufacturing and service industries, agriculture, explosives, engineering, industrial pollution, mining and nuclear technology. The subjects covered include accident prevention, risk assessment, occupational medicine and hygiene, ergonomics, stress management, toxicology and safety engineering.

The MHAID database contains information on worldwide accidents or incidents involving hazardous materials that resulted in, or had the potential to lead to a significant impact on the public at large, including evacuation. The information covers all industries and transport. The data in MHAID is collected from regular international sources, including links to the full text of the source document or report where possible.

Failure and Accidents Technical Information System (FACTS)

http://factsonline.nl

FACTS (Failure and Accidents Technical information System) is an accident database, which contains information on more than 25200 (industrial) accidents and incidents involving hazardous materials or dangerous goods that have happened all over the world during the past 90 years. This database includes both accidents causing severe damage or danger and near misses. The level of detail and quality of the accident information is partially related to the seriousness and impact of an event. For the most serious accidents detailed information is available; most of it electronically.

Analysis Research and Information on Accidents (ARIA)

http://aria.developpement-durable.gouv.fr

The ARIA (Analysis, Research and Information on Accidents) database is operated by the French Ministry of Ecology and Sustainable Development. This database contains a list of incidents, which have produced or have the potential to produce an impact on the public such as damage to human health or public safety. Accidents have been collected since 1992, and there is a dominance of accidents that occurred in France, but some important foreign accidents are also registered. The total number of incidents collected by the end of 2012 is about 40’000. The events have occurred mainly in industrial or agricultural facilities.

6.1.4.1.3 Normalization of risk indicators

To ensure a fair, transparent and consistent comparison of risk indicators it is a necessary prerequisite that they can be expressed in a common format, i.e. that they are normalized to the same reference unit. Additionally, it is desirable that the risk indicators calculated in this study are comparable to previous evaluations carried out by PSI’s technology assessment group, and that the indicators produced here can be used in the integration chapter of this report. Therefore, risk indicators for hazardous substances are normalized to the unit of Giga-Watt electric year (GWeyr) for each substance.

In a first step, accident consequences were normalized to total production in the period 1990−2012 of each substance in OECD, since relevant accidents in all OECD countries were considered. The total OECD production is estimated as ca. 60% of global production for each substance, based on the ACC (2012) report. This approximation is made due to the lack of detailed information on OECD production. Furthermore, annual production data were not available for the whole period 1990−2012, which is why OECD production was considered constant. It is clear that this should be considered a rough estimate, but a brief web search also indicated that production levels were often quoted to be relatively stable. **Table 28** shows worldwide production estimates for caustic soda as well as benzene and toluene.

***Table 28**: Annual production in kg of each substance for OECD countries. Reference production years are 2002, 2006 and 2007 for Toluene, Benzene and Caustic Soda, respectively.*

Hazardous Substance	**Annual Production** (kg)	**Production (1990–2012)** (kg)	**Reference**
Caustic Soda	4.67E+10	1.07E+12	(USGS, 2007)
Benzene	1.70E+10	3.91E+11	(CEN, 2006)
Toluene	1.02E+10	2.35E+11	(METI, 2003)

In the second normalization step, risk indicators per kg were converted to GWeyr. For this purpose the Swiss base case of a geothermal power plant as described in WPs 3 and 4 (Chapters 4 and 5) was used. It is assumed that the power plant is able to generate 1.49E+9 kWh. Based on the conversion that 1 GWeyr equals 8.76E+9 kWh, the base case plant is expected to produce a total of 1.70E-1 GWeyr over its entire lifetime.

According to WP4 1 kg of caustic soda is used per 1 meter of drilling. As a first approximation, the use of caustic soda is considered constant for the entire drilling phase. Therefore, it is likely that the entire amount of caustic soda used in the drilling phase is overestimated, since it is only needed under specific conditions, i.e. to stabilize the pH, and not during the entire drilling phase. By considering a drilling depth of 5000 m and 6 wells over the plant lifetime of 30 years, the total amount of caustic soda used in the geothermal drilling phase equals 30’000 kg.

In case of working fluids, the amounts used are based on the sum of the initial input (see **Table 28**) and the quantity of substance that must be used in order to fill up the initial value due to an assumed annual loss of 8% (see WP4, Section 5.5.5). These results are considering a 1-unit power plant. However, the base case 5.52 MW power plant is modeled with 5.05 units, see WP4, Section 5.5.4. In **Table 29** the total use for 30 years lifetime of working fluids for the power plant under consideration are shown.

***Table 29**: Total amount of working fluid used over the entire lifetime (30 years) of a 5.52 MW power plant, considering a yearly loss of 8% of the initial input.*

Hazardous Substance	**Initial Input (kg)**	**Total Losses over the entire lifetime (30 years) (kg)**	**Total amount of working fluid used over the entire lifetime (30 years) (kg)**	**Total amount of working fluid used over the entire lifetime (30 years) for a 5.05 unit power plant (kg)**
Benzene	436	1046.4	1482.4	7486.1
Toluene	432	1036.8	1468.8	7417.4

The information about the use of hazardous substances for the deep geothermal power plant under consideration is then used to estimate the various risk indicators. The normalization factors for each substance in this study are shown in **Table 30**.

***Table 30**: Normalization factor for risk indicators. It is calculated as the ratio between the total amount of substance used at the power plant and the product of the total worldwide production in the time period 1990−2012 of the substance and the power plant total production in GWeyr over its entire lifetime (30 years).*

Hazardous Substance	Production (1990−2012) (kg)	Used amount of substance in deep geothermal power plant (kg)	Power plant production (GWeyr)	Normalization Factor (1/GWeyr)
Caustic Soda	1.07E+12	3.00E+4	1.70E-1	1.64E-7
Benzene	3.91E+11	7.49E+3	1.70E-1	1.13E-7
Toluene	2.35E+11	7.42E+3	1.70E-1	1.86E-7

6.1.4.2 Overview of accidents with hazardous substances

The structure of the pooled database for the three hazardous substances included 22 fields per accident record (**Table 31**). The field information source refers to the database in which the accident was reported, while the ID Number is an identification number used in the database compiled for this study to clearly identify each incident. Data fields 3 to 6 cover the date and the year of the accident, and some geographical information that corresponds to the place of occurrence (country, city). Then, the type of industry and the industry group (i.e., transport, storage) is recorded for further event classification. Incident type refers to the type of accident (e.g. release). Data fields 10 to 13 describe the consequences of an accident, and field 14 reports if a fire occurred. After this, information on the involved substance is provided (fields 15-17), followed by financial loss data (fields 18-20). Finally, accident cause and a full-text abstract are given.

***Table 31**: Information structure of the poolded database as collected from the primary accidents databases.*

1	Information Source	12	Evacuations (Y/N)
2	ID Number	13	Evacuees
3	Date of Accident	14	Fire (Y/N)
4	Year of Accident	15	Substance Name
5	Country	16	Amount of Substance Released
6	City	17	Measurement Unit for Substance Released
7	Industry Type	18	Financial Loss (Y/N)
8	Industry Groups	19	Financial Loss
9	Incident Type	20	Currency
10	Fatalities	21	Accident Cause
11	Injuries	22	Abstract

Figure 95 shows the contributions of the different databases to the final accident compilation. Data from ERNS and FACTS have the highest shares with 48% and 34%, respectively. The category "Other" represents accidents that were reported in more than one database.

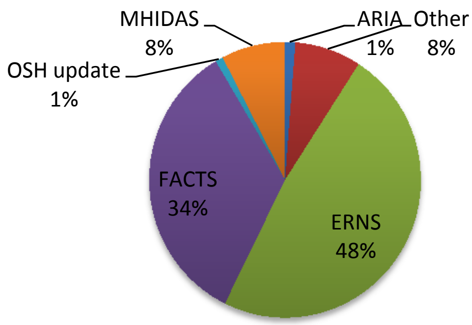

Figure 95: *Contributions of the different databases used in this study (1990–2012). The category "Other" denotes accidents that were present in more than one database.*

6.1.4.2.1 Drilling phase accidents: caustic soda

The annual number of accidents in OECD countries involving caustic soda and causing at least one consequence (e.g. fatality) is shown in **Figure 96**. In general, the mean number of accidents involving this substance in the last 23 years is approximately 13 per year. Furthermore, the annual data can be roughly divided into a phase from 1990–2005 with a higher average of 15 and a phase from 2006–2012 with an average of 8, suggesting that the number of accidents is on a decreasing path. However, it should also be noted that the last three years (2010–2012) exhibit substantially lower values than the years before, which might be partially attributable to underreporting that further strengthened the decrease since 2006.

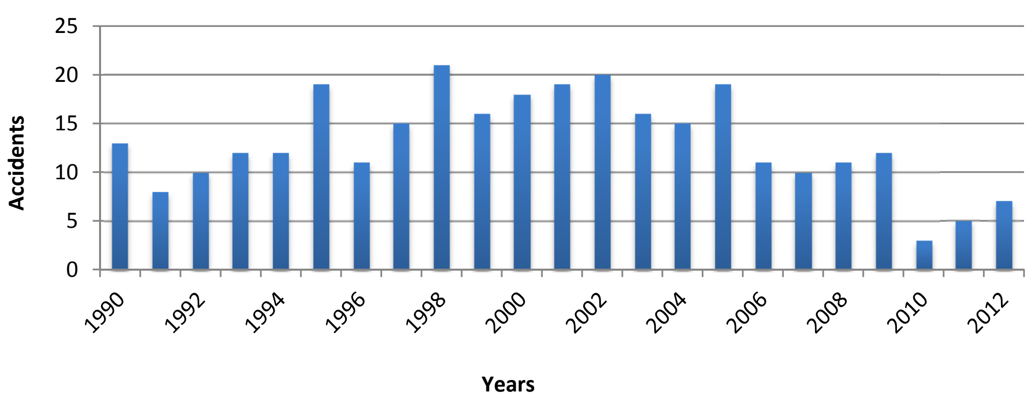

Figure 96: *Annual number of accidents in OECD countries involving caustic soda (1990–2012) that resulted in at least one consequence (e.g. fatality).*

Caustic soda can be used as an additive for the water mud in the drilling phase. For this reason, in this study only accidents that happened during storage, transportation and in the well drilling phase are included because they are considered to cover relevant activities with respect to geothermal systems. Furthermore, only accidents in road and rail transport are included, since this is the most probable means of transport in Switzerland. **Figure 97** shows the contributions of accidents in the various categories (panel a), and the division of transportation accidents (panel b).

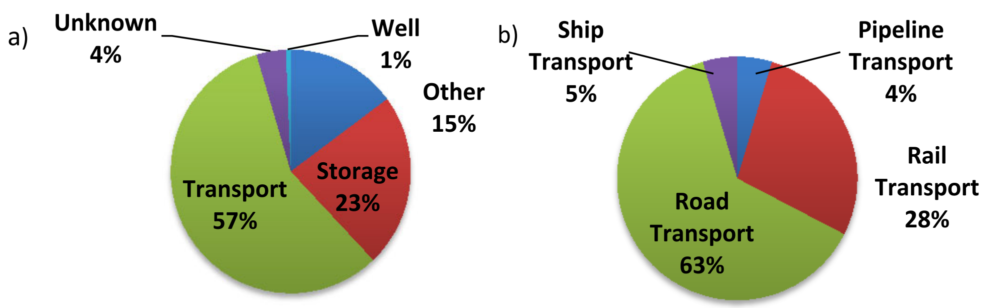

Figure 97: *a) Categories of accidents in the caustic soda dataset. The categories "Other" and "Unknown" refer to accidents that happened in other sectors, but in the former the sector is known (e.g. manufacture), while in the latter it is unknown. b) Accident types in the transportation phase.*

Based on the above-mentioned criteria, the final dataset for accidents involving caustic soda was constructed.

Figure 98 depicts the annual total numbers of accidents as well as the contributions of the categories well drilling, storage and transportation. Compared to **Figure 96** the final dataset contains 246 instead of 303 accidents. Therefore, the mean number of accidents per year is reduced to ca. 11, which are ca. 2 accidents per year less than the starting dataset (**Figure 96**). The final accident dataset for caustic soda is strongly driven by transportation accidents, followed by storage accidents, whereas well drilling accidents are negligible.

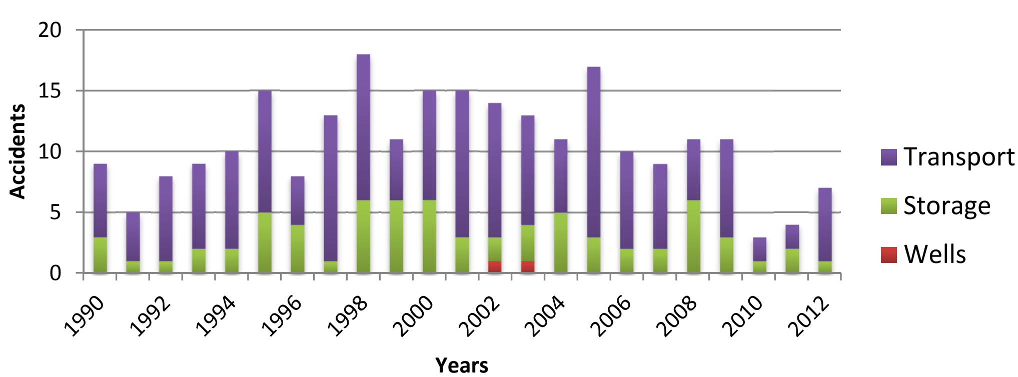

Figure 98: *Total accidents per year involving caustic soda in the well drilling, transport (rail and road) and storage sectors analyzed in this study.*

6.1.4.2.2 Working fluid accidents: benzene and toluene

Figure 99 shows the annual numbers of accidents in OECD countries related to benzene and toluene that caused at least 1 consequence (e.g. fatality). The contributions of toluene and benzene accidents are 58% and 42%, respectively.

The mean number of accidents involving these two substances in the last 23 years is approximately 15 per year. Similar to caustic soda accidents, it appears that the annual numbers of accidents for working fluid are generally lower after 2004 than in the years before. It is possible that this downward trend is amplified by a combination of increased safety and underreporting, particularly in the last years of the observation period.

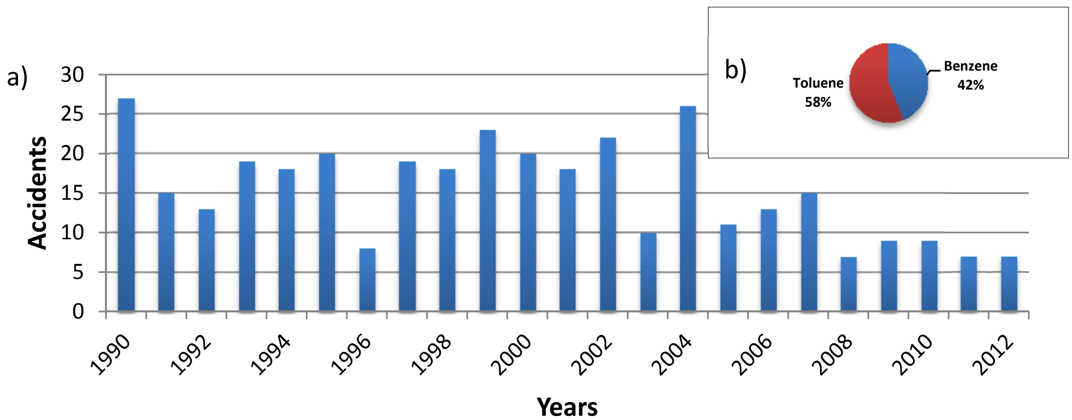

Figure 99: *Contributions of toluene and benzene to working fluid accidents in OECD (1990–2012).*

Benzene and toluene are used in the operational phase of deep geothermal systems only. Thus, we consider in this study only accidents related to the storage, the transportation and the use of these substances. Accidents in the use phase include pipes and tubes that were affected due to valve, well, pump failures, etc. and that can be associated to ORC binary cycle systems (**Figure 100**a). These accident types can be grouped in a separate category called geothermal accidents (**Figure 100**b).

Figure 100b shows the contribution of the accidents in storage, transportation and geothermal type accidents that are analyzed in this study. Accidents classified as non-geothermal are excluded from the analysis. In this study only transportation accidents attributable to pipelines, road and rail are considered. The reason for this is that on the one hand the substances are circulating in pipes in an ORC system, and on the other hand road and rail are the most probable options to transport toluene and benzene on-site in Switzerland (**Figure 100**, **Figure 100c**).

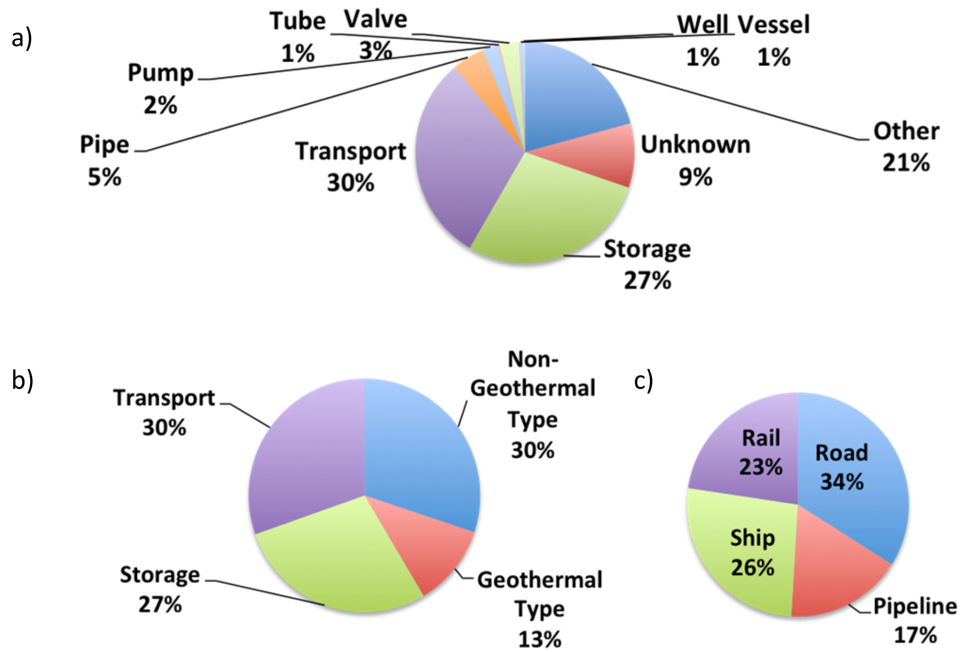

Figure 100: *a) Types of accidents in the benzene and toluene datasets. The categories "Other" and "Unknown" refer to accidents that could not be assigned to any category. However, in the former the sector is known (e.g. manufacture), while in the latter it is not. Both of these categories are not considered in this study b) Four main groups of accidents can be distinguished, but non-geothermal accidents are not considered in this study. c) Types of accidents in the transportation phase. In this study only accidents that happened in rail, road and pipeline transportation are included.*

Figure 100 a-b shows the final accident datasets in OECD countries for benzene and toluene, respectively. As explained above the categories transportation (i.e., pipeline, rail, and road), storage and geothermal type accidents were distinguished, and accidents that resulted in at least one consequence (e.g. fatality) were included in the analysis. Both substances exhibit a similar pattern to **Figure 99**, i.e. annual numbers of accidents were generally higher in the years 1990−2004 compared to 2005−2012. In the case of benzene the three accident categories contributed rather equally, whereas for toluene transportation and storage accidents were more important than geothermal type accidents.

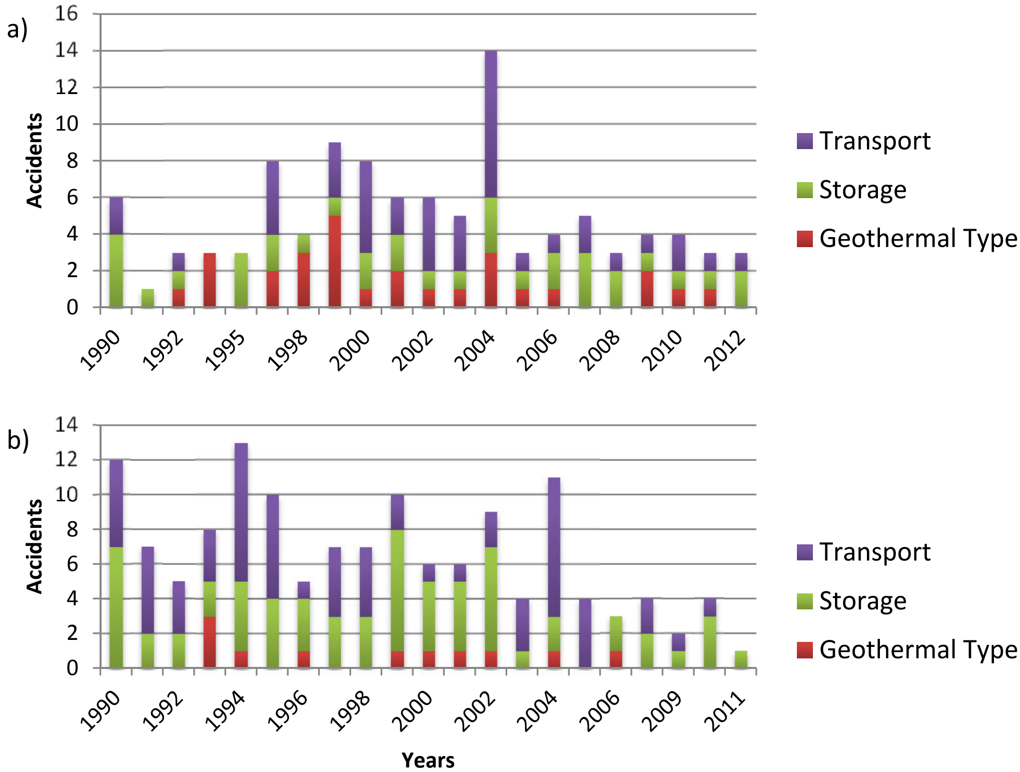

Figure 101: *Annual numbers of accidents and corresponding shares for transportation (rail, road and pipeline), storage and geothermal type accidents (1990–2012). a) Benzene; b) Toluene.*

6.1.4.3 Risk indicators for hazardous substances

Based on the previously described accident datasets and the normalization procedure, specific risk indicators for the three hazardous substances can be calculated. **Table 32** summarizes for each substance the numbers of accidents and associated consequences in OECD countries for human health, environmental and economic impacts in the years 1990–2012. It is important to note that non-normalized consequences can be strongly influenced by single events. For example the significantly higher number of evacuees for benzene is due to a rail transport accident in the USA in 1992 that caused the evacuation of 80'000 people. Risk indicators were calculated for all types of consequences listed in the table, except for economic loss because accident data were most scarce for this indicator (less than 10 per substance).

Table 32*: Summary of the numbers of accidents and associated consequences in OECD countries for accidents with at least one consequence (e.g. fatality) in the period 1990–2012.*

Hazardous Substance	**Immediate Fatalities** Acc/Fat	**Immediate Injuries** Acc/Inj	**Evacuees** Acc/Eva	**Release (Metric Tons)** Acc/Rel	**Economic Losses (USD)** Acc/EL
Caustic Soda	17/39	177/1386	38/15263	113/3389.34	9/1.72E+06
Benzene	14/45	54/1273	91/96513	51/10474.56	5/3.76E+07
Toluene	31/37	110/1291	61/7826	47/1235.41	7/5.44E+07

6.1.4.3.1 Immediate fatalities

Figure 102 shows the immediate fatality rates for each hazardous substance. The immediate fatality rates for the various hazardous substances are in the range of 10E-6 per GWeyr. However, drilling additives (caustic soda) seem to be more risky compared to the working fluids, although the order of magnitude is the same.

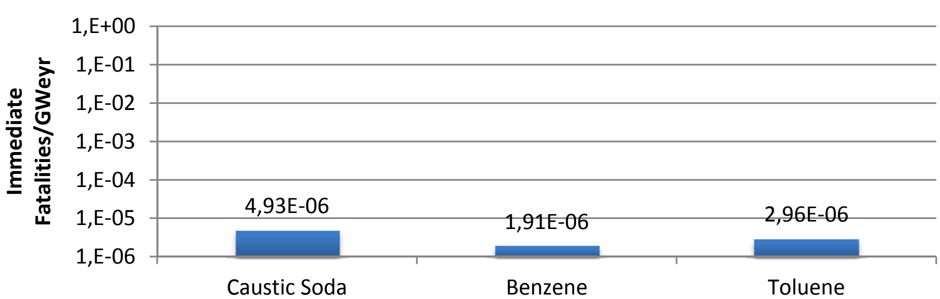

Figure 102: *Immediate fatality rate for the three hazardous substances analyzed in this study for OECD countries (1990–2012).*

6.1.4.3.2 Immediate injuries

Figure 103 shows the immediate injury rates (immediate injuries/GWeyr) for the three analyzed hazardous substances. This risk indicator varies between 10E-4 to 10E-5 per GWeyr. Overall, drilling additives (caustic soda) appear to perform worse than the working fluids.

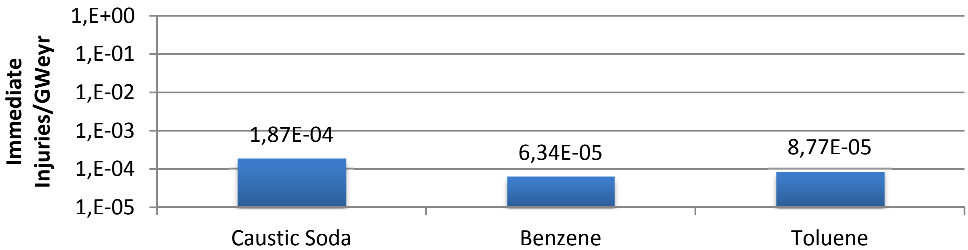

***Figure 103:** Immediate injury rates for the three hazardous substances analyzed in this study for OECD countries (1990–2012).*

6.1.4.3.3 Evacuees

Figure 104 shows the evacuee rates (evacuees/GWeyr) for the hazardous substances analyzed in this study. The evacuee rates are between 10^{-4} to 10^{-3} per GWeyr. The value for benzene is about one order of magnitude higher than caustic soda, and even two for toluene.

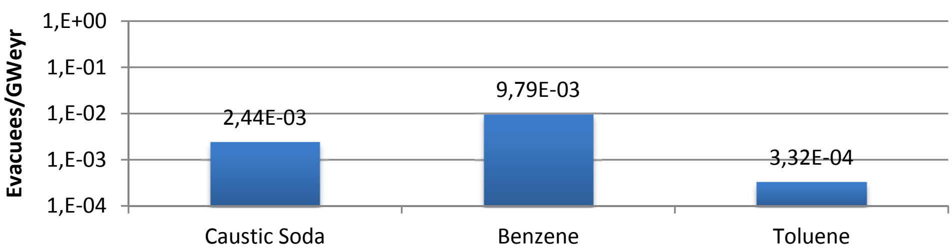

***Figure 104:** Evacuee rates for the three hazardous substances analyzed in this study for OECD countries (1990–2012).*

6.1.4.3.4 Accidental release

Figure 105 shows the release rate (total amount of substance released/GWeyr) for each hazardous substance analyzed in this study. This risk indicator is in the range of 10^{-4} to 10^{-5} per GWeyr. In particular, results for drilling additives (caustic soda) indicate a higher risk of release compared to the working fluids, which exhibit rather similar risk levels.

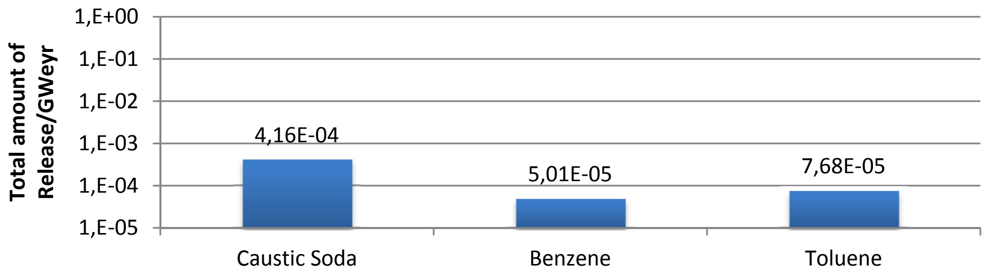

Figure 105: *Total amount of substance released rates for the three hazardous substances analyzed in this study for OECD countries (1990–2012).*

6.1.5 Blowouts

Blowouts can occur both during well drilling and operation. Although deep geothermal and O&G wells differ in temperature (higher in deep geothermal), production pressure (lower in deep geothermal), and production rates (higher for deep geothermal) (e.g. Tester et al., 2006), the risk of onshore blowout as estimated for O&G can be generally considered a sufficiently accurate starting point. However, Switzerland has only very small gas and no oil reserves (e.g. BFE, 2007). Therefore, in this study, only natural gas blowout accidents are considered as a relevant proxy for deep geothermal systems located in Switzerland.

6.1.5.1 Methodological Approach

Since Switzerland neither had nor has significant exploration and production activities in the natural gas sector, blowout accidents in the whole OECD are considered. This extension in geographical coverage is based on the assumption that OECD countries have stricter regulatory frameworks and thus higher safety standards compared to non-member countries. It has been shown in previous studies that OECD countries generally have lower accident risks and comprise a more homogenous group than non-OECD (e.g. Burgherr and Hirschberg, 2008b, Burgherr and Hirschberg, in press).

The Energy-related Severe Accident Database (ENSAD) was used to compile relevant natural gas blowout accidents (see Section 6.1.3). Furthermore, the FACTS database (see Section 6.1.4.1.3) searched for additional data that could potentially complement the accidents available in ENSAD.

The database ENSAD uses seven criteria to distinguish between severe and smaller accidents (Hirschberg et al., 1998; Burgherr and Hirschberg, 2008a). An accident is considered severe if it a meets one or several of the following severity thresholds:

- at least 5 fatalities or
- at least 10 injured or
- at least 200 evacuees or
- an extensive ban on consumption of food or
- releases of hydrocarbons exceeding 10’000 (metric) tons or

- enforced clean-up of land and water over an area of at least 25 km^2 or
- economic loss of at least 5 million USD (2000)

In this study both small and severe accidents are considered to ensure a consistent calculation of risk indicators for blowouts and hazardous substances (see Section 6.1.4.3). Furthermore, the same boundary conditions with respect to the time period (1990−2012) and geographic coverage (OECD) were chosen to define the final blowout dataset.

Finally, risk indicators for blowout accidents were normalized to GWeyr to enable direct comparisons with the corresponding indicators for hazardous substances (see Section 6.1.4.1.3). For further information on indicator normalization see for example the following publications and references therein (Burgherr et al., 2013, Burgherr et al., 2014). Risk indicators for the USA were normalized using statistical data published by the U.S. Energy Information Administration (EIA, 2014). **Table 33** shows the US onshore and offshore natural gas production for the years 1990−2012.

Table 33: *Onshore and offshore natural gas production in the USA for the period 1990−2012. Million tonnes of oil equivalent were converted to GWeyr using a generic efficiency factor of 0.35 (Hirschberg et al., 1998).*

Location	Production (Mtoe)	Production (GWeyr)
Onshore	9071	5480
Offshore	2141	1293

6.1.5.2 Overview of blowout accidents in the natural gas chain

The final blowout dataset (28 accidents) combining accidents from the ENSAD and FACTS databases is shown in **Figure 106**a. Overall, more than three quarters of all accidents are contributed by ENSAD, another 18% by FACTS, and only 4% were found in both databases (category "Other"). The majority of blowout accidents happened onshore and offshore in the USA (82% of the total), followed distantly by Canada and Hungary (**Figure 106**b). The shares of onshore and offshore accidents are 75% and 25%, respectively (**Figure 106**c).

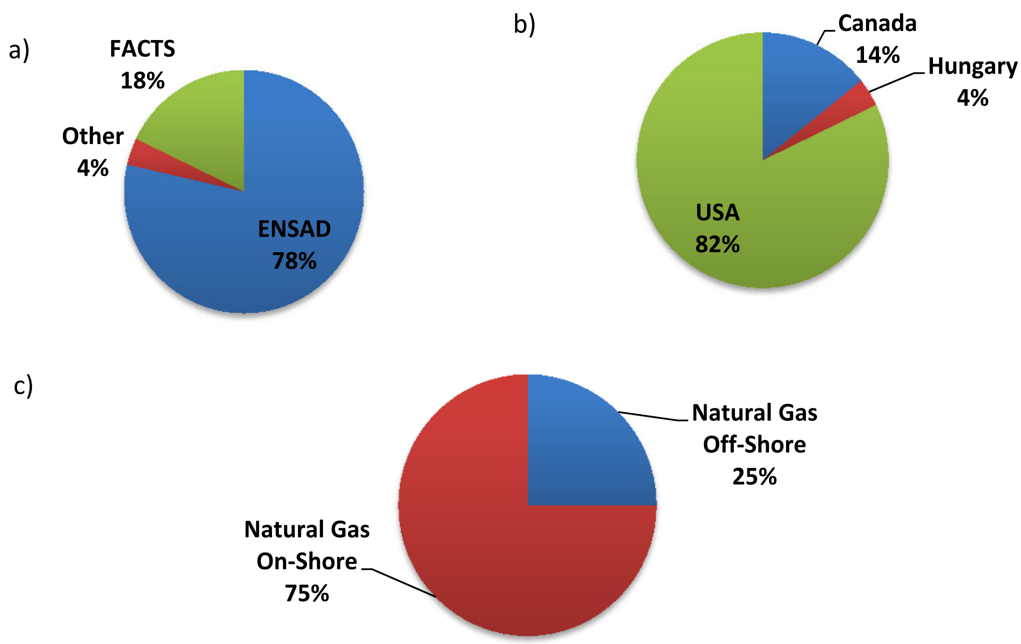

Figure 106: *a) Contributions of the different databases to the final dataset of natural gas accidents in OECD (1990–2012). The category "Other" denotes accidents that are present in both datasbases. b) Country shares of blowout accidents. c) Contributions.*

This might be possibly explained because onshore winning areas could also affect the general public (e.g. evacuation) if not located too far from populated places, while in case of offshore accidents the consequences are normally restricted to workers only. In summary, available onshore and offshore blowout data for the years 1990–2012 are dominated by accidents that took place in the USA. Therefore, subsequent risk indicator calculation is limited to USA rather than the whole OECD.

6.1.5.3 Risk indicators for blowouts

As discussed in the previous section, OECD accident data for blowouts are strongly dominated by USA. Therefore, risk indicators are calculated for USA, instead of the whole OECD. Furthermore, a distinction between onshore and offshore accidents is made to illustrate the differences.

Figure 107 shows the distribution of onshore and offshore accidents in the USA causing at least one type of consequence (fatality, injury or evacuee) over the period of observation (1990–2012). The frequency of onshore accidents is ca. 0.95 per year, which is about three times higher than offshore (0.3 accidents per year). However, the figure also clearly indicates that only a very limited amount of data is available, and thus the results should be interpreted with adequate caution.

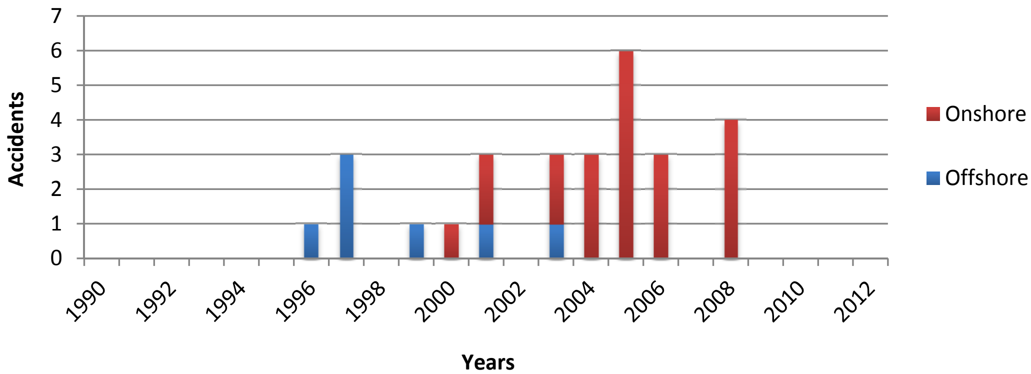

Figure 107: *Annual onshore and offshore blowout accidents in the US natural gas sector for the years 1990–2012.*

A summary of blowout accidents causing at least one type of consequence (e.g. fatality) is given in **Table 34**. While data for fatalities are relatively similar for onshore and offshore blowouts, there are clear differences in terms of injuries and especially evacuees. The significantly higher number of evacuees in onshore accidents is partially attributable to a single accident in 2006 that caused the evacuation of 2000 people.

Table 34*: Summary of blowout accidents with at least one consequence type (e.g. fatality) that occurred in the USA in the period 1990–2012.*

Blowout Location	Fatalities Acc/Fat	Injuries Acc/Inj	Evacuees Acc/Eva
Onshore	4/4	8/15	9/3493
Offshore	3/6	0/0	2/57

Normalized blowout risk indicators were calculated for fatalities, injuries and evacuees (**Figure 108**). The available data were not sufficient to calculate other indicators such as the amount of hydrocarbons released and the economic loss per GWeyr. The fatality rate for offshore accidents is one order of magnitude greater than onshore. For injuries only an onshore risk indicator could be estimated, which is clearly higher than the corresponding fatality rate. Normalized indicators for evacuees are by far the highest, particularly in the case of onshore blowouts. However, this is due to the previously mentioned accident that led to the evacuation of 2000 persons.

Overall, the results of this analysis suggest that blowouts potentially pose a higher risk than the use of hazardous substances (compare Section 6.1.4.3) for current deep geothermal projects with regard to human health effects. However, environmental impacts due to accidental releases of hazardous substances should not be neglected because it is not only the amount released that determines the consequences, but also toxicity and exposure levels as well as location-specific factors.

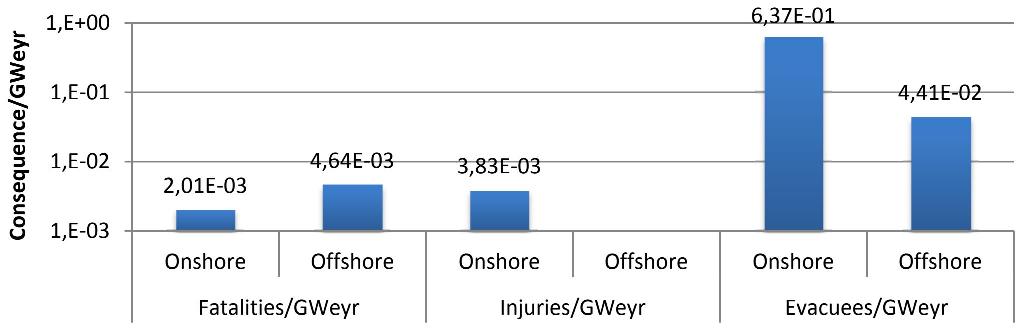

Figure 108: *Consequence rate (e.g. Fatalities/GWeyr) risk indicators for onshore and offshore blowouts in USA.*

6.1.6 Conclusions and recommendations

6.1.6.1 General remarks

Comparative risk assessment (CRA) is a mature and well-established discipline, and in the past decades numerous important conceptual and methodological advancements were achieved. Furthermore, CRA is nowadays strongly connected to the broader conceptual frameworks of sustainability, energy security, critical infrastructure protection and risk governance.

It is of utmost importance that CRA strongly relies on a consistent and comprehensive basis, upon which a variety of risk indicators can be systematically calculated to ensure an objective and quantitative comparison of the strengths and weaknesses of different energy technologies.

For this purpose, in the early 1990s the Paul Scherer Institut (PSI) started a long-term research activity, at the core of which is its Energy-related Severe Accident Database (ENSAD).

6.1.6.2 Accident risks of deep geothermal systems

A comprehensive risk assessment of deep geothermal systems should take a holistic perspective to adequately address the various risk aspects that can cause an accident, and accordingly can affect human health, the environment, property and economic activities.

This chapter starts with a concise overview of the different accident risks that should be taken into account when evaluating deep geothermal systems, both in the drilling and operational phases. Then an in-depth analysis for hazardous substances and blowouts is presented, which normally receive much less attention due to the public focus on induced seismicity.

Generally, the risk in both petrothermal and hydrothermal systems are similar, since drilling and operational phases are the same, except for the risk associated with the use of chemicals during hydraulic stimulation, which is a phase related to petrothermal systems only.

In this study, three hazardous substances were assessed, namely caustic soda that is a mud additive in the drilling phase, and benzene and toluene that are working fluids in the operational phase of the ORC binary cycle.

Risk indicators were estimated based on data of historical accidents with these substances in OECD countries during the period 1990−2012. Such an approach is considered representative for Swiss conditions because of similar regulatory frameworks and safety levels on the one hand, and because only accidents were considered that can serve as a relevant proxy for deep geothermal systems on the other hand.

Accident consequences were normalized to the base case geothermal power plant as described in Chapter 5, which allows direct comparisons among different risk indicators (hazardous substances vs. blowouts) and different types of consequences (e.g. fatality, injury, etc.). In other words, all risk indicators are expressed as consequence or impact per GWeyr.

Overall, results for hazardous substances in drilling and operational phases point towards low risk levels in OECD countries, which are also considered representative for Switzerland. Generally, caustic soda exhibited the highest risks, except for evacuees where benzene performed worst.

Blowout risk was approximated using corresponding natural gas accidents in OECD countries that occurred in the period 1990−2012, since no specific historical experience for deep geothermal systems is available. The final blowout dataset was strongly dominated by accidents that took place in the USA, and therefore it was decided to calculate risk indicators only for the USA. Additionally, onshore and offshore accidents were compared to provide an additional comparison.

The fatality rate for onshore blowouts was one order of magnitude lower than for offshore. In the case of injuries only an onshore rate could be calculated due to missing data for offshore. Normalized indicators for evacuees were by far highest, particularly in the case of onshore blowouts. However, this is due to a single accident that resulted in the evacuation of 2000 persons.

In conclusion, the results of these analyses indicate that blowouts potentially pose a higher risk than the use of hazardous substances for current deep geothermal projects with regard to human health effects. However, environmental impacts due to accidental releases of hazardous substances should not be neglected because it is not only the amount released that determines the consequences, but also toxicity and exposure levels as well as location-specific factors.

Therefore, a comprehensive risk assessment for deep geothermal systems should consider a broad variety of risk aspects, and not just focus on induced seismicity.

Finally, in addition to the quantitative risk assessment results stated above, an in-depth literature review revealed further areas of potential concern. Due to their composition, geofluids are a possible risk to human health and the environment. Published studies describe different impacts associated to geofluids. For example, acids could corrode the cement in the borehole with potentially disastrous consequences to the environment. Furthermore, the brine that accumulates in the geofluid cycle can become an issue due to its chemical composition. In fact, if not correctly treated, it can harm the workers as well as the environment due to the presence of hazardous chemicals such as arsenic. Lastly, it has been shown in different countries (e.g. Germany, Turkey, France) that geofluids could contain traces of radionuclides. However, the radioactive doses to the public and workers are expected to be below the prescribed limits, according to studies published so far.

6.1.6.3 Future research recommendations

The current case study for hazardous substances and blowouts yielded interesting results and valuable insights; however, it should also be seen as a stimulus for further research.

To overcome the observed limitation in available historical accident data, on the one hand additional information sources should be explored, and on the other hand evaluations should be complemented by novel statistical approaches as well as scenario modeling.

In the case of hazardous substances, toxicity and exposure levels need to be incorporated into the analysis.

Projects such as Geotherm-2 and SCCER Supply of Electricity provide excellent opportunities to expand assessment of accident risks for deep geothermal systems beyond current state-of-the-art.

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6.2 Seismic risk

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6.2.1 Introduction

The Earth's crust is critically stressed in most places (Townend and Zoback, 2002), and it is a well-established fact that man-made perturbations to the stress conditions – for example through fluid injection (e.g. hydraulic stimulation and fracturing, waste water disposal and CO_2 storage (e.g. Nicholson and Wesson, 1990; Evans *et al.*, 2012; Zoback 2012), fluid extraction (e.g. Segal, 1989), reservoir impoundment (e.g. Talwani, 1997; Gupta 2002), mining (e.g. Gibowicz, 1990; Gibowicz and Lasocki, 2001), chemical alteration (Atkinson, 1984; Simpson, 1986) – can lead to enhanced seismic activity. Induced seismicity has received increased attention in the past few years, because a number of subsurface energy projects have been delayed or canceled because of felt earthquakes and the concerns they caused. Managing induced seismicity is thus increasingly one of the most relevant challenges for geo-energy applications around the world that alter the stress and pore pressure conditions in the deep underground (Ellsworth, 2013; Giardini, 2009; Zoback, Kohli, Das, and Mcclure, 2012). For mining-related activities, induced earthquakes have been known to the local population for many decades, other technologies, such as deep geothermal applications and shale gas fracking-related activities have only in the past few years been challenged by the occurrence of induced seismicity.

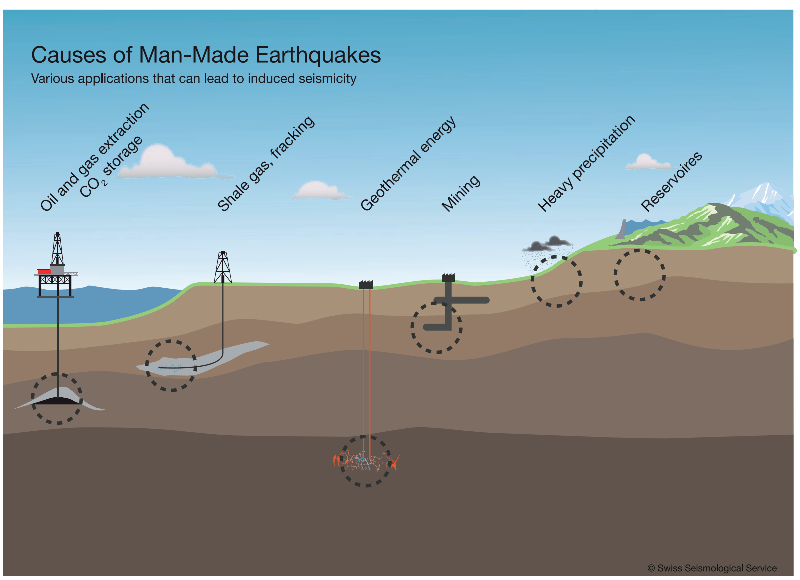

Figure 109: *A selection of underground engineering applications where induced seismicity may occur.*

Induced seismicity is in many cases an undesired by-product that operators strive to minimize as much as feasible. In other applications, such as EGS, induced earthquakes are a required element, a necessary tool for creating a permanent permeability enhancement in the reservoir. It is also an important tool to monitor the reservoir evolution both in space and time, allowing operators and scientists to optimize energy exploitation, and to improve their understanding of the physical conditions within the reservoir. However, in either case the associated nuisance, the potential seismic hazard or the threat to cap rock integrity related to induced earthquakes can delay, or in some cases stop, geo-energy projects (Ellsworth, 2013; Giardini, 2009; Zoback *et al*., 2012).

Induced earthquakes have received growing attention by the public, the media and regulators. This is partially because they have increased in number and in magnitude with increasing human activity: For example, induced earthquakes caused by fracking-wastewater related projects in the eastern US seem to have more than tripled the rate of naturally occurring M ≥ 3.0 earthquakes since 2010 (Ellsworth, 2013). This has caused induced earthquakes as large as magnitude 5.7 in Oklahoma in 2011 (Keranen, Savage, Abers, and Cochran, 2013), an earthquake that caused several 10's of millions of US$ in damage and is considered a 'game changer' by American scientists. Likewise, the 2011 M5.1 Lorca earthquake in Spain is believed to be an induced earthquake, caused by water extraction from an aquifer. Fracking-related projects in Blackpool (UK) and in the Horn River Basin (BC, Canada) have been delayed. Earthquakes of up to magnitude 3.6 in the Groningen gas field are currently causing increasing concern in the local population and substantial investment in monitoring and building retrofitting. In Switzerland, deep geothermal energy projects in Basel in 2006 and St. Gallen in 2013 have been abandoned or halted because of the earthquakes they induced. In **Figure 110** we show an incomplete map of areas where induced seismicity has been reported.

However, it is important to remember that while the economic impact of induced earthquakes has been substantial, they have so far caused very few injuries and few, if any, fatalities. This compares to more than 15'000 people dying on average every year through earthquakes and earthquake related effects (tsunamis, landslides, fires).

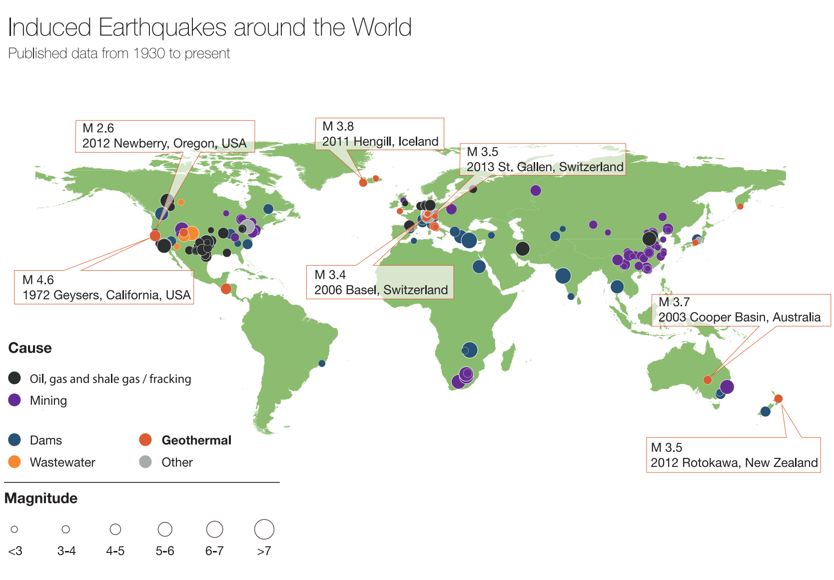

Figure 110: *Map of the World, circles mark the epicenters of induced earthquakes, color-coded by type. The size represents the magnitude. A selection of induced seismicity events related to deep geothermal energy projects is tagged.*

6.2.2 Induced earthquakes

6.2.2.1 Terminology

Earthquakes in response to man's engineering activity have been labeled by many adjectives: e.g. man-made (anthropogenic), artificial, stimulated, induced, or triggered. Some researchers have proposed to classify man-made earthquakes on a physical basis as 'induced' if the human activity causes a stress change that is comparable in magnitude to the shear stress acting on a fault to cause slip, or as 'triggered' should the stress change only be a small fraction of the ambient level (e.g. Bossu, 1996; McGarr and Simpson, 1997).

Unfortunately, the scientific literature has never made consequent use of this definition, and many cases that are commonly labeled 'induced' should correctly be labeled 'triggered' when following the definition above (McGarr, 2002). Furthermore, there is a continuous gradient between the two definitions and a strong dependency of the classification result on the physical model used. The exact contribution of tectonic stresses versus human induced perturbation is generally unknown, making a distinction highly arbitrary. In addition, in the public awareness and also in legal implications this distinction is irrelevant at best, more likely it adds confusion. Therefore, in the context of this report, we will use the term induced and triggered interchangeably, with no physical meaning or causality implied.

6.2.2.2 Differences between natural and induced earthquakes

While the size of induced seismic events is typically smaller than the largest observed natural events in the same location, they are governed by the same physics and generally indistinguishable from natural events (i.e., Deichmann and Giardini, 2009; Goertz-Allmann *et al*., 2013). One of the key challenges is, therefore, to reliably separate natural and induced events, for example when insurance issues are concerned. However, induced earthquakes differ in three important respects from natural earthquakes:

1. Because they are caused by human activity, the public reaction and legal implications are fundamentally different. People affected by induced earthquakes will react very differently − they will arguably in most cases be much less tolerant of such events due to their human-made nature and will expect compensation for damages.

2. While natural earthquakes can neither be controlled nor predicted, mitigation and control are to some extent an option for managing the hazard and risk posed by induced seismicity. A causal link exists between the actions (pump rates, pressures etc.) and the reaction of the ground. However, the physical mechanism may not always be clear, and there may be substantial delays in the reaction.

3. They are often very shallow, and near urban areas, which generally increases the level of ground shaking that the population and the building stock are exposed to.

6.2.2.3 Physical causes of induced earthquakes

Induced earthquakes are caused by a range of physical mechanisms, acting at different spatial and temporal scales. These are summarized schematically in **Figure 111** and the main mechanisms are briefly explained below. In a typical application, these various mechanisms will act together to a varying degree. Note that to a lesser extent it is also possible that the earthquake rate is actually locally reduced by the human activities; however, given the generally low background rate, a drop in productivity may often be observed.

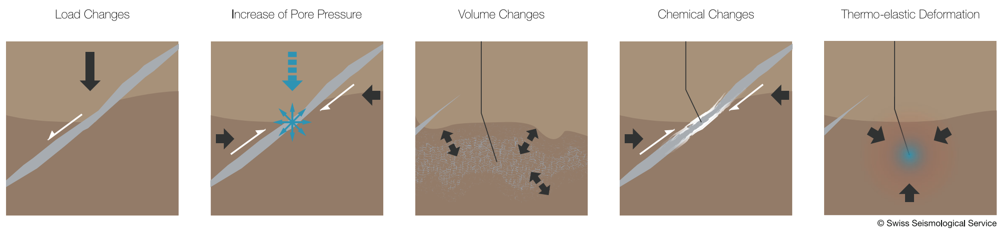

***Figure 111:** Schematic representation of the physical mechanism that can induce earthquakes.*

Pore Pressure Changes: Increasing the pore pressure on pre-stressed faults may eventually cause these faults to rupture, releasing a (generally small) fraction of the tectonic stresses accumulated over centuries prematurely. A reduction of pore pressure alternatively will lead to stabilization, hence a reduction in earthquake rate. A special natural case of pore pressure changes are rain induced earthquakes, documented in Switzerland by Husen *et al*. (2007), also see also **Figure 112**.

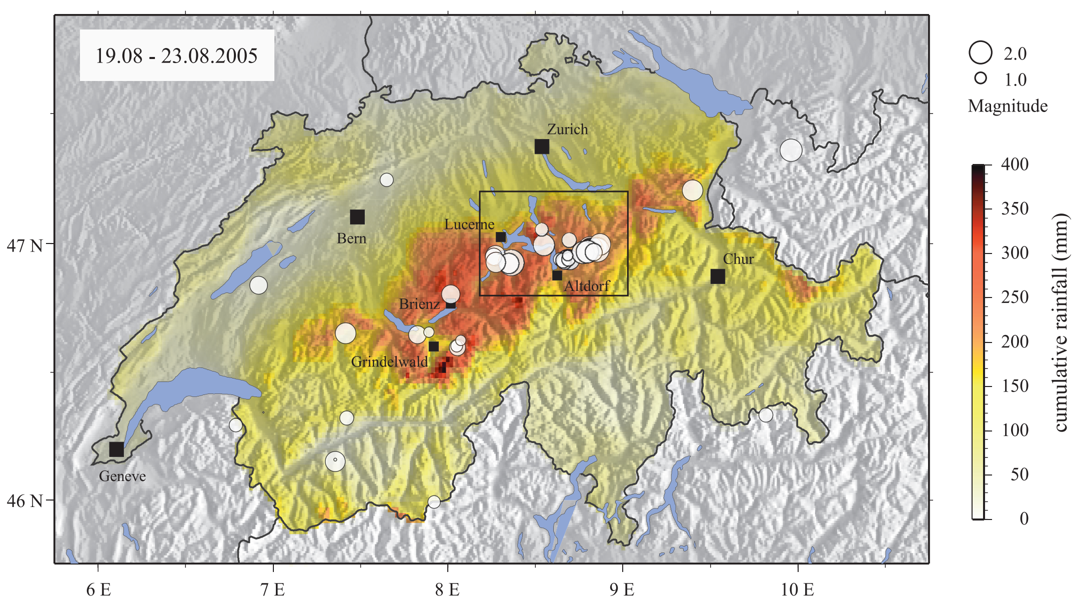

***Figure 112:** Cumulative rainfall (colour coded) and observed seismicity (white circles) in Switzerland for the time period between August 19 and 23, 2005 (Husen et al. 2007).*

Earthquake–Earthquake Interactions: The static and dynamic stress changes of induced earthquakes may in themselves act as triggers for additional earthquakes (Catalli, Meier, and Wiemer, 2013). These stress changes can in some cases also inhibit further seismicity.

Triggering by the passing of dynamic waves has in rare cases for large events been observed thousands of kilometers from the epicenter (i.e., Husen *et al*., 2005).

Deformation Related Changes: Volume changes in the underground through injection or extraction of fluids (i.e., hydrocarbon or geothermal production) or material (i.e., mining) will change the strain/stress conditions on nearby faults that may (or may not) be tectonically pre-stressed. If the loading exceeds locally the critical fault strength, an earthquake will be induced. Load changes at the surface of the earth through reservoir impoundment are a specific case of deformation related changes, as is thermo-elastic deformation (see below).

Chemical Alterations: Through chemical alteration, such as acidization, clay formation and mineral deposition, existing bonds of pre-existing and pre-stressed faults can be altered. If the bonds are weakened, induced earthquakes may release a fraction of the tectonically occurred stresses prematurely. If the bonds are strengthened, ductile deformation (or creep) can transition into 'stick-slip' (seismic) deformation (e.g. Marone, 1998).

Temperature Changes: Cooling or heating of the reservoir rock by injecting fluid causes local thermal contraction or expansion. Cooling opens fracture apertures; thereby changing the permeability, flow velocity, pressure gradient and injectivity. Thermo-elastic deformation also locally perturbs the state of stress. This potentially releases locked segments of pre-stressed fracture interfaces. Radiating stress readjustment can then trigger further seismicity away from the zone of temperature change.

While there is a reasonable understanding of the underlying physical, chemical and geo-mechanical processes at work, at least in a macroscopic sense, forecasting induced seismicity remains a major challenge during all stages of underground projects. The problem of induced seismicity partially defies the current state-of-the-art in modeling and risk assessment concepts, because:

- The Earth crust is critically stressed in most places and crisscrossed with faults of all sizes. Both the location and current loading status of these faults are rarely known. The current stress level of faults can in general not be imaged using geophysical techniques.
- Stress distribution and material properties on the reservoir scale are highly heterogeneous and largely unknown.
- Earthquake ruptures are complex and highly dynamic processes; predicting with confidence how large a rupture may grow is currently impossible. Run-away ruptures that rupture beyond the reservoir area, releasing stress on tectonically pre-loaded faults, cannot be ruled out.
- The risk profile and public discussion is often dominated by infrequent and rare large events (low probability, high consequence events), where few or no observations exist and models are extrapolated well beyond their calibrated range.

As a result, the forecast of induced seismicity and the hazard and risk that it may pose is often highly uncertain. These uncertainties in our understanding, as well as the variability of the relevant parameters, must be captured to deliver a solid risk assessment (i.e., SERIANEX (2009); Mignan *et al*. (2014); **Figure 113**). Induced seismicity management is consequently increasingly moving away from mostly deterministic approaches to Probabilistic Seismic Hazard and Risk Assessment (PSHA/PSRA). Analogously to other PSHA studies, the variability of ground motions prediction is a major contributor to uncertainty (Douglas *et al*., 2013). However, as opposed to time-independent PSHA, the problem of induced seismicity is very much time-dependent and operations related, thus the "source" part of PSHA is much more relevant and coupled to mitigation strategies.

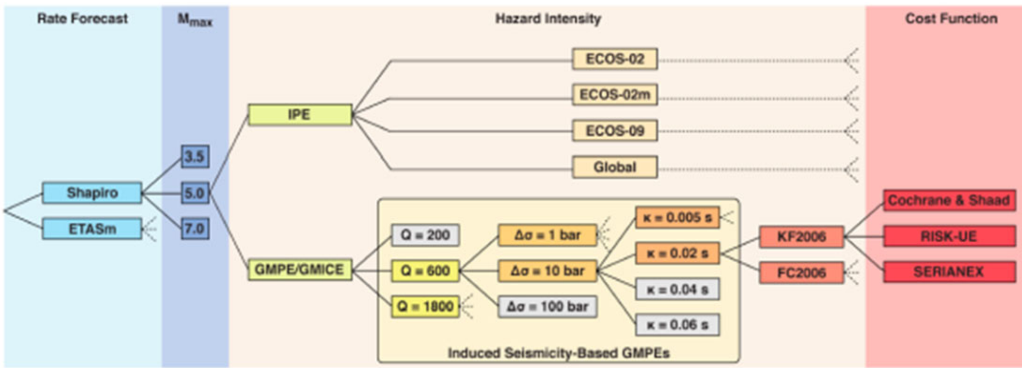

Figure 113: *Example of a logic tree designed to capture the uncertainty in induced seismicity hazard assessment for the Basel deep geothermal project (Migan et al., 2014).*

6.2.2.4 Pre-drilling indicators of seismogenic response

The vigor of the seismogenic response of the underground at a given location is difficult to forecast with confidence before the in-situ conditions are well known, and even then surprises and changes in the characteristics with time are common. Before the start of a project, there are only general indicators of average behavior that in combination can be used to get a rough forecast of the expected induced seismicity:

- **Injection volume:** The larger the volume of rock is affected by stress changes, the more events are likely to happen. This is a first-order geometrical effect. Whether maximum possible event size also scales with the affected volume or fault area is currently a debated issue (Baisch *et al*., 2010a; Gischig and Wiemer, 2013; McGarr, 2014).
- **Closed versus open systems:** In an ideal closed system, the operation will reach a steady-state and pore pressure changes remain confined to a certain volume. Seismicity in such systems should level off with time (i.e., Soultz). In open systems, the pressure or strain footprint is growing with time, and seismicity in such settings will be more variable, sudden increases are possible when critically stressed patches are reached by the pressure/strain changes. Seismicity in such settings can be sporadic (i.e., Landau), increasing with time (Groningen Gas Field) or more or less steady (Paradox Valley).
- **Depth**: Deeper systems are generally believed to produce more induced earthquakes, a consequence of the strength profile of the earth crust: Differential stresses will increase with depth, natural earthquakes are likewise less frequent in the top 1–3 kilometers of the earth's crust. Modeling suggests that the increase in seismogenic response due to the increase will overcome the geometrical effect of the decay in

ground motions with distance (Gischig and Wiemer, 2013), however there is so far surprisingly little empirical evidence for the depth dependence.

- **Rock type**: Crystalline basement rocks are typically believed to be more seismogenic than sedimentary rocks (Evans, *et al*., 2012).
- **Background seismicity:** The assumption that areas of lower natural seismicity also are areas less likely to respond with high levels of induced seismicity, or with lower maximum magnitudes is intuitive. Evans *et al*. (2012) suggested, based on a European database, that indeed areas with lower background hazards (defined arbitrarily as peak ground acceleration (PGA) values < 0.08) also have lower maximum observed magnitudes. To investigate this potentially important relation further, we have updated the Evans *et al*. (2012) database, adding data from outside of Europe. As seen in **Figure 114**, these additional data suggest that the hypothesis of low PGA regions producing lower maximum magnitude events can be rejected.

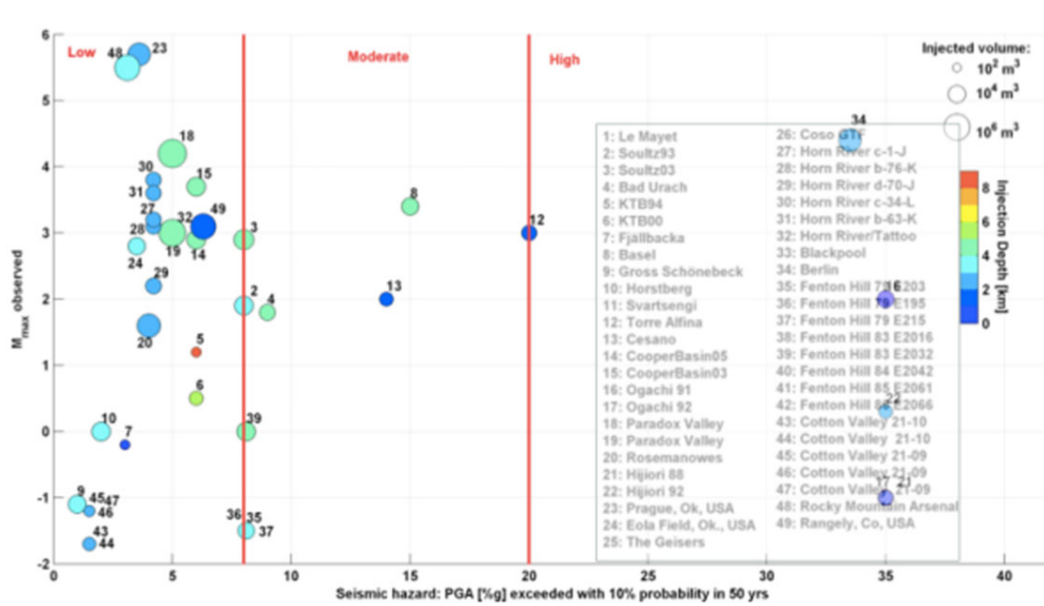

Figure 114: *Scaling between the local Peak Ground Acceleration with 10% probability of being exceeded in 50 years (PGA, in percent of gravity), derived from the Global Seismic Hazard Assessment Program (GSHAP) map and the expected maximum observed magnitude. The dataset is expanded from Evans et al. (2012). Markers are colored according to injection depth and have shapes corresponding the injected volume.*

- **Pore pressure change:** In general, the higher the (differential) pore pressure changes the underground is subjected to, and the more rapid these changes, the more likely are induced events. Seismicity often starts only once the pressure changes have exceeded a certain minimum threshold. On the other hand, it is known that faults very close to failure can be triggered by very small pore pressure changes (e.g. Rothert *et al*., 2003).

- **Nearness to critically pre-stressed and extended seismogenic faults.** Injections near known active fault systems greatly enhance the chance of inducing earthquakes. For some applications, such as waste-water disposal, the rule of thumb therefore is 'stay away from active faults' (Zoback *et al*., 2012).
- **Stress and fracture heterogeneity**: The in-situ stress clearly plays an important role in determining the seismogenic response of the underground. Pre-existing differential stress on a pre-existing fault is a pre-requisite for inducing hydroshearing events. In areas where the stress conditions are very close to lithostatic ($\sigma 1 \approx \sigma 2 \approx \sigma 3$), inducing larger earthquakes is much less likely. Likewise, the complexity and heterogeneity of the stress field and the fracture network is important, but often poorly known before drilling.
- **Natural size distribution:** Areas where the relative earthquake size distribution of natural earthquakes (the b-value of the Gutenberg-Richter law) is shifted towards high values ($b > 1$) may also produce fewer larger induced events and more small ones. Gischig *et al*. (in preparation) suggest that these may be favorable conditions for creating a geothermal reservoir with acceptable seismic hazard. Volcanic or geothermal regions, such as the GEISER (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs), Taupo or parts of Iceland, are typically characterized by high b-values, and shallower reservoirs at lower differential stresses, which may explain why these have had fewer problems with induced earthquakes despite having been in production for many years.
- **Traffic light settings**: Potentially damaging events are less likely to occur when traffic light systems are set conservatively. This means, interruption thresholds are set lower and injections therefore are interrupted earlier. However, more conservative traffic lights will have a string impact on the commercial success rate of the projects.

6.2.3 Earthquake hazard and risk in Switzerland

6.2.3.1 Natural seismicity of Switzerland

More than 800 micro-earthquakes are recorded in Switzerland every year, but only 10 – 15 are felt by the local population. An earthquake that causes slight non-structural damage is expected on average every 10−20 years. Based on the evaluation of historical earthquakes (Earthquake Catalogue of Switzerland, ECOS-09, (Faeh *et al*., 2011)) and paleoseismological records, we know that events of about magnitude 6, where widespread damage is possible, have occurred on average every 50–150 years within or near to Switzerland. Most experts would agree that earthquakes up to magnitude 6 can in principle occur anywhere in Switzerland, but their occurrence rates are highest in Valais, the Basel region and Graubünden.

6.2.3.2 Local site amplification

Earthquake ground motion on soft soils is amplified relative to hard rock sites at similar distances from the source. This is known from theory and observations (Fäh *et al*., 2011). As a consequence of amplified ground motion, the earthquake impacts are higher – this includes increased damage to structures. Since local soil conditions and geology in Switzerland are highly variable in space (the spectrum covers everything from hard rock over moraines to flood plains), taking into account local site amplification is an important factor for site-specific hazard and risk assessment. In the past century, cities with their suburbs and industrial areas have grown into former flood plains. These big alluvial plains experience very high amplification of earthquake ground motion. Buildings on such sites are especially in danger of suffering increased damage. Consequently, taking into account local site amplification has an influence on loss estimation and seismic hazard, both for natural and induced earthquakes. Risk studies should therefore include site amplification effects. **Figure 115** shows an indicative site amplification map for Switzerland as published by Fäh *et al*. (2011).

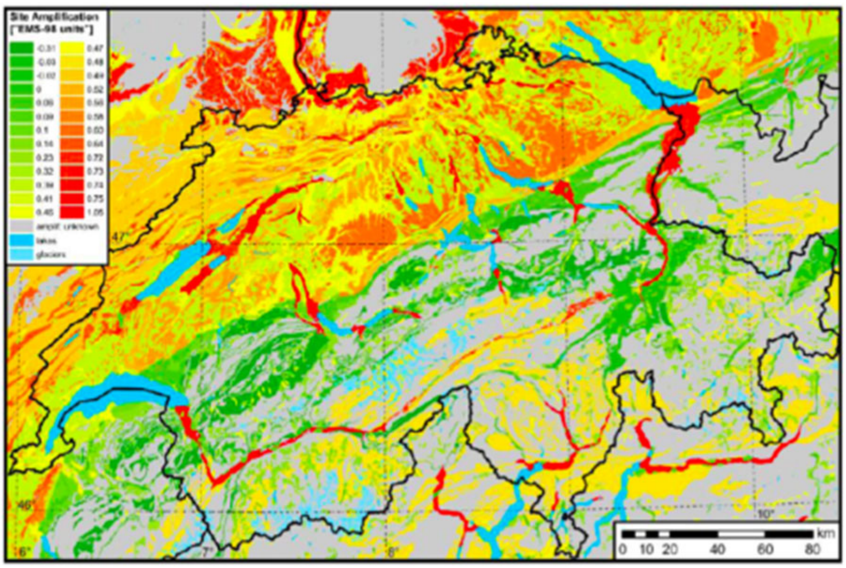

Figure 115: *Indicative site amplification map for Switzerland (Fäh et al., 2011).*

6.2.3.3 Earthquake risk

Seismic hazard assessment is only the first step in assessing and limiting the risk. Seismic risk is by definition the combination of seismic hazard, local soil conditions, exposed inventory (i.e. habitat density) and vulnerabilities of exposed structures (**Figure 116**).

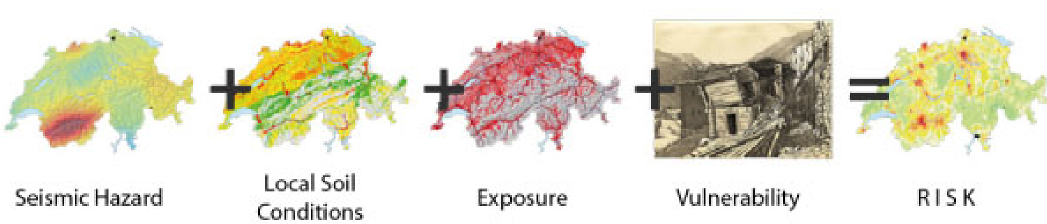

Figure 116: *By definition seismic risk is a combination of seismic hazard, local soil conditions, exposed structures and their vulnerabilities.*

An illustrative example that seismic risk is a combination of different factors is a comparison between the indicative hazard and risk map of Switzerland (**Figure 117**). While the cantons of Wallis and Basel are exposed to a high seismic hazard, hot spots of seismic risk must not coincide with these areas: Local soil conditions, exposed structures and vulnerabilities contribute a considerable part to the final risk map. For example: Despite the fact that the city of Zurich is situated in an area with low seismic hazard, it is considered as a high risk area – this especially because of its high exposure.

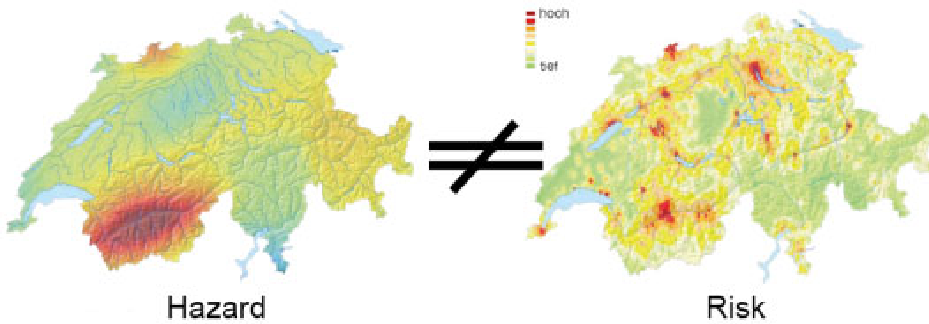

Figure 117: *Indicative seismic hazard (left) and risk (right) map of Switzerland. The maps show clearly that hazard is unequal risk. Although i.e. Zurich is situated in a low-hazard zone, the seismic risk is considered to be high. This reflects the definition of risk: Since it is a combination of hazard, local soil conditions, exposure of structures and its vulnerabilities, a big city enhances the risk due to its large exposure.*

6.2.4 Induced seismicity in the context of deep geothermal energy

6.2.4.1 Types of geothermal energy systems

Based on resource target depths, geothermal projects can be subdivided into 'near-surface' and 'deep geothermal projects'. Typical applications for near-surface geothermal projects are e.g. (groundwater) heating pumps or ground-coupled heat exchangers – both wide-spread types of use in Switzerland. As a general rule, a project is considered as a deep geothermal energy project at depths of 400−500 m downwards. There are no known induced events related to either closed systems or to shallow geothermal applications.

Depending on reservoir temperatures and exploitation types, geothermal energy projects can be further subdivided. Electricity production through geothermal energy is worldwide dominated by high-enthalpy reservoirs, often in the vicinity of volcanic areas where underground temperatures tend to be in the order of several hundred degrees centigrade. Low-enthalpy reservoirs can be found anywhere else, with the difference that deep wells are necessary to get target temperatures of 100–200 degrees centigrade in order to produce electricity. Low-enthalpy reservoirs further can be subdivided into three different types: hydrothermal and petrothermal systems as well as deep heat pumps. Prominent examples are Basel (2006, petrothermal), St. Gallen (2013, hydrothermal) and Zurich (2010, deep heat pump).

Hydrothermal systems target permeable rock formations where water ideally flows already. This was for example the concept of the St. Gallen geothermal project, where a fault zone in a Mesozoic aquifer was targeted. In contrary, petrothermal systems usually are not situated in permeable rock formations, in other words, water naturally could not circulate with sufficient flow rates. In order to achieve these flow rates, permeability needs to be enhanced by geo-engineering. Therefore this type of geothermal energy is also called *'Enhanced or Engineered Geothermal Systems' (EGS)*. An overview of all the above-mentioned types of use is illustrated in **Figure 118**.

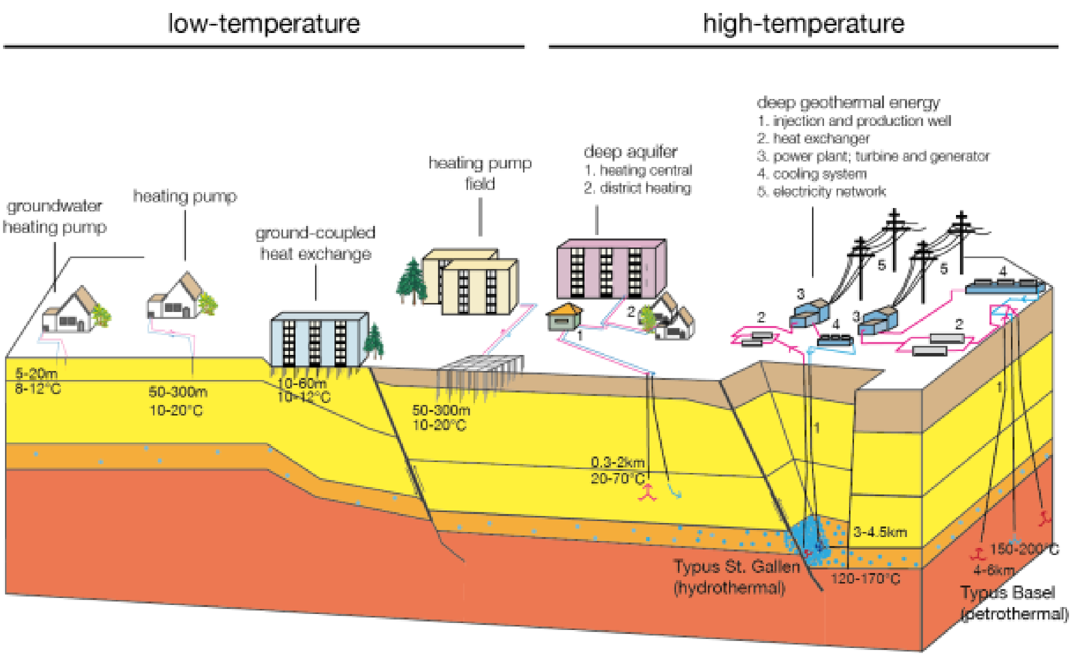

Figure 118: *Illustrated are different types of geothermal energy exploitation. Generally a distinction between low and high temperature geothermal projects can be made. Low temperature geothermal energy projects include widespread systems such as (groundwater) heating pumps or ground-coupled heat exchangers (at very low depths). However, high temperature geothermal systems target deeper target zones up to several kilometers underground. In this case, hydrothermal and petrothermal systems are distinguished. In case of hydrothermal systems, permeable rock formations where water ideally circulates already are targeted. In contrary, petrothermal systems are not permeable enough that water could circulate and need to be engineered: By injection of water at high pressure, permeability is enhanced.*

6.2.4.2 Induced seismicity related challenges for deep geothermal application

As stated in the introduction, induced seismicity is not at all exclusive to deep geothermal energy exploitation. However, deep geothermal energy production is especially challenged right now, because of the following reasons:

1. Deep geothermal energy projects are often planned near urban areas, because district heating is sometimes the primary target and also in the case of electricity production, local heat usage will greatly enhance the economics of the systems.

Because risk is the product of hazard, exposure and fragility, the seismic risk of deep geothermal projects near urban areas is much higher. While some nations, such as Australia, have the option of minimizing the exposure and hence the risks by avoiding settlements, this alternative is not readily available for deep geothermal energy in nations such as Switzerland, because potential reservoirs are located primarily near the densely populated areas in the alpine foreland, and because potential users of heat from combined heat and power plants must be local.

2. In the case of EGS, induced earthquakes are the tool of choice for creating a reservoir, and the economic success in terms of the heat output is directly dependent on the number and size of induced events. Balancing reservoir creation and seismic hazard is thus needed and a task not well understood.

3. In the case of deep hydrothermal projects, target zones are often major fault zones, because here the permeability is typically much higher. Because the existing pre-stresses and the potential for reaction cannot be imaged directly through geophysical methods, there is a danger that targeted fault zones turn out more seismogenic than hoped for (i.e., St. Gallen, 2013).

4. Deep geothermal energy, especially EGS, is a new technology, triggering a different and generally more skeptical risk perception than for established technologies such as mining or oil and gas production. There is also limited experience, empirical evidence and best practice from which to draw.

Currently, risk management of induced seismicity is also a scientific challenge, because reliable and validated methodologies and tools to assess and monitor the risks do not exist (i.e., Giardini, 2009; Majer *et al.*, 2012). This is a consequence of two factors: Our limited understanding of the physical processes taking place, but even more so our limited knowledge of the physical conditions (i.e., 3D stress and strength heterogeneity, pre-existing faults, permeability distribution etc.) at the depth where the reservoir creation is taking place. As a consequence of the magnitude 3.4 earthquake (damages >6M CHF) triggered during the 2006 Basel EGS project, it is now universally accepted that the future development of geothermal resources near urban areas critically depends on the ability to assess and mitigate the nuisance, and potential seismic risk, posed by induced seismicity (Giardini, 2009; Kraft *et al*., 2009; Mena, Wiemer, and Bachmann, 2013).

6.2.5 Selected examples of induced seismicity related to deep geothermal projects

6.2.5.1 United States (contribution by E. Majer)

Induced seismicity has been recognized as a potential risk but also as a useful tool in reservoir management, both in the stimulation phase as well as in the production phase. The most prominent demonstration of induced seismicity has been at The Geysers geothermal steam field in Northern California, which is sparsely populated. The Geysers initially started out as a pressurized hydrothermal reservoir, but soon it was recognized that water depletion was happening and fluid replacement started. The maximum size earthquake has been an M 4.6 in the 1970’s. (See **Figure 119**) Over the years more and more water has been injected until today’s rate is a total of 95’000 cubic meters/day. Although there have also been many magnitude 4+ events since the 4.6, the seismicity was limited to that level until today. Other seismicity of note is a Magnitude 2.6 event that occurred during an EGS demonstration at Newberry Crater. The total injection volume was 42'000 cubic meters over a month. This was a "true" EGS experiment in a volcanic area in central Oregon. All other induced seismicity has been in existing geothermal fields. The other longest existing fields at Coso (California) and the Salton Sea CA) have exhibited induced seismicity (due to reinjection) of Mag 2.5 and Mag 5.1 (Brodsky *et al*, 2013). Other producing fields in the western US exhibit seismicity below Mag 2.0, with a rare occurrence of Mag 2.0 to 2.5. From a regulatory standpoint most geothermal projects use the USDOE induced protocol as a starting point (all USDOE funded projects are required to use it), but there is no regulatory agency that has a standard procedure. The Bureau of Land Management (USBLM), however, is developing a regulatory procedure for induced seismicity. In summary, induced seismicity is an important consideration for the US Geothermal community, both from a hazard assessment and a reservoir optimization standpoint. Protocols and best practices have been generally accepted by the stakeholders and have allowed all projects to go forward. It is recognized that there are still outstanding research questions with respect to hazard assessment and reservoir behavior that need to be addressed to optimize and advance geothermal resources.

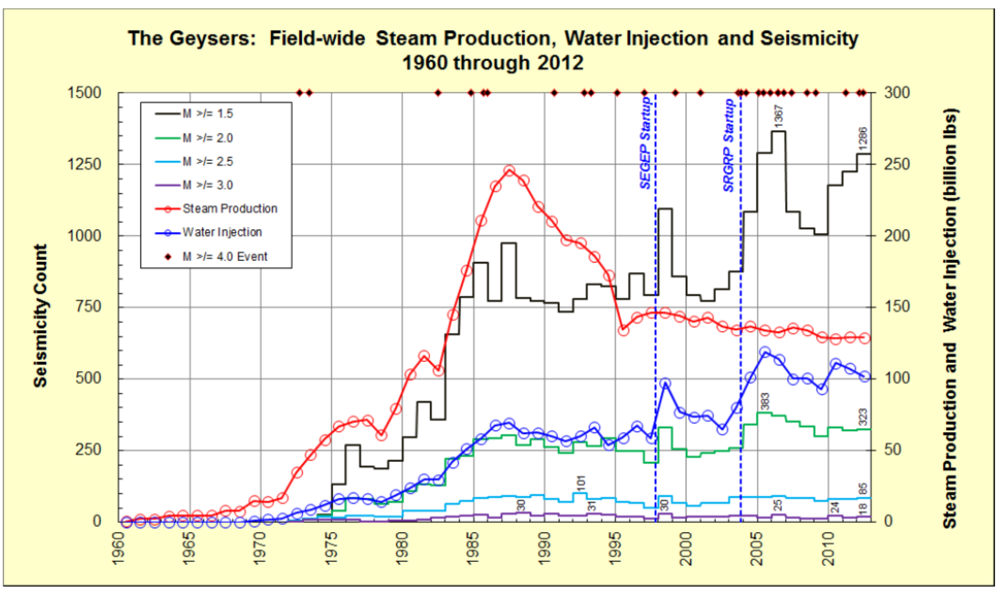

Figure 119: *Seismicity versus injection and production in the Geysers geothermal field (Craig Hartline, Calpine Corp.).*

6.2.5.2 New Zealand (contribution by C. Bronley)

In New Zealand, a tectonically active high-temperature setting, changes in the deep injection strategy at several conventional high-permeability geothermal developments have resulted in significant levels of induced seismicity (up to M_L 3.5). The triggering mechanism is associated with the indirect effects of increased fluid flow driven by pressure gradients through a fracture network, with failure occurring on favorably-oriented fractures throughout the network. The causes are subject to ongoing research and may be local temperature or pressure transients, hydrothermal alteration, or local stress perturbations unlocking fracture asperities. One notable example is the Rotokawa Field (Sherburn *et al*, 2013). Here, about one event of M>2 (potentially felt) within a depth range of 1.5 to 3 km occurs per month. The event rate tripled following production expansion in 2010. Issues to address include a better understanding of the reasons for the observed high b-slope and shallow hypocentre depths in these high temperature regimes (up to 340 ^{o}C), and the influence of the brittle-ductile transition zone on present-day and future seismicity as the reservoir cools.

6.2.5.3 Australia (contribution by B. Bendall and M. Malavazos)

To date, two separate EGS projects in Australia have undertaken massive hydraulic stimulation of their respective reservoirs. Both projects, namely Geodynamics Limited's Cooper Basin Project and Petratherm Limited's Paralana Project, are located in remote areas of South Australia and regulated under the South Australian Petroleum and Geothermal Energy Act 2000, which adopts a risk-based approach to operational approvals. Through the risk assessment process required under the Act, the induced seismicity risks associated with these projects were assessed. Albeit being minor, the risks were managed through setting threshold peak ground velocities (PGV) and ground motion levels at critical infrastructure locations and approval conditions were set to ensure that ground motion was not exceeded at these locations.

As an example, Geodynamics have undertaken massive hydraulic stimulation operations on six wells between 2005 and 2012. On average, over 20'000 events were recorded during the course of a single stimulation operation, with the largest single event recorded being a 3.7 M_L during the 2003 stimulation of Habanero 1 well. However no damage or community concerns eventuated from this event or from the stimulation operations as a whole. Although current operations have not posed substantive risks to the wider community due to their remote locations, any future projects, which may be sited closer to population centres, will undergo a similar risk assessment process commensurate to the risks of that individual project.

6.2.5.4 Iceland (contribution by S. Kristjánsdóttir)

In September and October 2011 four earthquakes of magnitude above M_L 3, the largest M_L 3.8, were observed in association with re-injection of geothermal wastewater in the Hengill area, SW Iceland. The power company operating the Hellisheidi power plant is obligated to inject the wastewater fluid back into the system below the groundwater table. Small earthquakes (less than M_L<3) were recorded during the drilling of the injection boreholes. The earthquake activity increased shortly after the start of the injection in the beginning of September 2011, culminating in the M_L 3.8 event and slowly decreasing as re-injection continued. As of February 2014 seismicity is still observed at the injection site. Induced seismicity had not been an issue before at other injection sites in Iceland, i.e. at the Svartsengi power plant on the Reykjanes Peninsula and at Grauhnukar in the Hengill area, the previous injection site at the Hellisheidi power plant.

The induced events in the Hengill area have been defined as triggered earthquakes due to the fact that they occur in a tectonically active region and are thought to be *triggered* by minor stress changes caused by the injection of fluid into the system. The induced events in the Hengill area have led to a change in public opinion and it is foreseen that policy regarding the planning and operation of power plants will be changed, requiring power companies to observe seismic activity before and during production in the geothermal field. With seven geothermal power plants in operation and more on the drawing board there is growing concern among the public over the potential effects of these induced or triggered earthquakes.

6.2.5.5 Switzerland: the Basel petrothermal project (2006)

The Basel EGS project (Häring *et al*., 2008) aimed to become one of the first commercial power plants based on deep geothermal heat extraction from crystalline rock. It was planned to enhance reservoir permeability at about 4−5 km depth by injecting fluid at high pressure over a time period of more than two weeks. A seismic monitoring system was installed along with a hazard and risk management scheme − the 'traffic light system' suggested by Bommer *et al*. (2006). The monitoring system included six borehole sensors at depths of 300 m to 2700 m depth. More than 900 events with magnitude larger than the magnitude of completeness (M_c 0.9) were recorded and located (Bachmann *et al*.,2011).

The injection rate was increased in a stepwise manner, until maximum injection rates of 57 l/s were reached on the fifth day of stimulation. Shortly after, an event of magnitude M_L 2.6 occurred. In response, the injection rate was reduced, and, a few hours later, totally stopped. A M_L 3.4 (corresponds to M_w 3.2) event, widely felt in the city of Basel, occurred about 5 hours later. Three more felt events of magnitude about 3 occurred in January and February of 2007. **Figure 120** illustrates the seismicity during this project.

The aversion of the population and the media to the project caused by these earthquakes led to temporary suspension of the experiment. In 2009, the project was fully cancelled as a consequence of a comprehensive risk study (SERIANEX, Baisch *et al*., 2009). Allegedly, damage caused by the earthquakes included mostly fine cracks in plaster, which corresponds to an EMS intensity V. Insurance claims by homeowners reached about 6 million CHF, most of which were also paid for. The risk study by SERIANEX was subsequently repeated and extended by Mignan *et al*. (2014), although the major findings did not change.

The Basel geothermal data, however, have been the basis of countless scientific studies and in this sense have been an important contribution for advancing the understanding of EGS systems. It illustrates the importance of pilot and demonstration projects for advancing our understanding: Without the drilling and subsequent stimulation very little would have been learned. Although it is always easy to claim after the fact that we have learned how to avoid a Basel scenario, Mena *et al*. (2013) and Gischig and Wiemer (2013) presented simulation results that shows how the vigor of seismogenic response of the underground could already have been estimated with confidence after 2−3 days and, given the planned injection strategy, an M_L 3.4 event was likely to occur. Such forecasting models were not in place in 2006, but are available today (see Section 6.2.7.4 Adaptive Traffic Lights Systems (ATLS)).

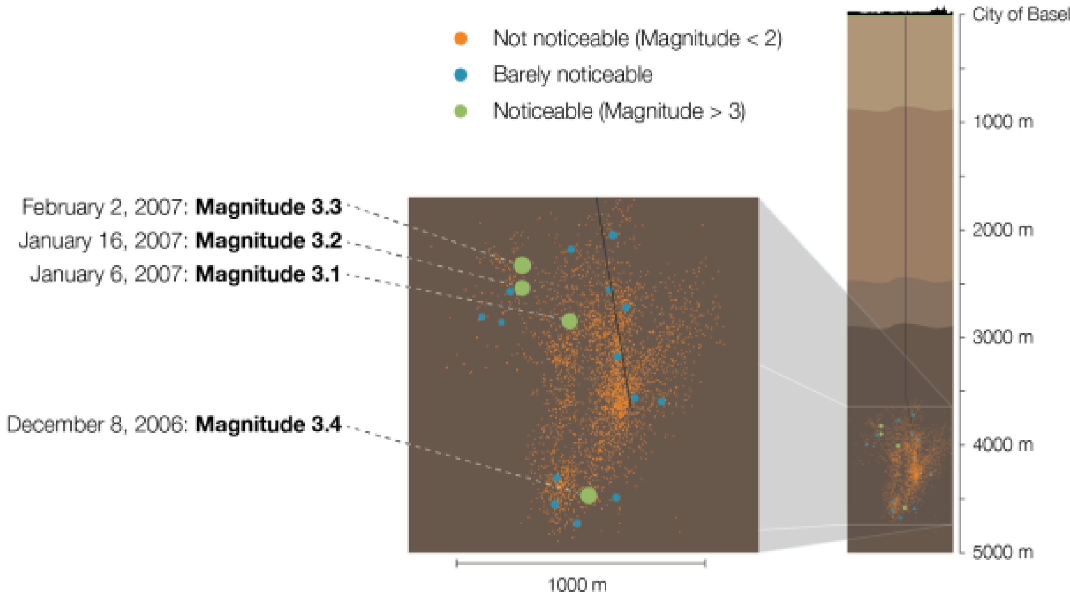

Figure 120: *Seismicity observed during and following the 2006 reservoir stimulation beneath the city of Basel. Events above* M_L *3 are pointed out.*

6.2.5.6 Switzerland: the St. Gallen hydrothermal project (2013)[30]

The story of the deep hydrothermal energy project in St. Gallen is not free of irony in the sense that the project was initially conceived to be by design earthquake-free, the antipode to the failed EGS beneath the city of Basel. The failure of the visionary Basel EGS project caused a major setback for advancing deep geothermal energy to crystalline environments around the world (Giardini, 2009). The 2013 St. Gallen event, in terms of surface shaking, almost a repeat of the 2006 Basel event, has the potential to cause a similar setback for the exploitation of deep hydrothermal energy near urban areas. It also challenges some of the assumptions commonly made in the hazard and risk assessment of, as well as mitigation strategies for, induced seismicity overall.

The St. Gallen geothermal project is targeting the same geological layers, the Malm and Muschelkalk of the Molasse sedimentary basin (Figure 121) that have been tapped by a number of successful deep geothermal projects in southern Germany. These projects draw up to 150 l/s of 120 °C hot water from depths of around 3300–3400m below sea level, producing in the case of the project in Unterhaching up to 70 MW of thermal and 3.3 MW of electrical energy. To comply with regulatory requirements, as well as to replenish the aquifer, the cooled water is re-injected into the same aquifer at distances between the well shoes of typically > 1 km.

[30] We report this sequence in more detail because little is published so far.

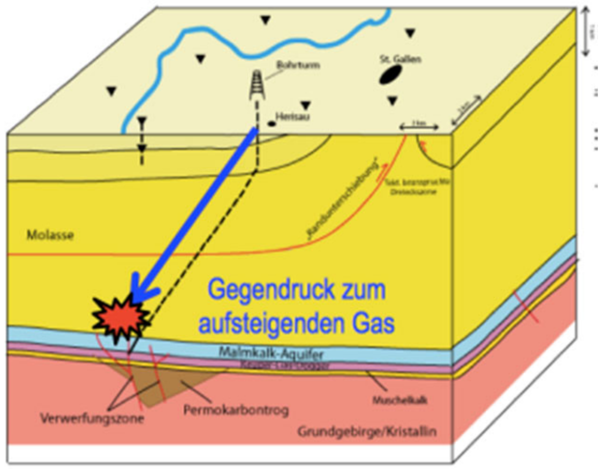

Figure 121: *Schematic view of the setting of the St. Gallen hydrothermal project.*

In addition to targeting sedimentary layers with expected higher permeability, hydrothermal projects often target pre-existing fault zones with typical widths of around 10−100 meter, because these are known as zones of higher permeability (Faulkner *et al*., 2012). This approach is enhancing the chances of finding sufficient permeability to operate a deep geothermal reservoir with sustained high flow rates. To find the most favorable target for the drilling, a high-resolution 3D seismic survey was conducted near St. Gallen, in 2010, covering 310 km^2. The survey revealed a pronounced shear zone, oriented NNE-SSW with a length of about 30 km, termed the St. Gallen Fracture Zone (SGFZ). The project operators, the utility company of St. Gallen, concluded that this fault zone was hardly active seismically, based on the lack of recent seismic activity. Drilling commenced in early 2013, the target depth of 4450m was reached in early July.

In late 2012, the Swiss Seismological Service had installed a seismic monitoring network, consisting of six three-component surface seismometers and one shallow (205 m) three-component borehole station (**Figure 122**). The primary objectives of the network were (1) to provide the operators with near-real time information on possible induced events, (2) to distinguish with confidence natural and induced earthquakes, and (3) to monitor in detail the micro-seismicity expected to be observed during a planned acid and optional hydraulic stimulation. Such stimulations are quite common as a means to enhance the coupling of the well to the surrounding aquifer. They are much smaller in injected volume, and shorter in duration, than the reservoir stimulation processes that are part of the creation of an EGS system. Past projects in the Molasse had not produced felt earthquakes during the drilling and reservoir establishment phase, although some minor events with magnitude of less than 3.0 had been reported during the reservoir operation phase (Evans *et al*. 2012).

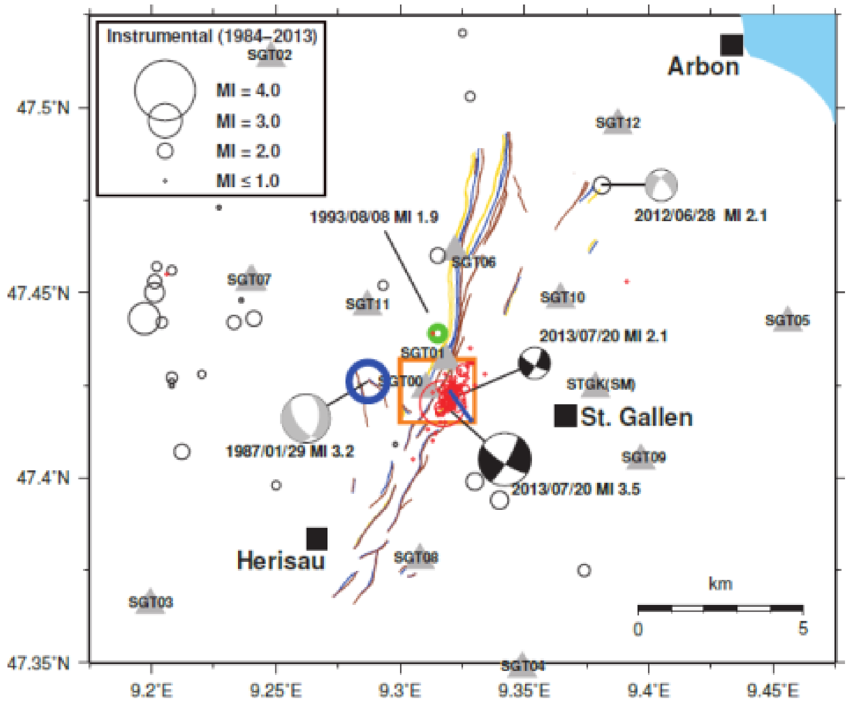

Figure 122: *St. Gallen and surroundings. Shown are the seismic stations (grey triangles, named SGTxy) used to survey possibly induced seismicity, seismic events (circles) and known faults (coloured lines).*

The reservoir characterization started on July 14 with an injectivity test, when cold water was injected into the open-hole section. Temperature logs had indicated the presence of at least two fracture zones within this section. In total, 12 micro-earthquakes were detected, all of them of magnitude 0.9 or below. On July 17, two acid stimulations were performed, each injecting 70 m^3 of diluted hydrochloric acid into the reservoir. The seismicity during these tests (**Figure 123**) did not exceed M_L 1.2 and was judged to be well within the expected range.

The initial event of the 'well control' sequence, with a magnitude 1.6, triggered the 'yellow' threshold of the so called "traffic light system" in operation. Traffic light systems are a major element of the mitigation strategy for managing induced seismicity (i.e., Zoback, 2012; Haering, 2008; Ellsworth, 2013), and a yellow alarm requested stopping the pumps. However, because of the ongoing well-control operation, stopping the pumps would likely have caused a renewed increase in the gas content and wellhead pressure, possibly to levels dangerous for the equipment. Operators therefore decided to continue pumping. The seismicity during this period intensified (**Figure 123**), with a M_L 2.1 event at 12:30 a.m. on July 20th. Seismicity remained constrained to within a few hundred meters of the borehole.

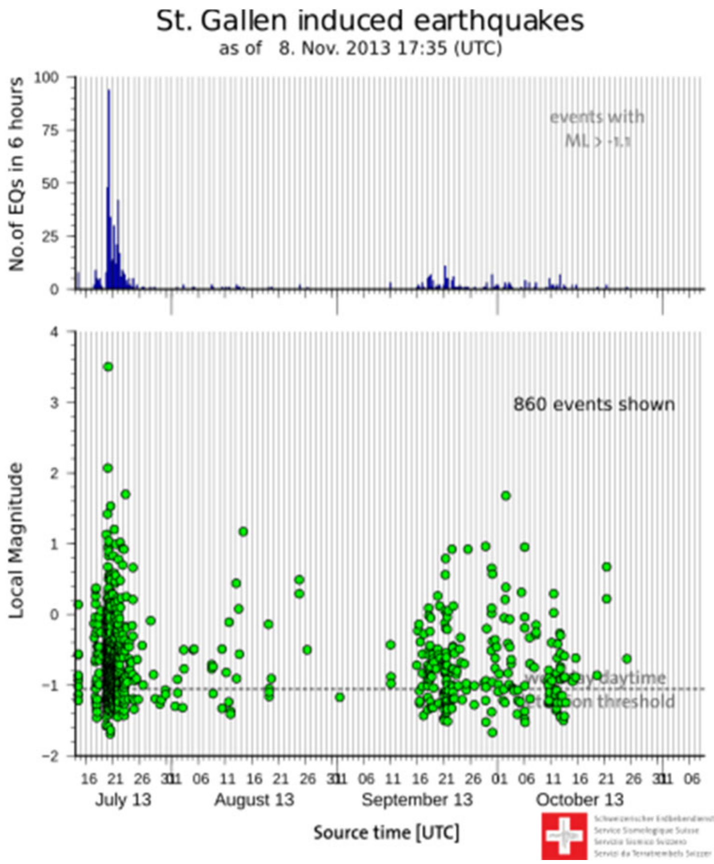

Figure 123: *Time evolution of the seismicity during the St. Gallen hydrothermal project.*

At 5:30 local time, the largest event of the sequence occurred, with a magnitude of M_L 3.5 (M_w 3.3). The earthquake initiated near the borehole. The subsequent analysis of the corner frequencies of the events showed that the event had a comparatively low stress drop of 3.5 bars (1.5–5.8 bars), substantially lower than 10 bar stress drop measured using the same technique for the M_w 3.2 event in Basel. A lower stress drop indicates a relative slower but longer rupture − and a rupture with less high-frequency content. This lack of high frequency energy may be the reason why the St. Gallen event, despite the fact that it had a similar magnitude and ground motions in terms of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) was reported typically one macroseismic intensity lower than the 2006 Basel event (European Macroseismic Scale Intensity IV versus V, respectively, based on the analysis of more than 400 online questioners). Consequently, only a few dozen reports of damages were received, as compared to several thousand in the case of Basel.

Once the production test started on October 15, seismicity essentially stopped immediately along the entire activated fault system. No event has been reported since October 21. This is additional evidence that the seismogenic fault segment is highly sensitive to pore-pressure changes and can be turned on, and off, easily. The evaluation of the production test and logs shows that flow is limited to the fracture zone. While the temperature at depth of more than 140 °C is within the projected range, the estimated production rates of 5 l/sec are much below the commercial minimum target of 50 l/s.

The implications of the St. Gallen project are significant, especially for hydrothermal projects, since they revealed that the current understanding of and management strategies for induced seismicity are limited and need to be re-thought in a number of areas:

1. Hydrothermal geothermal power systems in sedimentary rocks, so far considered benign in Switzerland with respect to induced seismicity, have been proven to induce events similar in size to EGS. While 3D seismic surveys become ever more capable of imaging fault systems to target the drilling, as long as our ability to judge if a fault is critically pre-stressed remains poor, unpleasant surprises are possible.
2. The M_L 3.5 earthquake and overall activity of the sequence lie well outside of the scaling laws that relate the injected volume of water and the maximum expected magnitude. This suggests that these scaling laws do not describe a hard truncation due to the limited area influenced, but that run-away ruptures are possible. Future projects thus will have to consider that with a small probability larger events may be induced, which is a lesson learned also after the 2011 M 5.8 Prague (Oklahoma) event. In the case of St. Gallen, the imaged SGFZ extends for about 30 km, long enough to support a M 5.5 event or more, but it is unknown if the multiple imaged segments, each only 1−2 kilometers long, can indeed connect to support a larger main shock.
3. The seismic response to the injectivity test, as well as to the acid stimulations, did not suggest that such a large event was possible. This lack of predictability of the system limits near-real time hazard assessment.
4. Traffic light systems to manage induced seismicity cannot always be engaged as planned, a fact so far ignored in risk assessment. Future projects must also consider the coupling and feedback between hazards.

6.2.6 Models to forecast induced seismicity

This section is adopted from a recent review of modeling approaches by Gischig and Wiemer (2013).

6.2.6.1 Statistical forecast models

Statistical methods to forecast seismic hazard are described for example by Bachmann *et al*. (2011) and Mena *et al*. (2013), and have been tested in a pseudo-prospective manner for the EGS stimulation at Basel in 2006. Because of their robustness and efficiency, they are most useful for real-time traffic light applications. Mena *et al*. (2013) show that both an adaptation of a widely used earthquake clustering model, the Epidemic Type Aftershock Model (ETAS) (Bachmann *et al*., 2011; Ogata, 1992), as well as the model class suggested by Shapiro *et al*. (2010), can forecast the seismicity during the Basel stimulation quite well in a simulated near-real time application. The Shapiro model forecasts the rate of induced seismicity during injection experiments as a function of a site-specific parameter (the so-called seismogenic index) and the injected fluid volume. Mena *et al*. (2013) also show that a combination of these models, where the relative weights are updated at each time-step according to the relative performance of each model, is superior to an individual model in its robustness and forecasting ability.

However, while powerful in near real-time applications, such statistical models have clear limits: They account for the underlying physical processes governing induced seismicity only to a limited degree. The two aforementioned models only consider injection volume as information. All other parameters rely on calibration against observed seismicity data, which must be done for each individual site. Hence, they have limited forecasting capabilities for longer time periods, alternative injection scenarios, and post-shut-in behavior.

6.2.6.2 Physics-based models

Physics-based models can potentially overcome the shortcomings of statistical models that only include a limited degree of physics. As they describe physical processes more comprehensively, they may perform better as forecasting models. Additionally, they have the capability of exploring the sensitivity of reservoir performance and induced seismicity to various processes (i.e. stress redistribution, thermal contraction, etc.), site-specific conditions (i.e. initial hydraulic properties, in-situ stress state, etc.) and design parameters (i.e. injection volume or pressure, reservoir depth and size). However, a drawback of those models is the numerous parameters that are often badly constrained and difficult to calibrate against observations.

Such physics-based models rely on numerical methods to simulate (thermo-) hydro-mechanical processes in geothermal reservoirs. So far they have mostly been used in scenario-type applications, because running them in near-real time during an ongoing stimulation is challenging. Generally, full thermo-hydro-mechanical coupling in a fractured medium containing multiphase fluids must be included in a numerical model to appropriately account for most phenomena associated with fluid-driven seismicity. Another essential but rarely met requirement for their use in a seismic hazard analysis framework is the ability to forecast the magnitude-distribution of induced events. We here give a short review of simulators that have been used in the induced seismicity context: The code FRACAS was presented by Cacas (1990) and Bruel (2007), and applied to the EGS system at Soultz-sous-Forêts (Baujard and Bruel, 2006). The predefined fractures are assigned a stress state depending on the tectonic stress field and a failure criterion that governs the ability of the fractures to shear. Fracture permeability is updated as a function of shearing-induced dilation. The code HEX-S presented by Kohl and Mégel (2007) similarly accounts for enhancements of fracture permeability through shear dilation. The model does not include stress transfer and cannot compute event magnitudes. A 2D model was developed by Baisch *et al*. (2010b) to account for both slip-dependent permeability and stress transfer within the modeling plane. It can calculate the magnitude of individual events from the amount of slip and the slipped area. It was applied in the risk study conducted after the Basel injection experiment (Baisch *et al*., 2009). It was able to reproduce a number of characteristics of the induced seismicity, such as post-injection seismicity and the occurrence of the largest events after shut-in. McClure and Horne (2011) present an approach which includes slip governed by rate-and-state friction, and present a generic study to explore the role of injection pressure on magnitudes of induced events. They found that larger injection pressure results in larger magnitudes. Rutqvist *et al*., (2002) and Rutqvist (2011) suggest a combination of the far-developed commercial simulators FLAC3D and TOUGH2. Pressure diffusion and heat transport are solved with TOUGH2. At each time step the pressure and temperature fields are transferred to FLAC3D, which solves the hydro-thermo-mechanical response of the rock mass. The method was applied at the Geysers geothermal site to explore effects of decreasing reservoir temperatures on enhanced seismicity (Rutqvist and Oldenburg, 2008). The approach is very powerful in including various processes associated with fluid properties and reservoir mechanics. However, it currently cannot simulate the magnitude of large numbers of earthquakes.

While the aforementioned physics-based approaches are successful in simulating various phenomena associated with reservoir creation and induced seismicity, none of them has ever been used in induced-seismicity PSHA. Most existing models allow stochastic variability of parameters (such as fracture orientation or extent, friction parameters, stress parameters, etc.), but they do not systematically present the uncertainty in our knowledge of these critical parameters. They also typically do not forecast meaningful magnitude distributions that extrapolate to the very rarely observed events. These events, despite being rare, dominate the hazard and risk at lower probability levels (i.e. Mena *et al*., 2013).

6.2.6.3 Hybrid models

Bachmann *et al*., (2012), Goertz-Allmann and Wiemer (2013) and Gischig and Wiemer (2013) introduced a so-called hybrid model to be used in PSHA, which strives to combine the advantages of statistical and physical models. These models combine a linear or non-linear flow model and a *stochastic seed model* built from basic geomechanical considerations, as suggested by Rothert and Shapiro (2003). In addition to the approach by Rothert and Shapiro (2003), the Geomechanical Seed Model (GMS) includes the possibility to produce magnitudes, and can thus be calibrated against observed seismicity, for example by adjusting to the density of faults in the stimulated volume. The model is able to explain a wide range of observations: The overall earthquake size distribution (or b-value), the observed spatial distribution of b-values, the observed stress drop as a function of distance (Goertz-Allmann, Goertz, and Wiemer, 2011) and the fact that the largest events may often be observed shortly after shut-in.

6.2.7 Mitigation strategies

6.2.7.1 Risk assessment in all project phases

To reduce the risk of induced seismicity as much as feasible, different risk assessment techniques during the different project phases are necessary. With increasing project progress more knowledge about the underground and its seismic activity is available. Thus, is makes sense to continuously integrate this new knowledge and update early risk studies. Starting to monitor the underground seismically well in advance of a project’s start provides valuable information about background seismicity. An overview of different project phases and associated risk assessments is given in **Figure 124**.

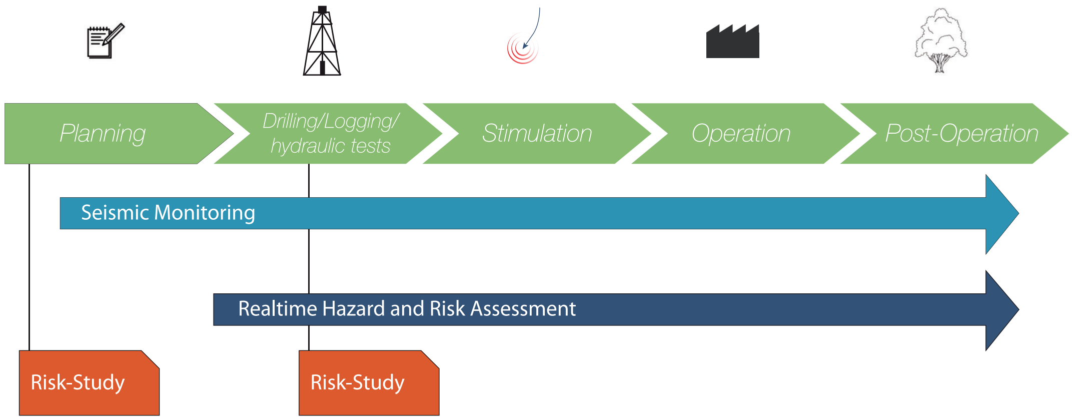

Figure 124: *Since knowledge of the underground increases the further a project advances, risk studies need to be updated. New information may be crucial and might change early risk assessments in a more advanced project phase. Additionally, seismic monitoring of the project area can deliver important information about background seismicity.*

6.2.7.2 Protocols for addressing Induced seismicity

The objective of protocols for addressing induced seismicity associated with EGS is to provide a flexible protocol that puts high importance on safety while allowing geothermal technology to move forward in a cost effective manner. The most established one was published by Majer *et al*. (2007); it was updated in 2012 (Majer at al., 2012). These protocols are recommendations specifically for the US, but in most sections they are generally applicable. They provide important and well-balanced guidelines for future projects. However, they currently remain rather vague with respect to advice on how to actually perform the hazard and risk assessment of induced seismicity (Step 6).

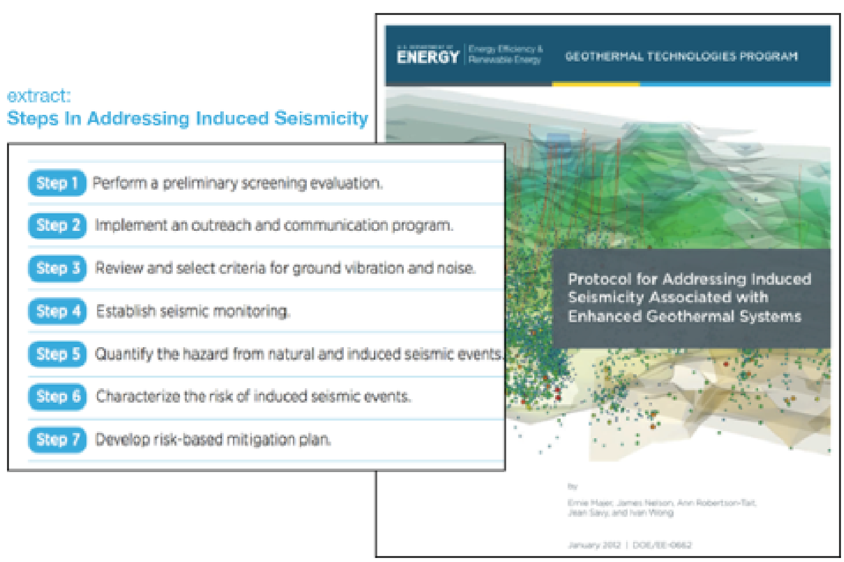

Figure 125: *An extract of "Protocol for addressing Induced Seismicity Associated with Enhanced Geothermal Systems", published by the US DOE. While these guidelines were written for the US, they are also generally applicable for Switzerland.*

6.2.7.3 Traditional traffic lights systems

The most widely used tools so far for hazard and risk management and mitigation, and an integral part of 'protocols' or best practice recommendations (i.e., Majer *et al.*, 2012; Ellsworth, 2013) are so called traffic light systems, first proposed by Bommer *et al*. (2006) for the 'Berlín' geothermal project in El Salvador. This approach was also adopted by the EGS projects in Basel (Häring *et al*., 2008) and in 2013 for the St. Gallen hydrothermal project. In both cases, the operators were well aware of the possibility of inducing earthquakes strong enough to be felt. To monitor earthquake activity and to be prepared for hazard mitigation actions, they adapted the 'traffic-light' system to be based on three components:

1. public response,
2. observed local magnitude and
3. peak ground velocity (PGV; see Häring *et al*., 2008 for details).

In a four-stage action plan, the injection of fluids in Basel would either be

1. continued as planned (green),
2. continued but not increased (yellow),
3. stopped (orange) or
4. stopped and a "bleed-off" initiated (red), where bleed-off means to actively release fluids out of the borehole.

The traffic-light system threshold levels were defined somewhat ad-hoc and mainly based on expert judgment. The pressure reduction and eventual bleed-off of the system in Basel during the critical days around December 8, 2006 was consistent with the actions stipulated in the traffic-light systems. However, the ultimate failure of the Basel EGS project suggests that the standard traffic-light system as defined was not a sufficient monitoring and alerting approach (see Bachmann *et al*. 2011; Mena *et al*., 2013). In the case of St. Gallen, the situation was somewhat different: Here the yellow threshold of the traffic light was triggered, but the proposed action – stopping the injection for at least 6 hours – was not taken because of the concern about the gas pressure in the well.

6.2.7.4 Adaptive Traffic Lights Systems (ATLS)

A new generation of '**Adaptive Traffic Light Systems**' (ATLS, **Figure 126**) is currently being developed by scientists at ETH Zurich, forming the seismicity-related safety components of future control systems for hydraulic stimulation and long term operation. Key ingredients of such ATL systems are:

Forward looking: Rather than being reactive schemes (i.e., a certain observed magnitude/ intensity triggers a certain action), ATL systems are centered on robust, forward-looking models that make probabilistic forecasts on the expected future seismicity based on a range of key parameters (current seismicity, current and planned pressures, permeability, static coulomb stress changes, etc.). Such forward-looking systems anticipate, for example, that the probability of inducing the largest events in the hours after shut-in is substantial (i.e., Bachmann *et al*., 2012; Görtz, Allmann and Wiemer, 2013). The most advanced systems will not only limit the hazard and risk to acceptable levels, but also jointly optimize seismicity and reservoir creation (Gischig and Wiemer, 2014).

Probabilistic: Forecasts are made within a fully probabilistic framework that considers

- the epistemic uncertainties stemming from our limited understanding of the physical processes acting during the stimulation, and
- the aleatory variability of the processes itself.

Such a probabilistic framework also integrates the view of the broader, informed community by representing the center, body and range of knowledge. A technical approach to this is to integrate model alternatives in a logic tree structure to characterize the uncertainties arising from our limited knowledge numerically (Mignan *et al*., 2014). Induced seismicity hazard and risk assessment is thus elevated to the quantitative analysis level common for most critical infrastructures. By integrating the forecasted rates of events for all magnitudes in the hazard and risk space, it also allows consideration of highly unlikely but extreme events, without letting them become showstoppers in public communication.

Adaptive: The forecasted seismicity and resulting risk is updated – automatically, as much as possible − on the fly as new data becomes available. All data is integrated using Bayesian principles, meaning 'prior' knowledge is combined with newly acquired data, depending on the degree of confidence in the data and its past performance in forecasting. Therefore, models need to be updated on the fly as new information is collected. The updating strategy in terms of parameters to be estimated, time window and magnitude ranges to fit them to, is critical and an intrinsic component of each model. Updating too many parameters, or fitting data to time windows of insufficient length, may lead to less robust models. Mena *et al*. (2013) show that such an optimally on-the-fly combined model performs better than individual models. It is also smoother in its earthquake rate forecasts and subsequent hazard estimates.

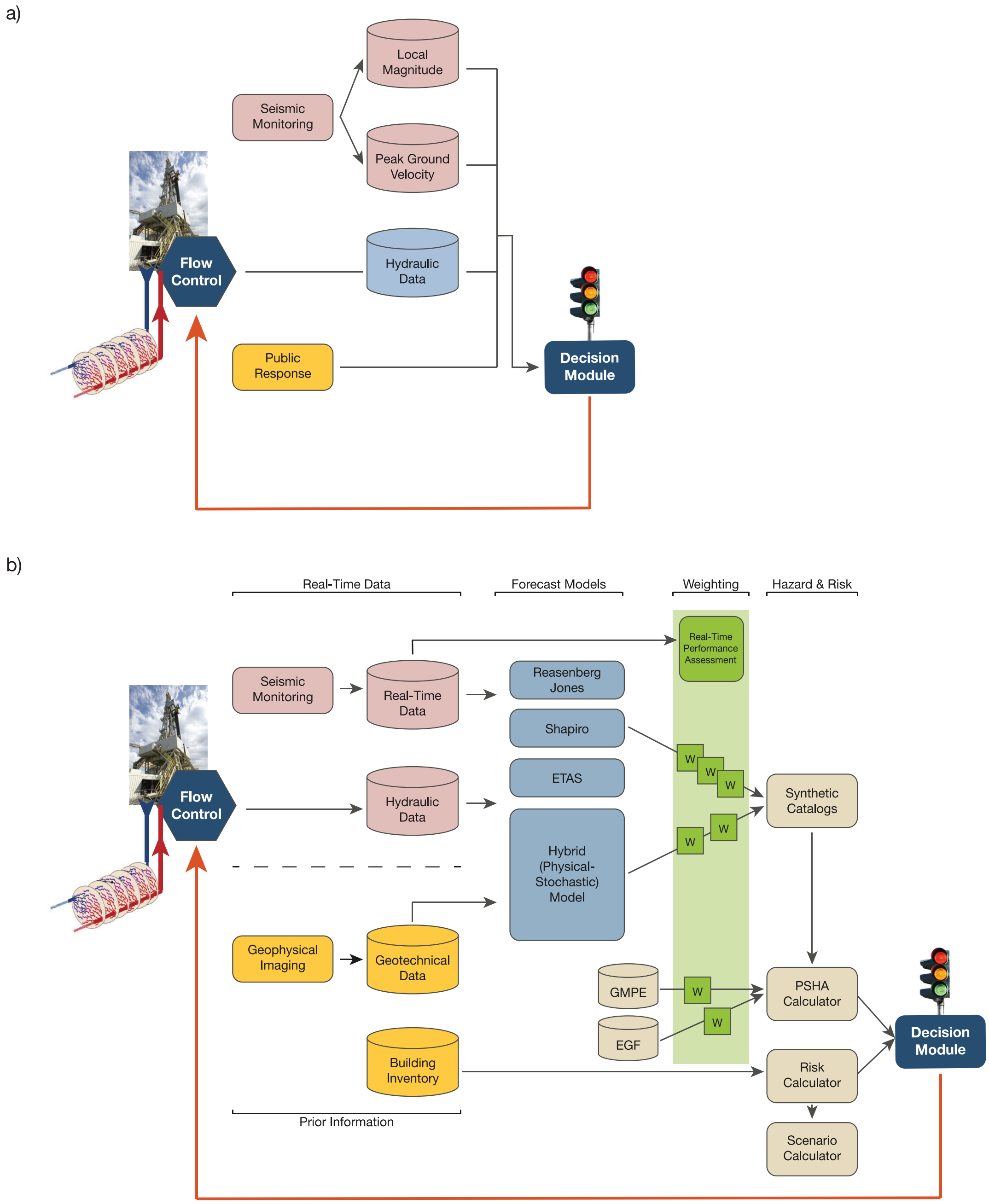

Figure 126: *a) Classical Traffic Light System. Decisions are based on observed magnitudes and ground motions. Thresholds are defined in a static manner taking geotechnical information into account to the extent possible. b) Proposed Advanced Traffic Light System. Decisions are based on a forward-looking, probabilistic and adaptive framework. Models are assessed in near real time and weighted accordingly.*

6.2.8 Summary and recommendations for future geothermal projects

6.2.8.1 General remarks

A. Induced seismicity poses a serious challenge to the public acceptance, regulatory compliance and economic viability of future deep geothermal projects in Switzerland. This challenge must be taken seriously and addressed in adequate ways. However, induced seismicity is not limited to deep geothermal projects but poses a challenge to a wide range of applications, including hydro dams, mining, oil and gas production and tunneling. While the economic impact and the impact on public acceptance are substantial, the actual damage to properties has been minor so far, with negligible impact.

B. Limited knowledge about the underground leads to uncertainties in the assessment of seismic hazards and risk. Given our current level of understanding of the processes, and given the existing mitigation strategies, a small chance of inducing a felt earthquake, or even a damaging earthquake, will remain in future projects. Assessing the likelihood of such low probability and potentially high consequence events is a challenge common to many technologies.

C. Deep geothermal energy projects in Switzerland carry a certain degree of seismic risk, and it is unlikely that in the medium term this risk can be significantly reduced. Operators and regulators should accept this fact and discuss it openly with the public and decision makers. The seismic hazard and risk can be assessed, albeit with uncertainty, and limited through mitigation strategies. Whether such a risk is acceptable, and when the potential benefits outweigh the risks, is ultimately a political decision.

D. The most effective strategy to reduce seismic risk is to stay away from densely populated areas.

E. In EGS, most of the seismicity will occur during reservoir creation, especially if the system created is largely closed and hence its pressure footprint is stationary. In hydrothermal systems, induced seismicity is observed to be generally stronger during the years of operation of the systems. Due to the lack of experience with the long-term operation of EGS projects, it cannot be excluded that these systems will behave in a similar way.

F. The exploitation of deep hydrothermal resources targeting large and tectonically active faults is complicated by the fact that a reliable assessment of the re-activation potential, and hence the seismic hazard, is difficult. Geophysicists are not able to image the level of tectonically accrued stresses on faults, and it is thus difficult to assess with confidence the probability of a run-away rupture on such systems.

G. Seismic monitoring and real-time data analysis is a key element of the safety of an operation. Experiences of past projects imply that real-time monitoring and reaction plans such as traffic light systems, coupled to hydraulic operation management, can significantly mitigate the seismic risk and contribute to the safety of the operation. However, there is a trade-off between safety and commercial success of an operation. The more conservatively a traffic light is set, the lower the seismic hazard but also the less likely the chance of achieving a commercially viable underground heat exchanger.

H. Forecasting the vigor of the seismogenic response of the underground before drilling is difficult − only vague indicators exist. Future projects should take more care to evaluate and model the seismogenic response based on the observed in-situ conditions during the reservoir stimulation in near real-time.

I. Insurance is an important element of public acceptance and resilience.

J. Seismic imaging in 2D and 3D can add important information to the understanding of the seismotectonic context. Future EGS projects should keep a safety distance of a few kilometers from major fault zones, especially ones that are active or easily reactivated in the contemporary stress field. However, faults, especially near vertical strike slip ones, cannot usually be imaged in the crystalline basement, severely limiting the usefulness of such surveys.

6.2.8.2 Risk studies

Project-specific seismic hazard and risk studies are crucial for future geothermal energy projects. They are generally conducted as part of the environmental impact studies at a cantonal level, but should be reviewed by independent experts. Such studies should at a minimum include the following points:

1. Natural seismicity in the study region.
2. Calculation of shaking scenarios for possible seismic events (this should also include extreme events with low occurrence probabilities).
3. Existing local microzonations (ground motion amplification effects) should be taken into account.
4. Identification of fault zones within at least 5 km of the project area.
5. Probabilistic assessment of the seismic hazard and risk posed by the project, including consideration of the uncertainties.
6. Drawing up a state-of-the-art monitoring, mitigation and intervention concept for induced seismicity.

6.2.8.3 Seismic monitoring of future projects

A. Adequate seismic monitoring for all future deep geothermal projects is essential. First, the seismic response of the underground to geotechnical operations is recorded immediately, and counter measures can start early on. Second, seismic monitoring provides essential information to distinguish between natural and induced seismicity, which may be important in cases of legal dispute. Finally, monitoring will deliver important data for advancing our understanding of the reservoir creation and management, mechanisms of induced seismicity, as well as our ability to model these phenomena.

B. Although the Swiss Seismological Service (SED) operates one of the best seismological networks in Europe, in most cases its density will neither be sufficient to provide the detection threshold nor allow the localization accuracy necessary to monitor future geothermal projects. Requirements for a basic surveillance of geothermal energy projects were recently defined by an expert group (Empfehlungen zur Überwachung induzierter Seismizität – Positionspapier des FKPE (Baisch et al., 2012)). *These guidelines have been further developed and adapted to Switzerland by the SED in the framework of the* BFE-funded project GEOBEST, and will be published soon.

C. Seismic monitoring according to the Forschungskollegium Physik des Erdkörpers (FKPE) requirements should start at least 6 months in advance of the construction phase of a project. In this way it is possible to test the performance of the network and the alarm system, and to assess the level of background seismicity in the study area. The recorded background seismicity can further be used to calibrate the network magnitude scale against the magnitude provided by the SED.

D. Relevant project data (seismological, geophysical, hydrological, etc.) should ideally be well documented and accessible for science and teaching. An open data policy will contribute to the public acceptance of the project and can add significantly to improving the knowledge and understanding of induced seismicity, and at the same time contribute to public acceptance.

6.2.9 Future R&D needs

A. The understanding of induced seismicity, and the ability to forecast it, has advanced greatly over the past 8 years, owing largely to the data and experience from the Basel and St. Gallen projects, and supported through a range of projects funded by the academic community and industry. These efforts need to continue over the next few years. The current continuity outlook in Switzerland is favorable right now, because funding through the SCCER SoE, NF70, ETH Zurich, BFE and possibly Horizon2020 can be combined with industry efforts in a strong alliance.

B. Validation of the emerging induced-seismicity modeling tools and mitigation strategies is now the most important need of the community. Future pilot and demonstration projects are key to these validation efforts.

C. Studying induced seismicity at the scale of a deep underground laboratory offers an opportunity to significantly enhance the understanding and forecasting ability of induced seismicity related to reservoir creation in a repeatable, controllable and safe environment. Most of the processes relevant for induced seismicity are scale invariant – so they can be studied in-situ, for example using a setup at the scale of 1:10. The observed micro-earthquakes would then be on the order of magnitudes from -4 to 0, posing no risk.

D. Research in deep geothermal energy needs to be increasingly cross-disciplinary, because solving the coupled problem of efficient reservoir creation while limiting seismic risk requires experts from geophysics, geology, mineralogy/petrology, physics, engineering and computation to work closely together as a team. Overcoming the previously existing fragmentation between different communities in the R&D efforts is needed.

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6.3 Approaches to risk management

We have not addressed current approaches to risk management as undertaken by industry. Similarly we have not addressed the requisite regulations that are in place to ensure that industry activities manage risk to as low a level as reasonably practicable.

To this effect, permitting and regulatory authorities generally institute directives, binding guidelines, self-reporting guidelines for incidents, and sanctioning methods to ensure compliance. Industry in turn meets the challenge of clean and safe operations by establishing Health, Safety, Security and Environmental Management Systems that rest on industry-wide accepted, regulated and auditable processes and procedures.

There are a range of potential hazards associated with deep geothermal activities, which range in severity from little or no effect, to worst case events of multiple fatalities and extensive asset and environmental damage. In order to provide assurance that all potential hazards and effects have been identified and can be demonstrated to be effectively managed, industry generally develops a Health, Safety and Environmental (HSE) Case for key operations in the development of a deep geothermal energy project.

The HSE Case is the documented output of the program of formal HSE assessment and provides assurance of the effective working of a Health, Safety, Security and Environment (HSSE) Management System at the location for the duration of the project.

The objectives of this HSE Case are to demonstrate compliance with business practices, a systematic application of HSE assessments including a listing of all significant HSE hazards (the 'hazard and effects register'). An HSE Case also demonstrates how hazards and effects are managed for the project and that plans and equipment are in a state of readiness for recovery in the event that control is lost.

For major hazards, HSE Systems need to demonstrate, to the extent reasonably possible and to a level of detail commensurate with the level of risk, that all foreseeable and credible major hazards that have the potential to cause multiple fatalities, major asset damage, major environmental effect or considerable adverse impact to the reputation of the participating companies have been identified, assessed and that suitable and sufficient barriers and recovery preparedness measures have been specified, so that risks associated with these hazards have been reduced to a level that is ALARP (as low as reasonably practicable).

For non-major hazards HSE Systems demonstrate that procedures and practices necessary to control workplace occupational health and safety hazards arising from hazardous activities (e.g. hot work, working at height, manual handling, etc.) will be in place. Controls include Permit to Work (PTW) systems, training and job safety analyses, including responsibilities for preparing, updating and implementing the procedures necessary to ensure the ongoing management of workplace hazards.

6.4 Risk perception

Risks are associated with specific concerns that individuals and social groups may attribute to these risks. They also comprise the subjective perception of various risk aspects. Although deep geothermal energy is conceived as a new renewable energy source with low CO_2 emissions, whether society will easily accept this type of energy infrastructure is not well-known. The risk of induced seismic events is one of many issues, in addition to methane leakage, groundwater contamination, or accumulated radioactivity, for example, which deserve close attention when communicating with the public. A thorough understanding of accidental and other risks and the respective concerns of the general public and specific stakeholder groups is required for a potentially successfully integration of geothermal energy on a large scale into Switzerland's energy mix.

Thus, the following guiding questions will be dealt with in this task:

- What do we know about the risk perception of different contested energy infrastructures worldwide, for example, wind power, carbon capture and storage (CCS), and nuclear waste in general, and deep geothermal energy specifically?
- What do we know about the risk perception of deep geothermal energy in Switzerland and the underlying causes, specifically seismic hazards as well as groundwater contamination, or accumulated radioactivity, for example, of these perceptions? What concerns and beliefs are expressed? How did they develop over the years?

To answer these guiding questions, a literature review is combined with a content analysis of newspaper articles about deep geothermal energy.

6.4.1 Literature review: Public perception of geothermal energy

Corinne Moser & Michael Stauffacher (ETHZ)

A literature search on the Web of Knowledge indicates that little social scientific literature has been published on the issue of deep geothermal energy (topics geothermal + perception: 16 hits; topics geothermal + social acceptance: 7 hits; 6 June 2013). A quick overview of these articles shows a comprehensive published social scientific research portfolio on risk perception and social acceptance of deep geothermal energy does not exist. In addition, (Gross, 2013) concluded that "So far, geothermal power (…) has received little attention from social sciences and humanities research compared to other renewables such as wind or solar power."

The aim of this paper is to review the existing literature on public perception of deep geothermal energy worldwide. As an interesting complement, we also focus on comparable energy-related technologies such as CCS, wind power, and nuclear waste. Since deep geothermal energy shares characteristics with these technologies, this comparison could provide potentially interesting insights and learning opportunities for understanding public perception of deep geothermal energy.

6.4.1.1 Public perception of deep geothermal energy

Large-scale survey results about the public perception of deep geothermal energy have not yet been published. However, a handful of studies exist investigating the risk perception of deep geothermal energy in various countries.

A media analysis in Germany examined the public discourse on deep geothermal energy in German newspapers between 1999 and 2009 (Leucht, 2010, 2012). The analysis of 570 articles revealed a mixed discourse, which seemed quite positive regarding deep geothermal energy in the beginning (before 2005) and later became more skeptical about the issue (particularly between 2008 and 2009, possibly due to the spectacular "water fountain" induced by drilling activities in Wiesbaden for near-surface geothermal energy applications). The three most important topics in the articles were 1) investments in new geothermal facilities, 2) technological aspects of deep geothermal energy, and 3) renewable energies. Among the top 10 topics, some risks are present: induced seismicity/earthquakes (ranked 6), drilling problems (ranked 8), general risks (technology, environment, social and financial aspects, ranked 10). In a related study, (Wallquist and Holenstein, 2012) investigated the public perception of deep geothermal energy in four German sites (Unterhaching, Landau, Bruchsal, and Brühl). They conducted 28 qualitative explorative interviews. Results indicated that the perception of deep geothermal energy varied widely across the four studied sites. There is a broad spectrum regarding perception of risks, benefits, trust in operating companies, and acceptance. The authors concluded that this multitude of perceptions seemed to be based on the different experiences that the participants had had in the four communities (i.e., earthquakes, and use of geothermal heat). There seems to be no societal consensus regarding the use of deep geothermal energy. However, there seems to be consensus among participants that a fair open-planning and decision-making process is a prerequisite for a successful project.

In Australia, the perceptions of and support for deep geothermal energy were investigated in five group workshops (in 2008 and 2009, a total 329 participants from the public; see Dowd et al., 2011). Participants were informed about different technologies as well as climate change and could discuss them in order to form opinions. Support for geothermal energy was medium (less than support for solar energy, wave/tidal, wind power, but more support than for hydro, natural gas, biofuels, CCS, nuclear, and oil). Participants judged their level of knowledge of deep geothermal energy as similar to their knowledge of CCS, nuclear power, and wave/tidal energy. The participants were most interested in receiving more information about CCS and geothermal energy after the workshop. In a more qualitative approach, several key concerns were identified regarding deep geothermal energy; the most important referred to water consumption and induced seismicity. Seismic activity due to deep geothermal energy is perceived as a threat, while water is considered a scarce resource in Australia. Additional concerns are related to CO_2 emissions from underground and possible relocation of townships in order to install geothermal facilities (Dowd *et al.*, 2011; Ashworth, Paxton, and Carr-Cornish, 2011).

Other articles focused on case studies throughout the world and describe positive and negative examples (Popovski, 2003). Success stories often seem related to intense public involvement in project planning and implementation and/or combining the geothermal project with other pressing goals of a community. Some projects that had been successful in the beginning also developed adversely, for example, because of political reasons (i.e., privatization, short time horizons). Negative stories often seem to relate to the perception of negative environmental impacts (i.e., noise, smelly water, visual impairment of the landscape), expected negative economic effects (i.e., on tourism), and perceived unfairness (i.e., power production for a neighboring community and not for one's own community). An interesting example is Iceland. Although Popovski (2003) described Iceland as a successful story, critical voices exist. Krater and Rose (2009) in particular criticized the image that deep geothermal energy is a renewable (limited lifetime of bore holes due to destruction), carbon-neutral energy source with low environmental impact (i.e., release of heavy metals and toxic elements, impact on landscape and wilderness areas).

Another case example concerns Hawaii where a strong plea was made for more local orientation in planning geothermal projects (Canan, 1986). Since the late 1970s, there has been a public controversy in Hawaii about deep geothermal energy. The main concerns are related to impairment of tourism, impairment of biological uniqueness, and locally unwanted industrialization due to available cheap electricity (i.e., the aluminum industry). Later attempts to educate the public or to resolve the conflict through mediation failed due to erosion of trust (Walker, 1995). However, Canan (1986) argued that there could also be benefits for the islands such as money, job opportunities, and new energy-related industries. She concluded that energy development should occur at the community scale by taking into account respective opportunities and concerns.

Similarly, Goldstein and colleagues (2011) pointed out numerous benefits for people affected by deep geothermal projects, such as job opportunities during exploration, drilling, and operation of the plant. They also mentioned the potential to alleviate poverty in developing countries as well as provision of local services by the respective operators (i.e., roads, schools, hospitals).

6.4.1.2 Public perception of carbon capture and storage

Reiner and colleagues (2006) conducted surveys in the United States (USA), the United Kingdom (UK), Sweden, and Japan and concluded that the levels of awareness of CCS were very low in all surveyed samples: Only between 4% (USA) and 22% (Japan) of participants had heard or read about CCS. Due to these low levels of awareness, public acceptance surveys might not yield reliable information. More qualitative investigations therefore focused on ideas people hold about CCS (Wallquist, Visschers, and Siegrist, 2009; Palmgren, Morgan, De Bruin, and Keith, 2004). By interviewing 16 Swiss, Wallquist and colleagues (2009) found that people were concerned about several issues involving CCS. More technically oriented concerns refer to over-pressurization of the reservoir (image of a potentially exploding balloon underground), harm to ecosystems due to CO_2 exposure, leakage (gas will come up again), induced earthquakes due to drilling and injecting CO_2 (some participants even directly referred to the deep geothermal project in Basel), as well as an "out of sight/out of mind policy" (some participants directly referred to nuclear waste management). More societally oriented concerns refer to lack of sustainability (i.e., no incentives to increase energy efficiency, fighting only symptoms), hindering investments in renewable energy technologies, rebound effects, and NIMBY (not in my backyard). A subsequent survey among 654 Swiss participants quantified the findings from the interviews (Wallquist, Visschers, and Siegrist, 2010). The most important factors explaining risk perception of CCS are societally oriented concerns (i.e., CCS is merely "combating the symptoms" rather than contributing to the necessary shift in energy supply technology, CCS gives wrong incentives, CCS competes with the development of new renewables) and concerns about CO_2 leakage and pressurization.

In an experimental setting, communication strategies for CCS were analyzed (Wallquist, Visschers, Dohle, and Siegrist, 2011). Participants first received basic information about CCS and responded to questions (knowledge questions, risk perception, benefit perception). After two months, the same participants received more detailed information and responded to the same questions again. Results indicated in general that more extensive information decreased perceived risk and increased perceived benefits as well as knowledge about CCS. A more detailed analysis, however, revealed that the relationship between information and knowledge, risk and benefit perception also depends on the type of information given and that a “the more the better approach” cannot be supported.

As a consequence of realizing the importance of societal aspects in siting CCS projects, Wade and Greenberg (2011) suggested complementing the technical site characterization for a CCS project with social site characterization (i.e., regarding specific needs, collaboration with the community) and provided a respective Social Site Characterization Toolkit.

Stephens and Jiusto (2010) provided an interesting comparative study of CCS and EGS regarding technological status, environmental benefits and risks, competing discourses, strengths and composition of actor networks, and investments and financial support. A dominant element of public discourse on CCS is the narrative of “inevitability of continued use of coal; this reasoning assumes that coal is so cheap, abundant and embedded in existing electric power systems that its continued growing use globally is a virtual certainty. With this set of assumptions, CCS is viewed as essential for reconciling the inevitability of continued coal use with the imperative for climate change mitigation” (Stephens and Jiusto, 2010). In contrast, the discourse on EGS is less pronounced as it has received much less public attention compared to CCS. One emerging element might be the following: “EGS as a ‘killer app’ (i.e., system transforming application) that represents a discourse focused on the potential of various EGS attributes including a large renewable energy resource with distributable, baseload potential and minimal environmental impact” (Stephens and Jiusto, 2010). One main conclusion regarding the comparison between the two technologies is that “CCS thus can be viewed as being supported by and contributing to the stabilization of the “entrenched regime” of the current coal-based energy system, while EGS represents a niche technology that might ultimately be disruptive to the mainstream regime” (Stephens and Jiusto, 2010). Therefore, different interest and stakeholder groups support both technologies. Although CCS has strong support from the traditional coal industry, “the EGS network is much thinner, newer, and less powerful” (Stephens and Jiusto, 2010). This also results in tremendous differences regarding financial investments in the technologies.

6.4.1.3 Public perception of wind power

Although issues such as public perception and public acceptance are the focus of social scientific publications on CCS, publications on wind energy seem to be broader. They cover issues such as risk perception and acceptance but also the broader context as well as procedural and justice aspects.

According to Wüstenhagen, Wolsink, and Bürer (2007), social acceptance of wind energy (among other renewable energies) is different from fossil fuel technologies due to the following important characteristics: i) The infrastructure is often small scale (thus, the number of siting decisions is increased); ii) lower energy densities and a higher relative visual impact; iii) resource extraction happens above the Earth's surface, thus enlarging visual impact; and iv) most renewables do not compete with fossil fuel technologies (resulting in trade-offs "between short-term costs and long-term benefits," Wüstenhagen *et al*., 2007).

A survey among 13,091 European Union (EU) citizens (from 12 member states of the EU) showed that public acceptance of wind energy in general seems quite high. Among a set of seven energy technologies (solar, wind, hydroelectric energy, natural gas, biomass energy, coal, and nuclear energy), wind energy was the second preferred technology (after solar energy). Sixty percent of participants were strongly in favor of wind energy, while 29% were generally in favor of this technology (European Commission, 2011).

Concrete projects, however, reveal a different picture. Eiser, Aluchna, and Jones (2010) investigated attitudes regarding wind energy in two Polish communities: one affected by proposals for nearby wind farms and an unaffected control community. Compared to the unaffected community, participants from the affected community were significantly less convinced that wind energy is a good idea in general, that wind energy is good for the local community, and that wind energy brings economic benefits. In general, the affected community was less in favor of wind farms. In addition, participants from the affected community were less concerned about the political relationship with Russia and Poland's dependence on Russian gas. Similar tendencies were found in the UK. Respondents of a survey were less supportive of local wind energy farms compared to the general wind energy development in the UK (Jones and Eiser, 2010). Analyses also suggest that opposition is not driven solely by spatial proximity. The anticipated visibility of wind energy farms influences opinions on wind energy farms.

This discrepancy between general support and local opposition is often framed as NIMBYism (Kraft and Clary, 1991). However, Bell, Gray, and Haggett (2005) offered a different explanatory framework for this pattern. They distinguished between a social gap (discrepancy between general acceptance of wind energy and low number of realized projects in the UK) and an individual gap (discrepancy between general support and local opposition to wind energy, i.e., NIMBYism). They provided three explanations for the social gap: i) democratic deficit (decision-making processes are heavily influenced by an unrepresentative minority of opponents); ii) qualified support (support for wind energy might be coupled with conditions that are not recorded in standard surveys, i.e., no negative impacts on landscape, animals); and iii) the classical NIMBY explanation (Not In My Backyard; people are generally in favor of wind energy but not in their backyards).

Wolsink (2000) also criticized the debate on wind energy: "by labeling all protests as NIMBY one misses the multitude of underlying motivations" (p. 57). Surveys in three regions with wind farms in the Netherlands revealed that only 25% of participants displayed NIMBY preferences. Wolsink (2000) distinguished four types of resistance: i) positive attitude toward wind energy in general but opposition to projects in one's neighborhood, i.e., NIMBY; ii) general rejection of wind energy; iii) positive attitudes become negative during discussion and decision-making process about a specific project; and iv) generally in favor of wind energy but only under certain conditions, i.e., concerns about consequences for scenery and visibility, as well as interferences and nuisance (Wolsink, 2000). Furthermore, the decision-making process plays a crucial role. A "top-down policy style" assuming broad public support can result in the "engineer's and planner's fallacy" (Wolsink, 2000).

Gross (2007) analyzed community perspectives on wind energy in Australia from a justice perspective. Justice was defined not only in terms of the outcome but also the process. By procedural justice, she referred to "full participation in the process, the ability to express opinions freely and to be heard (voice), being treated with respect, being given adequate information, the impartiality of the decision maker" (Gross, 2007) as well as the ability to correct a decision. Important insights from her study included the following: Many community members felt that there had not been an appropriate consultation process. Even though there was a possibility of participating formally (i.e., by submitting a letter), participants did not feel that their voice would be heard or that they could express their perspectives on the wind project. Many community members also criticized the information as inadequate. The decision process had a direct impact on the community by creating "winners and losers" and, eventually, a "divided community" (Gross, 2007). A key finding of this study was that procedural and distributive justice must be considered in contested infrastructure projects. Her research also indicated a link between a fair process and acceptance: "The empirical research found that the procedural justice principles of appropriate participation, the ability of voice to be heard, adequate information, being treated with respect, and unbiased decision-making were considered important by interviewees in the case study" (Gross, 2007).

For Switzerland, a policy-oriented study analyzing four wind projects (Mont-Crosin, Crêt-Meuron, Sainte-Croix, and Saint-Brais) came to similar conclusions (Schmid and Schuppli, 2009). The authors applied a case study approach for each project. Analyses were based on document analysis and interviews with case experts. Results indicated that, among other factors, coherent planning, early information for people affected, and informal opportunities for participation enhance cooperative processes. At the same time, cooperative processes positively influenced local acceptance of wind energy projects.

6.4.1.4 Public perception of nuclear waste

For the issue of nuclear waste, social scientific studies encompassed a broad variety of issues ranging from risk perception and acceptance to much broader approaches, including procedural aspects as well as embedding in a general energy-related context.

Two surveys in Switzerland conducted in 2007 and 2011 by the Institute of Environmental Decisions (ETH Zurich, data not yet published) indicate that the mean acceptance of a deep geological repository in the participants' region decreased from 2.36 in 2007 to 2.07 in 2011 (scale from 1 = strongly opposed to 5 = strongly in favor). Perceived risks included health risks (for oneself and for future generations), transport accidents, damage to the environment, and economic risks. Perceived benefits included job opportunities, positive local economic benefits, low taxes, and improvement of regional infrastructure. For 2007, three clusters of respondents were identified regarding concerns, perceived risks/benefits, emotions, trust, and fairness regarding nuclear waste (Stauffacher, Krütli, and Scholz, 2008): "clearly positive" (n = 813), "clearly negative" (n = 483), and "moderately negative" (n = 890). This response pattern indicates that in the case of nuclear waste, there are not (only) proponents and opponents but also more ambivalent or indifferent groups (see also Seidl, Moser, Krütli, and Stauffacher, 2013a). The ambivalent or indifferent groups are particularly important in terms of the societal decision process.

Switzerland has a long history of siting nuclear waste. Initial plans to construct a repository in central Switzerland failed due to strong public resistance and two negative votes (Scholz, Stauffacher, Boesch, Krütli, and Wiek, 2007; Krütli, Flüeler, Stauffacher, Wiek, and Scholz, 2010). According to a case study in the respective region, this outcome probably occurred due to procedural weaknesses (Scholz *et al*., 2007). Investigating the fairness judgments of a directly adjacent community (Dallenwil) to the potential host community (Wolfenschiessen) revealed that people in Dallenwil still feel treated unfairly today. Even though the repository was planned in their vicinity, the community did not receive much attention from the implementer nor were they promised financial compensation. As the implementer (Nagra) concentrated most of its activities in the host community (Wolfenschiessen), people in Dallenwil were barely involved in the process (Krütli *et al*., 2010). Furthermore, erosion of trust due to conflicts of interest played a significant role, because the implementer depends financially on Swiss waste producers (mainly nuclear power plants). Therefore, the Swiss government took more responsibility and established a new stepwise site selection procedure that considers public participation in particular and other procedural fairness aspects (SFOE, 2008).

In siting nuclear waste, fair distribution is not possible in Switzerland due to geological constraints. For example, a repository cannot be built in a community where most (nuclear) power is consumed. Similarly, this decision cannot be based solely on local acceptance (i.e., due to expectations of lower taxes or other benefits), as has happened in Sweden, for example (Schori, Krütli, Stauffacher, Flüeler, and Scholz, 2009). Due to these constraints, procedural justice becomes particularly important. This statement is backed by a conjoint study (Krütli, Stauffacher, Pedolin, Moser, and Scholz, 2012). Participants ranked vignettes (i.e., different scenarios of future nuclear waste management in Switzerland) combining aspects of procedural justice, distributional justice, and outcome valence. Scenarios that included a fair process (i.e., transparent and participative process, open and comprehensive information) were top-ranked while distributive aspects played only a minor role. The authors therefore concluded that the process matters for a fair repository siting procedure for nuclear waste.

Different studies also pointed out that values are at stake in the perception of nuclear waste. Sjöberg (2000) investigated public opinion regarding nuclear waste in Sweden. He identified the value “tampering with nature” (which is described as involving interference with nature and displaying human arrogance and immorality; see Sjöberg, 2000) as an important predictor of risk perception of nuclear waste. An interview study also revealed that “safety” is an important value, which is at stake in siting decisions. Thus, participants consider not only their own safety but also future generations’ (Seidl *et al*., 2013b).

Furthermore, studies have found striking differences between laypeople and experts regarding nuclear waste (Flynn, Slovic, and Mertz, 1993; Flüeler, 2006; Skarlatidou, Cheng, and Haklay, 2012). Experts and laypeople differ regarding judged seriousness of risks (due to handling, transportation, and disposal) but also types of risks associated with nuclear waste disposal as well as images and mental models of a nuclear waste repository. According to the psychometric paradigm, laypeople seem to approach the issue with an intuitive and affect-laden approach whereas experts seem to adopt a more analytic view (Slovic, 1987; Fischhoff, Slovic, Lichtenstein, Read, and Combs, 1978).

These differences between experts and laypeople indicate the important role of social trust in experts (Siegrist, Gutscher, and Earle, 2005). Dawson and Darst (2006) argued that reciprocal trust is important for a successful outcome: not only trust by the public in nuclear authorities but also the trust that the government and industry put in society to play a responsible role in the site selection process. They further differentiated between pre-existing trust and trust generated through the site selection process and stressed that both are important.

However, we also find differences among different experts. The challenge of finding a site for a nuclear waste repository is an interdisciplinary endeavor. Even though the technical community has realized that they need expertise from social sciences and humanities due to the complexity of the tasks, experts from natural and technical disciplines still comprise the dominant "epistemic community" (Haas, 1992) in nuclear waste management (Stauffacher and Moser, 2010). This means that the different involved disciplines have their own field of expertise (i.e., risk communication or risk assessment) and that there is hardly any close interdisciplinary collaboration within the same field. This poses challenges for communication among experts but also between different experts and the public. A more integrated interdisciplinary collaboration could also imply more robust solutions, both technically and societally (Flüeler, 2006). One reason is that close interdisciplinary collaboration can reveal different "thought styles" (Fleck, 1980) of different disciplinary cultures, and thus, potential blind spots can be identified and discussed (Moser, Stauffacher, Krütli, and Scholz, 2012).

6.4.1.5 Comparison of deep geothermal energy with other technologies

Deep geothermal energy shares characteristics with energy technologies such as CCS, wind power, and nuclear waste storage. The following issues have been researched intensely for these comparable technologies and might be important in order to understand public reactions to deep geothermal energy. Furthermore, these issues might also provide useful and important insights into designing societal decision-making processes.

Values: One concern the Australian study refers to is the idea that "we are still creating destructive harm to the earth in search of energy" (Dowd *et al*., 2011). This indicates that values (i.e., "tampering with nature"; see Sjöberg, 2000) are at stake, similar to the case of nuclear waste disposal (Sjöberg and Drottz-Sjöberg, 2001). In addition, safety aspects are strongly valued (Seidl *et al*., 2013b), and this might play an even more pronounced role in the debate about deep geothermal energy after the seismic events in Basel in December 2006 and St. Gallen in summer 2013.

NIMBY and protest potential: In several reported case studies, the NIMBY effect was observed. Despite in general being in favor of renewable energies such as geothermal, people might not be willing to live near such a facility. This effect could be further pronounced in cases of large infrastructures that are highly visible. However, as in the case of wind energy, studies reducing public protest to NIMBYism alone earned widespread criticism (Wolsink, 2000), as the NIMBY effect assumes that opposition is based on a selfish motivation. Many other factors potentially lead to local opposition, for example, lack of procedural fairness, untransparent and non-participative decision processes, and lack of public engagement (Devine-Wright, 2011). As a reaction to potential non-involvement, the public or activists might develop different strategies to "break through the expertise barrier" (Parthasarathy, 2010) and re-balance power. Parthasarathy (2010) distinguished four strategies: i) deploying established expertise (i.e., engaging with experts who have a contra-position, organizing specific training); ii) introducing new kinds of facts (i.e., water pollution, CO_2 emissions, noise of underground facilities); iii) introducing new policy-making logics (i.e., promoting the precautionary principle; and iv) attacking bureaucratic rules (i.e., asking for a public vote).

Public participation and fairness: In the case of nuclear waste, public participation is a key element in the procedure for selecting sites in Switzerland (SFOE, 2008). Similar to the case of geothermal energy, sites are selected based on geological constraints. In this situation, procedural fairness has been demonstrated to be particularly important (Krütli *et al.*, 2012). Concretely, this could mean transparency in the siting process, communication of uncertainties and unknowns, communication of risks and benefits, and a participatory process in which the public can discuss and influence certain decisions (NRC − National Research Council, 2003). Kunreuther, Fitzgerald, and Aarts (1993) developed a "Facility Siting Credo" for locally unwanted land uses, including the following (selected) objectives: 1) institute a broad-based participatory process, 2) seek consensus, 3) work to develop trust, 4) choose the solution that best addresses the problem, 5) fully address all the negative aspects of the facility, 6) make the host community better off, 7) use contingent agreements, 8) consider a competitive siting process, 9) set realistic timetables, 10) keep multiple options open at all times, and 11) work for geographic fairness. This asks for a stepwise, participatory site selection procedure. A potentially useful example for learning about siting deep geothermal projects is the sectoral plan for nuclear waste disposal in Switzerland (SFOE, 2008).

Risks and high uncertainties: Deep geothermal energy imposes risks (for example, induced seismicity, particularly in the case of hot dry rock but also hydrothermal projects; see Evans and Deichmann, 2011). Induced seismicity potentially yields high damage and may represent a classical "high damage, low probability" problem that is challenging to communicate to the public (Hall, 2011). An additional characteristic of these risks is that they are human-made and perceived as being uncontrollable (high dread risk, see Slovic, 1987). Deep geothermal energy is also characterized by high uncertainties and even unknowns (i.e., about the discovery of hot water, characteristics of underground but also drilling risks, financial risks, and so on). A deep geothermal project is therefore a "real-world experiment" in which production of knowledge and its application are closely intertwined (Gross, Hoffmann-Riem, and Krohn, 2003).

Dependency on abstract expert knowledge and trust: Deep geothermal energy is a highly complex technology, and the public perceives and conceptualizes risks associated with deep geothermal energy differently compared to experts (Flynn *et al.*, 1993). The public's perceptions are shaped more by intuition, and experience, as well as the historic context. Thus, the seismic events in Basel probably triggered very different associations and concerns in laypeople compared to experts. Strict differentiation between experts and laypeople might also be problematic as local people are also local experts. Thus, they can provide context-related knowledge and experiences (i.e., living in an earthquake region) that could be important for developing local projects (Lidskog and Sundqvist, 2004). Such case-specific knowledge is a prerequisite for energy planning on the community scale (Canan, 1986). Therefore, large supra-regional or international energy companies might be regarded with skepticism. Furthermore, communication among experts can be a challenge, particularly if they come from different disciplines, have different "thought styles" (Fleck, 1980), and are occupied with different aspects of the problem.

From a more **perception-related perspective**, Gross (2013) pointed out an interesting issue. Normally, renewable energies are associated with things happening on the Earth's surface (i.e., wind, solar, water). However, geothermal energy depends on processes underground and risks that refer to induced seismicity are "located" underground. From this perspective, deep geothermal energy might therefore be more strongly associated with non-renewable energies such as coal, gas, CCS, or hydraulic fracturing compared to other renewable energies.

6.4.2 Content analysis: media articles on deep geothermal energy in Switzerland[31]

Nora Muggli, Corinne Moser & Michael Stauffacher (ETHZ) in collaboration with Christina Benighaus (DIALOGIK)

Since only restricted information is available about the current perception of deep geothermal energy, media reports were analyzed. A content analysis of selected newspaper articles on deep geothermal energy in Swiss newspapers should lead to better understanding of how geothermal energy is discussed in the media, which arguments are used, and which broader underlining narratives, ideas, etc., are used. Since most people lack personal experience and do not have a clear idea about this technology, we argue that the ways the media presents and discusses the issue can hint at the way how the broader public perceives and reacts to geothermal energy.

Content analysis is a rule-based method for systematically analyzing communication patterns with a coding scheme (Mayring, 2010). The content analysis focuses on topics, pro and con arguments, and frames in published newspaper articles about deep geothermal energy. The term "frame" thus refers to a certain perspective that is taken (i.e., by a journalist or by a stakeholder) on the issue at stake (Jönsson, 2011). Frames serve as heuristics for readers who have only a little knowledge about an issue (Donk, Metag, Kohring, and Marcinkowski, 2012). According to Entman (1993), framing means to ''select some aspects of a perceived reality and make them more salient in a communication text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation." Different interest or stakeholder groups might try influencing the frame for how geothermal is presented in the media and thus influence how the issue is perceived by the broader public.

Our analysis aims at revealing the media discourse on deep geothermal energy in Switzerland and at demonstrating how certain actor groups frame the issue. This is an important step in order to better understand public perception of deep geothermal energy since newspapers can substantially influence the formation of opinions and acceptance.

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[31] This primary research was made possible by a parallel project (Geotherm^2) financed by the Competence Centres Environment & Sustainability (CCES) and Energy & Mobility (CCEM) of the ETH Domain.

The analysis focuses on deep geothermal energy only and specifically tackles Swiss newspaper articles, but can also be compared with a content analysis of German newspapers of the same time period undertaken in parallel by DIALOGIK, Germany.[32]

We formulated the following research questions:

1. How often did Swiss newspapers report on geothermal energy in the last few years?
2. Which types of general arguments are prevalent in the debate on deep geothermal energy in Switzerland? How did pro and con arguments evolve over time?
3. Which actors appear in newspaper debates on deep geothermal energy?
4. Which actors favor which arguments about deep geothermal energy?
5. How is deep geothermal energy framed in the articles? How do the frames evolve over time?
6. How do different actors frame deep geothermal energy?

After defining the central question, we selected the newspapers and the time period to analyze. We chose the *Neue Zürcher Zeitung* (NZZ, as well as NZZ am Sonntag and NZZ Folio) and the *Tages-Anzeiger* (TA) because they are the core daily newspapers in the German-speaking part of Switzerland. Furthermore, we decided to analyze the time period of about 20 years from 1993 to 2013 (TA: 1997−2013).

6.4.2.1 Method

Articles were searched with different databases (such as Genios and Lexis Nexis or directly in newspaper archives). A combination of the keywords "Erdwärme OR Geothermie" was the most parsimonious strategy for gaining a comprehensive overview of the relevant articles.[33] For the NZZ (and NZZ Folio; NZZ am Sonntag), 674 articles were identified, for the TA 445.

Since the content analysis should focus on deep geothermal only, the articles had to be manually selected.[34] All articles were skimmed, and relevant articles were selected for the subsequent content analysis.[35] For NZZ and TA, the number of articles was thus reduced to 193 articles for the in-depth analysis.

These articles were analyzed with qualitative text retrieval and thematic coding. We followed three steps that we will explain in more detail. We developed the analysis and coding categories, coded the material, and then compiled and analyzed the coded material with the program MAXQDA.

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[32] For close cooperation, Corinne Moser, Michael Stauffacher (ETHZ), and Christina Benighaus (DIALOGIK) met in Zürich in May 2013 for a workshop to discuss the main ideas and research questions and to develop the concept, procedure, and the coding scheme (code tree) for the content analysis. The project partners also arranged five Skype conferences to consult about the code tree of the content analysis.

[33] Before we chose the two terms, we tried several terms such as "Tiefengeothermie," "hot dry rock," "Geothermie AND Triemli," etc., to find relevant articles that deal with geothermal energy.

[34] Unfortunately, automatic selection was not possible since journalists use the term geothermal for deep geothermal and shallow geothermal (heat pumps).

[35] To be chosen, articles had to fulfill the following criteria: i) the article topic was deep geothermal energy, and ii) the minimum length of the article was at least two paragraphs; press releases were not excluded.

Step 1: Developing the coding scheme

We developed codes for the level of single articles (i.e., style of article) and on the level of paragraph and sentences to identify all relevant arguments and frames. We followed the suggestions by Rössler (2010) to assign the following four codes to the respective text passages: i) topic, ii) evaluation, iii) actors, and iv) statements. This strategy identifies relevant actors, arguments, and frames independently but also in an integrated manner. This means that we can identify the relationships between different actor groups and their core arguments and how they frame the issue of deep geothermal energy (see the research questions). We differentiated between general arguments and actors' active arguments. As a general argument, we defined any statement listed in an article that is an argument for or against the use of geothermal energy. These general arguments do not have to be traced back to a person but can also be the statement by a journalist, for example: "Geothermal energy is environmentally friendly." An active argument, in contrast, is a statement that can be explicitly attributed to a certain actor. For example, "One citizen present at the information event was afraid of noise emission" or "The councilor says that the seismic risk is low." Frames do not refer to a specific statement but describe a process of selecting or highlighting specific information or aspects of reality (Entman, 1993). To operationalize this reference to the argument for and against geothermal energy in media, we used Hänggli and Kriesi's (2012) method. We reviewed all coded arguments and summarized them based on the content categories. This means that we understand frames as sets of arguments that share a specific perspective on the issue of deep geothermal energy.

The coding scheme was developed iteratively (Patton, 2002; Miles and Huberman, 1994). After we coded approximately 10 articles from Swiss and German newspapers, we discussed, reviewed, and expanded the scheme. We repeated this procedure two times to get an optimized code tree. We also secured intercoder reliability by coding samples of the articles independently by different researchers and discussing all coding differences. After this process, we optimized the code tree again and formulated a list of detailed descriptions and examples for each code. The final (slightly simplified) code tree is listed in the appendix.

Step 2: Coding of the selected articles

Text passages that refer to a specific category were coded. For example, if a text passage explained the risks of geothermal energy, we assigned the code "risk" to the text section. As suggested by Rössler (2010), multiple codes can be assigned to the same passage, so the relationships among the actors, arguments, and frames can be analyzed later.

Step 3: Analysis of the coded material

In this step, the frequency of the codes in each category in total and over the years was computed with the program MAXQDA. To answer our research questions, we also analyzed the frequency of the intersections between the arguments and the actors as well between the frames and the actors (code relations).

6.4.2.2 Results

How often did Swiss newspapers report on geothermal energy in the last twenty years?

Figure 127 shows the frequency of all articles (1119) over time along with important events that shaped the discourse on deep geothermal energy in Switzerland. The graph indicates that peaks in the frequency can easily be assigned to certain events taking place at that time. In 2006, a seismic event was triggered by the geothermal project in Basel and in 2013 another one by the project in St. Gallen. In addition, the number of articles increased when public votes were held. In 2009, there was a vote on the credit for the Triemli project. However, not all events are directly linked to deep geothermal energy. For example, in 2008 deep geothermal energy was mentioned in association with the vote in Zurich to phase out nuclear power. In addition, after the catastrophe at the Japanese nuclear power plant in Fukushima, the discourse evolved about phasing out nuclear power and renewable energies of which deep geothermal energy was often named, but rarely specified and discussed as a central theme.

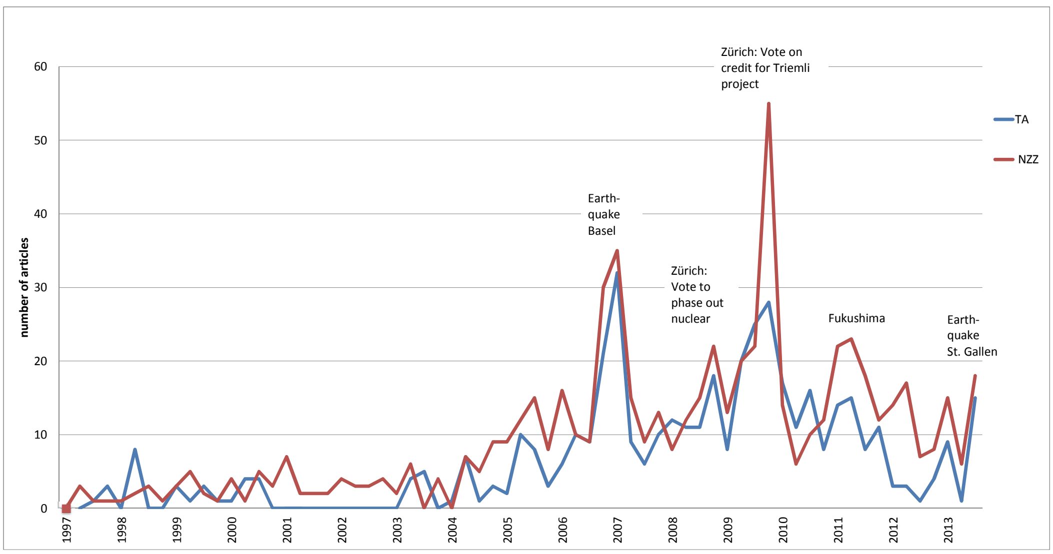

Figure 127: *Frequency of newspaper articles containing the keywords "Geothermie or Erdwärme" over time in TA and NZZ (N = 1119 articles).*

Most of the selected articles were published in the inland or local part of the newspapers. One hundred twenty of 192 articles focused on a single deep geothermal project in Switzerland. Fifty-two articles reported on several projects or regional issues that referred to deep geothermal projects. Only 12 articles focused on projects abroad. Consequently, the media debate on geothermal energy primarily was shaped by projects in Switzerland.

Which arguments are prevalent in the debate on deep geothermal energy in Switzerland? How do pro and con arguments evolve over time?

We identified and coded 16 pro and 26 con arguments (see the code tree in the appendix). In all selected articles, the sum of all con arguments is 795, and the sum of all pro arguments is 555. Thus, there are more diversity and more con arguments regarding deep geothermal energy in the newspaper debate. However, some arguments were mentioned only a few times and therefore are not very salient for readers. In **Figure 128**, the most frequent pro and con arguments are listed. In **Table 35**, examples of the most frequent arguments are presented and illustrated with respective text passages.

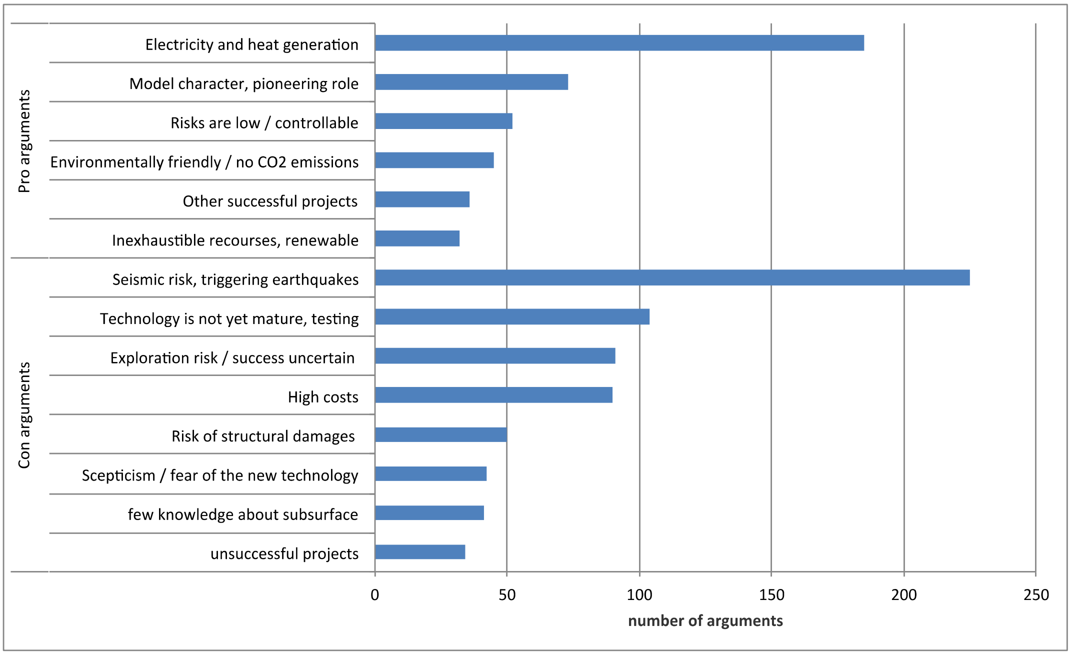

Figure 128: *Distribution of the most frequent arguments in NZZ and TA from 1997 to 2013 (N = 1100 arguments).*

Table 35: *Examples of the most frequent pro and con arguments.*

Pro arguments	
Electricity and heat generation	«Klappt das Vorhaben, könnte ein solches Tiefenwärmekraftwerk dereinst Strom für etwa eine Million Menschen produzieren.» [If the project is successful, it could produce electricity for one million people] (TA, 06.23.2011, «Schweizer Stadtwerke setzen auf neuartiges Geothermieprojekt»)
Model character, pioneering role	«Das Geothermie-Projekt im Sittertobel ist das derzeit grösste im Land. St. Gallen findet sich nicht ungern in der Pionierrolle (…)» [The geothermal project in Sittertobel is currently the biggest one in Switzerland. St. Gallen likes its pioneering role (…)] (NZZ, 01.07.2011., «Das Potenzial, auf dem wir sitzen»)
Risks are low/controllable	«Darin wurden die von Geothermal Explorers gemachten Aussagen wiederholt, einschliesslich des Hinweises darauf, dass das Deep Heat Mining die Erdbebenrisiken nicht erhöhe, sondern mindere.» [The statement by the Geothermal Explorers that the Deep Heat Mining project does not enhance seismic risk but reduces it was mentioned again.] (NZZ, 03. 02.2007, «Weiteres Erdbeben in Basel Geothermie-Projekt als Verursacher»)

Pro arguments	
Environmentally friendly (no CO_2 emissions)	«Diese Art der Wärmeversorgung ist attraktiv, weil sie CO_2-neutral ist und die Abhängigkeit der Stadt Zürich von fossilen Brennstoffen vermindert.» [This kind of heat supply is attractive because it is CO_2-free and reduces the dependency of Zurich on fossil fuels.] (NZZ, 01.02.2008., «Mit 3000-Meter-Bohrung nach Wärme suchen»)
Other successful projects	«Er (EWZ-Projektleiter) verwies auf Projekte in Frankreich und Holland, die seit Jahren problemlos funktionieren.» [He (manager EWZ) refers to projects in France and Holland, which work for years without problems.] (TA, 20.03.2009, «Geothermie-Bohrung beim Triemli kommt im Quartier gar nicht gut an»)
Inexhaustible recourses, renewable	«Erdwärme ist auch in der Schweiz eine nach menschlichem Ermessen unerschöpfliche Ressource.» [Ground heat in Switzerland is, as far as is humanly possible to judge, an inexhaustible resource.] (NZZ, 1998.07.07, «Unerschöpfliche Erdwärme/Eine unterschätzte Primärenergiequelle»)
Con arguments	
Seismic risk, triggering earthquakes	«In Basel ist das Geothermieprojekt definitiv gestoppt worden, weil das Risiko von starken Erdbeben zu gross ist.» [The geothermal project in Basel was definitively stopped because the seismic risk was too high.] (TA, 12.12.2009, no title)
Technology is not mature, testing	«Die Geothermie stehe noch am Anfang, die Technologien seien nicht ausgereift.» [Geothermal energy is in its infancy; the technology is not yet mature.] (NZZ, 11.02.2010, «Keine zweite Bohrung»)
Exploration risk/ success uncertain	«Noch ist allerdings ungewiss, ob dafür in mehr als 3000 Meter Tiefe genügend heisses Wasser vorhanden ist.» [It is thus far not certain if there is sufficient hot water 3000 meters below the surface.] (TA, 23.10.2009, «Geothermie: Fast alle Parteien befürworten die Bohrung»)
High costs	«Inzwischen wurde in Basel jedoch klar, dass das Geothermie-Projekt teurer wird als im Budget veranschlagt. » [Meanwhile, it is clear that the geothermal project costs more than estimated in the budget.] (NZZ, 08.09.2006, «Stärkere Unterstützung für Basler Geothermie»)
Risk of structural damages	«Viele Anwohner seien verunsichert und befürchteten Lärm und Risse in den Häusern.» [Many residents feel insecure and are afraid of noise emissions and damage to buildings.] (TA, 04.06.2009, «Einsprachen gegen Geothermie-Bohrung»)
Skepticism/fear of the new technology	«Das Geothermie-Projekt bezeichnet der Anwohner als ‹gefährlich› und ‹unberechenbar›, es sei voller ‹Widersprüche›.» [The resident describes the project as dangerous, incalculable and contradictory.] (TA, 09.06.2009, «Einsprachen gegen Geothermie-Bohrung”)

Pro arguments	
Little knowledge about geological underground	«In Zürich weiss man nicht einmal, wie es unter der Erdoberfläche aussieht.» [There is not even knowledge about the geological underground in Zurich.] (NZZ, 15.01.2009, «Geothermie kommt im Triemli-Quartier gut an»)
Unsuccessful projects	«In Basel war ein Projekt der Tiefengeothermie vor zwei Jahren gescheitert.» [In Basel, a deep geothermal energy project failed two years ago.] (TA, 03.12.2008, «St.Gallen startet Geothermie-Projekt»)

There are two core arguments on both sides. Electricity and heat generation are the dominant arguments mentioned in favor of the use of deep geothermal energy. Potential earthquakes and earthquakes already triggered by deep geothermal projects are the dominant arguments mentioned against the use of this technology.

The issue that deep geothermal is a relatively new technology is discussed from two sides. On the one hand, this enables actors (Switzerland) to take a leading and pioneering role and to provide important knowledge for further development. On the other hand, the existing knowledge gaps as well as lack of experience also indicate certain risks.

Most con arguments refer to risks. These are the high exploration risks and the risks of structural damage caused by induced seismicity. Skepticism and fear of the new technology are related to the often-reported seismic risks and their consequences. Furthermore, high costs and high uncertainties are important con arguments.

Countering the risk discussion, there is also the argument that the risks are small or controllable. Other pro arguments are that geothermal energy is environmentally friendly and inexhaustible. Furthermore, successful projects are mentioned as examples, such as the use of geothermal energy in Iceland.

Figure 129 shows the development of all pro and con arguments over time. The total number of pro and con arguments regarding deep geothermal energy increased. The fluctuation can be attributed to the concrete events. Before 2006, the pro arguments outweighed the con arguments; but after 2006, the con arguments are more frequent compared to the pro arguments.

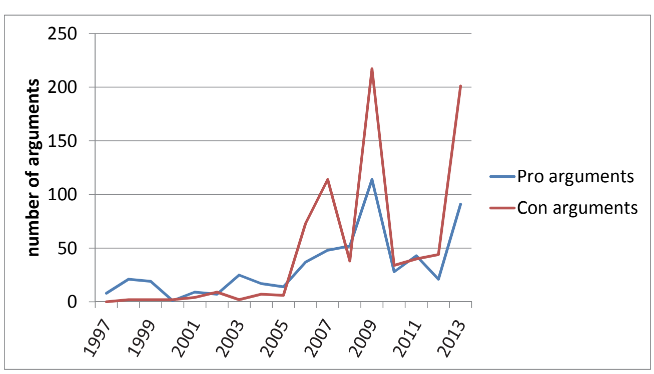

Figure 129: *Frequency of all pro and con arguments over time in TA and NZZ (N = 1350 arguments).*

Which actors appear in the newspaper debate?

As shown in **Table 36**, the actors named in the newspaper articles can be classified into four main groups. Within the first group, the deep geothermal industry and energy supply utilities such as EWZ and Axpo are dominant. Within the second and third groups, local actors play an important role. The deep geothermal energy industry, energy supply utilities, local authorities, and local politicians are the four actors most frequently mentioned in the analyzed newspaper articles (marked bold in **Table 36**).

The analysis of the actors illustrates that the debate on deep geothermal energy in Switzerland is mainly guided by political, industry, economic, and scientific perspectives. In particular, industry actors and public authorities are often mentioned in connection with deep geothermal energy.

Which actors favor which arguments?

Politicians are not named the most frequently, but their active statements (statements directly linked to an actor) are cited most frequently in the articles. In contrast, public authorities are often named but are cited less frequently with active statements than the other actor groups in the newspapers.

Within the politician and public authorities group, the pro and con arguments are quite balanced. In contrast, the majority of arguments from the deep geothermal industry actors favor deep geothermal energy, and the majority of arguments from science actors criticize deep geothermal energy (see **Figure 130**).

Table 36: *References to different actor groups in the discussion on geothermal energy.*

Groups	Actors	% (*n* = number of mentions)
Industry	**Deep geothermal energy industry**	19% **(*n* = 201)**
	Energy supply utilities	14% **(*n* = 149)**
	Sum	33% (*n* = 350)
Public authorities	**Local authorities**	19% **(*n* = 198)**
	National authorities	6% (*n* = 68)
	Cantonal authorities	2% (*n* = 23)
	Sum	27% (*n* = 289)
Politicians	**Local politicians**	14% **(*n* = 148)**
	National politicians	8% (*n* = 81)
	Cantonal politicians	2% (*n* = 19)
	Sum	23% (*n* = 248)
Science	Science undefined	8% (*n* = 81)
	Swiss Seismological Service ETH	6% (*n* = 59)
	University (UZH, ETH, etc.)	3% (*n* = 37)
	Sum	17% (*n* = 177)

Note: 100% = 1064 (total number of mentioned actors).

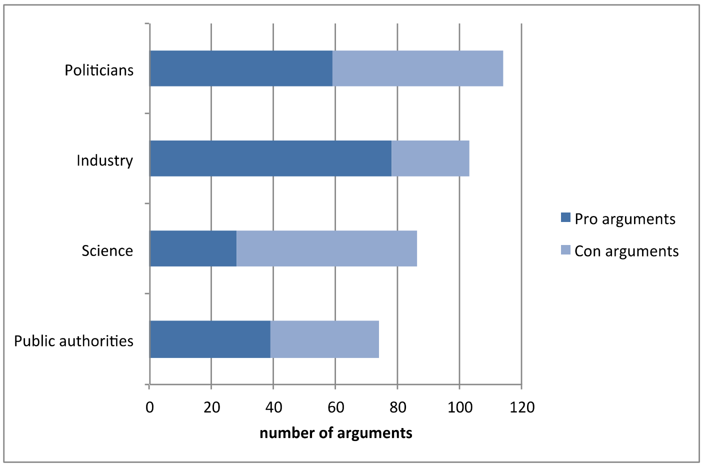

Figure 130: *Distribution of all pro and con arguments among the actors (N = 377 arguments attributable to specific actor groups).*

How is deep geothermal energy framed in the articles? How do the frames evolve over time?

We defined frames as sets of certain content-related arguments. Thus, frames used to characterize geothermal energy were identified by summarizing arguments based on their content. We defined the following frames: energy transition, risks, technology, and costs. In addition, we differentiate in each frame a con frame opposing deep geothermal energy and a pro frame supporting deep geothermal energy. **Table 37** shows the frames (cursive) we formed based on the arguments.

Table 37: *Allocation of arguments to the frames.*

Frames	Respective set of arguments
Energy transition	
Pro: Deep geothermal energy is the way to go in the upcoming energy transition and to substitute for nuclear power.	Heat and electricity generation, inexhaustible resource, base-load, environmentally friendly, available everywhere
Con: Deep geothermal energy is not a realistic option for the upcoming energy transition; there are more promising alternatives.	Wishful thinking/naïve goals, less efficient than other energy carriers
Risks	
Con: Deep geothermal energy has uncertainties and risks.	Seismic risk, triggering earthquakes, risk of structural damages, technical problems, groundwater contamination, risk of initial tension in subsurface, little knowledge about geological underground, high depression of the ground, water blister, gas, excess pressure in the bore hole

Frames	Respective set of arguments
Pro: The risks associated with deep geothermal energy are under control.	Risks are low/controllable, risk is worthwhile, prevention of earthquakes, geothermal energy is not riskier than other energy technologies, the earthquake would have occurred anyway
Technology	
Pro: The technology of deep geothermal energy has benefits and is successful.	Model character/pioneering role, other successful projects, no aesthetic landscape damage
Con: The technology of deep geothermal energy has drawbacks and is unsuccessful.	Technology is not mature, unsuccessful projects, noise emission, aesthetic landscape damage, high water consumption, limited life expectancy of the bore hole
Costs	
Pro: Deep geothermal energy is economic.	Cost-effectiveness, robust prices, self-sufficiency
Con: Deep geothermal energy is expensive.	High costs, exploration risks, time-consuming, need for infrastructure, deficit of qualified employees/materials, decrease in property values around the project

The number of arguments per frame in **Figure 131** gives an idea of the dominance of each frame in NZZ and TA. The most dominant frame is risk. Geothermal energy clearly is associated with risks in the media articles (362 cons, 82 pros). The second dominant frame is energy transition. Geothermal energy is framed as an opportunity for energy transition with few con arguments (293 pros, 21 cons). The technology frames are more balanced (114 pros, 154 cons). Last, the frame that geothermal energy is expensive or has a financial risk seems to be beyond controversy; there are only a few pro arguments (41 pros, 199 cons).

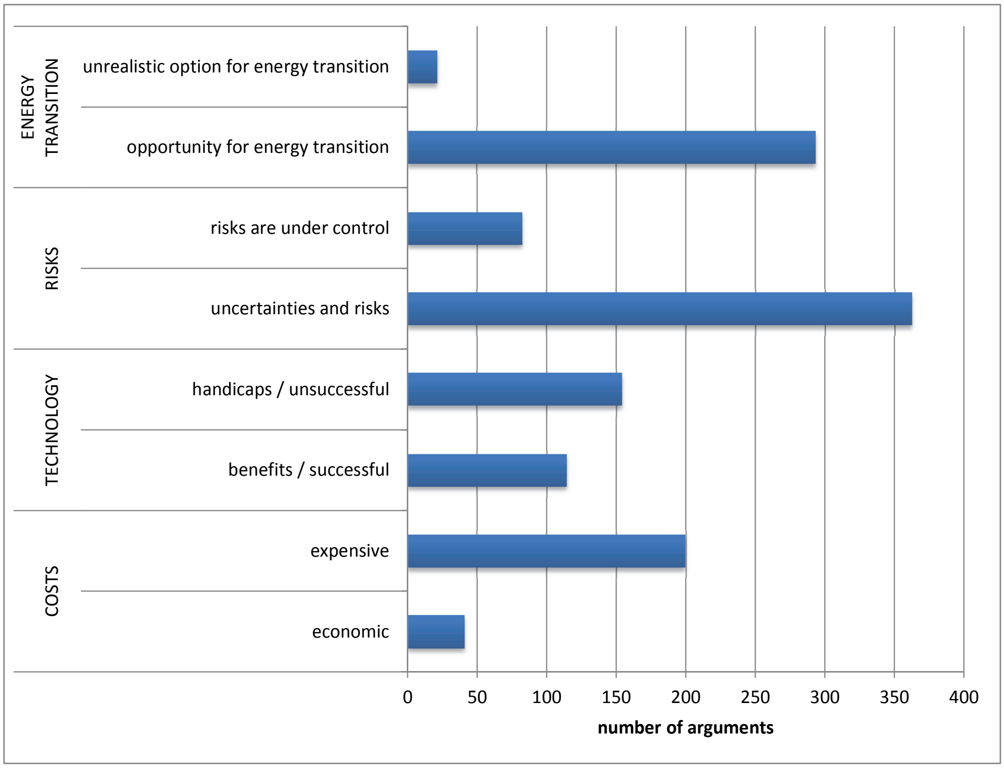

Figure 131: *Distribution of arguments within the identified frames (N = 1266 arguments).*

Figure 132 presents the development of the frames over the years. The framing is clearly influenced by the critical events pointed out. For a long time, geothermal energy was seen only as an opportunity for energy transition. This frame was particularly popular in 2009 when voting on the geothermal project in Triemli took place. In 2013, for the first time, statements doubted the project. New statements appear as frames in the discussion, for example, that the goals are unrealistic or the efficiency compared to established energy carriers is lower.

Before 2006, there was almost no association between geothermal energy and risks. The frame that geothermal energy has uncertainties and risks steeply increased in relevance in 2006 and 2007, when seismicity was triggered in Basel. The risks frame also increased in 2009 (credit vote for the Triemli project) and 2013 (seismicity St. Gallen). The frame that the risks of geothermal energy are small or controllable seems to be a reaction to the uncertainties and risks frame.

The reporting about the opposing and supporting technology frames is relatively balanced but also influenced by events. In 2006, 2009, and 2013, negative aspects and consequences associated with the technology outweighed the positive aspects and consequences associated with the technology.

The framing that geothermal energy costs a lot of money mainly appears around critical events and reaches the highest point in 2009 (discussion about credit for the Triemli project in Zurich).

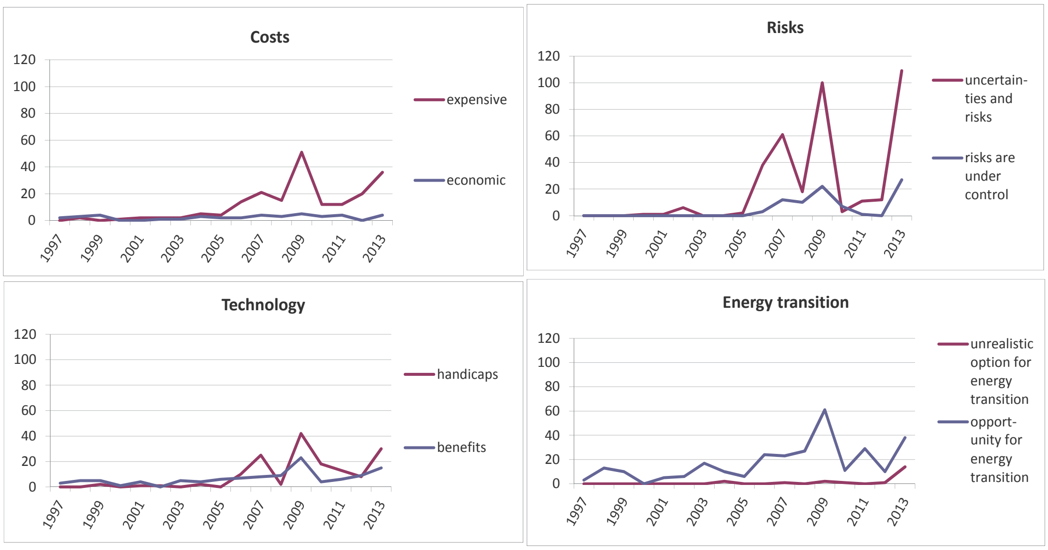

Figure 132: *Development of the frames over time (N = 1266 arguments).*

How do different actors frame deep geothermal energy?

Table 38 illustrates how different actors frame deep geothermal energy in Switzerland by showing the distribution of all arguments for each actor group among the frames. Please note that only active arguments were used to cluster the frames here. The framing strategies of the different actor groups can be characterized as follows.

Politicians in general do not seem to favor a specific frame but use different frames while talking about deep geothermal energy. It is striking that politicians often frame deep geothermal energy as an opportunity for the energy transition (i.e., to substitute base-load geothermal energy for nuclear power); they see deep geothermal energy as an important driver of the upcoming energy transition in Switzerland. Furthermore, some politicians also consider costs and tend to frame deep geothermal energy as expensive.

Public authorities did not emphasize a specific frame; the arguments are more or less proportional to the politicians' arguments. An exception is the frame "unrealistic option for energy transition," which public authorities mention less often, and the frame "uncertainties and risk," which they mention more often.

In contrast, industry actors mainly frame deep geothermal energy as an opportunity for the upcoming energy transition in Switzerland. Forty percent of all arguments by industry actors refer to this frame. Thus, together with politicians and public authorities, these actors push deep geothermal energy as an important technology for successfully transforming the Swiss energy system and substituting for nuclear power.

Scientists clearly favor the risks frame in the debate on deep geothermal energy in Switzerland. Interestingly, they use pro and con frames of risk but mention uncertainties and risks (45% of all their arguments) more often by especially pointing out seismic risks, rather than risks as controllable (20% of all their arguments).

Table 38: *Distribution of arguments of the different actor groups within the identified frames (N = 382 arguments attributable to specific actor groups).*

	Energy transition		Risks		Technology		Costs		Total
	Opport-unity (n=90)	Unrealistic option (n=12)	Uncertain-ties and risks (n=71)	Risks under control (n=66)	Benefits (n=33)	Handicaps (n=43)	Economic (n=14)	Expensive (n=53)	
Politicians (n=128)	21%	8%	9%	16%	9%	15%	3%	18%	100%
Public authorities (n=67)	25%	0%	19%	18%	4%	13%	1%	18%	100%
Industry (n=99)	40%	0%	6%	15%	13%	6%	8%	11%	100%
Scientists (n=88)	7%	2%	45%	20%	6%	10%	1%	8%	100%

6.4.2.3 Discussion and conclusions

The goal of the content analysis was to establish how the media presents the issue of deep geothermal energy, what arguments and actors are part of the discourse, and how they frame deep geothermal energy in Switzerland. Thus, the analysis provides an idea of what picture newspaper readers get from articles about deep geothermal energy, which issues are specifically focused on and thus emphasized. In the following, we briefly summarize and discuss the most important findings.

The media discourse on deep geothermal energy measured by the number of articles in TA and NZZ is dynamic over time. Events have a strong influence on the arguments used, especially on the proportion between pro and con arguments. The presence of arguments is strongly influenced by the seismic events in Basel in 2006, the vote on the Triemli project, and the final stop of the Basel project in 2009 as well as the induced seismicity in St. Gallen in 2013. Since these events are mostly negative, it is not surprising that there are overall more arguments against the use of deep geothermal energy than arguments in favor of this technology. Since 2006, con arguments generally dominate the discourse. During every event discussed in the media, the number of con arguments rapidly increase and outweigh pro arguments.

We distinguish four main actor groups and four frames that provide a clearer idea of the emphases in these actors' arguments. The analysis illustrates that in general energy transition and risks are the two most dominant frames in the articles on deep geothermal energy. However, different actor groups emphasize different frames. Whereas geothermal energy is seen as an opportunity for the energy transition from the perspective of industry, scientists emphasize the issue of risks associated with deep geothermal energy. The latter can be attributed to the classical procedure of media work: For highly abstract and complex issues, the scientists' perspective is sought. Since seismic risks are essential, journalists mainly address this very issue. Politicians and public authorities most strongly argue for geothermal energy as an opportunity for the energy transition but also refer to the costs of geothermal projects.

However, not much input from scientists is sought regarding the potential of deep geothermal energy for the energy transition. Further, existing or planned risk mitigation mechanisms are also hardly covered by media articles. For both aspects, science could play a valuable role by providing information.

We must acknowledge that this content analysis has some limitations. Care was taken to minimize the influence by the researchers (i.e., choice of coding scheme, coding process). The coding scheme was developed iteratively and in close collaboration between Swiss and German researchers. The coding scheme and detailed descriptions of the codes were discussed thoroughly, and inter-coder reliability was secured by crosschecking the codes of the independent coders. Actor analysis is critical since many actors can have different roles (i.e., a scientist working in industry). On the one hand, this is methodologically challenging for content analysis. On the other hand, it is also difficult for the public to get a clear picture of the relevant actors, their roles, and their responsibilities.

Given the restricted resources, we could not analyze newspapers from the French-speaking part of Switzerland. A content analysis similar to the one done based on articles in TA and NZZ could point to existing differences in the media discourse on deep geothermal energy. Further, an analysis of local newspapers could provide a more detailed view of regional political discussions. Speed-reading articles in the St. Galler Tagblatt (which is available online only since 2010 on Lexis Nexis) showed that the topics (established by the title of the articles) were similar to those in NZZ and TA, but clearly influenced by the project in St. Gallen and therefore entailed a more expanded political discussion, especially in 2010.

For further research, it would be interesting to measure directly how the public reacts to the different arguments and frames used by different actors. As a subsequent step to this media analysis, psychological experiments could offer more insights into these processes. Such experiments would potentially be relevant for public communication of deep geothermal energy in Switzerland.

6.4.3 Overall conclusions on public perception of deep geothermal energy in Switzerland

Deep geothermal energy is a novel technology still in development, and detailed information about its perception in Switzerland is largely absent. Thus, any conclusion about public perceptions must be taken with caution. Opinions develop over time and have not been fixed, certainly not in Switzerland as a whole but probably not even in those areas where projects led to seismic events (Basel and St. Gallen) and caused some immediate but different public responses. The present study thus looked at public perception from two complementary perspectives with a dynamic element:

- *International science literature* was reviewed, but a broad focus taken to allow for potential development paths in reaction to geothermal energy. At present, only scant evidence exists regarding the perception and acceptance of deep geothermal technology, particularly regarding seismic hazards. We thus have to rely on studies performed for other infrastructures, mostly contested ones such as nuclear waste repositories, wind power, and CCS. Even if one cannot transfer lessons from nuclear waste, wind power, and CCS directly, the reaction to these technologies still offers insights into potential future developments in public perception. Nuclear waste and CCS share characteristics that are important for their dominant negative public perception: the human-made nature and the low personal control of the risk (Slovic, 1987), the idea of “tampering with nature” (Sjöberg, 2000), the potential high damage with low probability (Kaplan and Garrick, 1981), the comparatively large infrastructure (high visibility), and the strong dependence on highly abstract expert knowledge. Thus, the possibility that opinions could easily develop similarly can certainly not be excluded but depends on the ongoing project developments and related public communication and engagement activities. Thus, the very process of planning, siting, and implementing geothermal projects must be closely followed by a carefully planned, continuously monitored, and scrupulously evaluated process of public and stakeholder engagement. Much can learned here from the siting of large, contested infrastructures, namely, nuclear waste disposal. In addition, the communication strategy followed in the project in St. Gallen[36] was certainly an important step in this direction. However, social site characterization (i.e., regarding specific needs, collaboration with the community) as proposed by Wade and Greenberg (2011) could certainly complement the technical site characterization for future (pilot) projects (see as well Brunsting *et al.*, 2013).

- *Media articles* in the Tages-Anzeiger and the Neue Zürcher Zeitung were analyzed systematically. Dynamics played an important role here from two perspectives: i) Dynamics in media coverage and the use of arguments was followed over time, but even more important, we claim that ii) media articles can serve as an early warning signal for potential opinion developments (Matthes and Scheme, 2012). Media articles can potentially have effects as agenda setters (what is reported by newspapers affects what is considered important by the public; see McCombs and Shaw, 1972) but also as framing devices (how the issue is framed by the newspapers affects which aspects are actually perceived by the public, see Entman, 1993). Different stakeholder groups can play a role here, as they can try impacting media articles but focusing attention on aspects the stakeholders deem essential for promoting their interests (Andsager, 2000). Media attention is largely driven by various events with news value: important public votes and seismic events surrounding concrete projects in Switzerland but also larger events such as the accident in Fukushima. Since bad news generally has greater news value (Galtung and Ruge, 1966), negative events are communicated much more. Regarding deep geothermal energy in Switzerland, the seismic events in Basel and St. Gallen triggered a large increase in media attention; in particular, the negative reactions in Basel led to the general overrepresentation of negative arguments. Looking at the various actor groups, the role of industry and science should be reflected. Although the first focused on the potential of geothermal energy for the energy transition, the latter emphasized risks and uncertainties. Given these groups’ societal roles as promoters of the technology and as critical risk analysts, respectively, this is not surprising. However, both actor groups can of course still consider whether they should communicate additional frames. Although industry members might themselves actively address risks and uncertainties as a major public concern, scientists could also focus on potential and existing risk mitigation strategies. Likewise, a more

[36] See e.g. in the informative webpage http://www.geothermie.stadt.sg.ch

balanced view from industry and science could be offered to the public. In addition, broader coverage of the technology's potential for the energy transition and the related cost implications could certainly inform the public's opinion development. In both frames, scientists are largely absent, an effect of the particular scientists selected by the media but perhaps as well of the existing evidence base in these areas.

Overall, this study points to public perception that is probably still highly volatile, with many people still holding ambivalent opinions. More knowledge is necessary to understand the present state of opinion and the potential mechanisms of opinion change. Events involving planned future projects and their media coverage will certainly play a considerable role in impacting and fixing public opinion. Thus, attention should be placed on these non-technical aspects of deep geothermal energy.

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6.4.5 Appendix

Table 39: *Code tree for content analysis.*

A) Level of article: Identifying and evaluating codes

- Article Number
- Newspaper
- Month and year of publication
- Title and subtitle
- Rubric
- Journalist
- Word count
- Relevance of article
- Style of article (i.e., interview, report, comment)
- Focus (i.e., local, national, abroad)
- Evaluation of deep geothermal energy (positive, negative, ambivalent, descriptive)

B) Level of paragraphs and sentences: Content-related and evaluating codes

Code	*Most important subcodes*	*Further subcodes*
Locations	Switzerland	St. Gallen, Basel, Zurich, etc.
	Germany	Unterhaching, Landau, etc.
	Others	France, Iceland, Kenya, Australia, etc.
Actors	Public authorities	Local, cantonal, national
	Politicians	Local, cantonal, national and respective parties
	Science	Science undefined, Swiss Seismological Service ETH, University (UZH, ETH, etc.)
	Deep geothermal energy industry	
	Energy supply utilities	
	Justice system	
	Population	
	Environmental organizations	
	Insurance companies	
	Nagra	
Arguments	Pro arguments	Electricity and heat generation, model character/pioneering role, risks are low/controllable, environmentally friendly (no CO_2 emissions), other successful projects, high potential, inexhaustible recourses, base-loadable, cost-effectiveness, robust prices, self-sufficiency, available everywhere, earthquake prevention, geothermal energy is not riskier than other energy technologies, the earthquake would have occurred anyway, no aesthetic landscape damage
	Con arguments	Seismic risk/triggering earthquakes technology is not mature, exploration risk/success uncertain, high costs, risk of structural damages, skepticism/fear of the new technology, little knowledge about geological underground, unsuccessful projects, technical

	problems, groundwater contamination, risk of initial tension in subsurface, high depression of the ground, water blister, gas, excess pressure in the bore hole, noise emission, esthetical landscape damage, high water consumption, limited life expectancy of the bore hole, time-consuming, need of infrastructure, wishful thinking/naïve goals, deficit of qualified employee/materials, decrease of property values surrounding the project, less efficient than other energy carriers

Notifications: In this code tree, only a selection of the codes used for this report is listed.

7 WP6: Legal Opinion

René Wiederkehr & Andreas Abegg (ZHAW), translated by Danielle Adams (ZHAW)[37]

7.1 Scenario and issue

The Centre for Technology Assessment TA-SWISS has commissioned a legal opinion of the TA-SWISS study on deep geothermal energy in Switzerland to add a legal perspective to the work already done by the PSI Consortium consisting of the Paul Scherrer Institute (PSI), ETH Zurich, and DIALOGIK Stuttgart.

The analysis is set against the background of the interdisciplinary project "Energy from the earth's interior: Deep geothermal energy as the energy source of the future?" It addresses the main legal issues currently under debate on the subject in Switzerland and highlights future legislative developments. The demarcation of responsibilities between the Swiss federal state and the cantons is of special interest in this context. The legal opinion aims to provide clear recommendations, in particular for policy-makers.

Based on an analysis of the legal framework, the following questions need to be answered:

a. Considering the current legal position, is a more intensive exploitation of deep geothermal resources possible?

b. To what extent does the current legal position take into account the public interest with regard to security, noise emissions, and the environment?

c. How might a future division of regulatory authority between the federal state and the cantons of Switzerland look like?

d. What regulatory measures might have to be addressed at the federal state level and would constitutional amendments be required?

e. What basic recommendations should be made to legislators?

7.2 Legal matters

Preliminary Comment: Geothermal energy can be harnessed in a variety of different ways. Key procedures include the following (see JAGMETTI, marginal no. 7417):

– Extraction of **geothermal energy from groundwater sources** using groundwater heat pumps as for the exploitation of shallow geothermal resources (to a depth of approximately 500m)

– Extraction of **geothermal energy using geothermal probes** with a double pipe filled with heat transfer fluid as for the exploitation of shallow geothermal resources (to a depth of approx. 500m)

– **Extraction of geothermal energy** using **hydrothermal or petrothermal systems** as for the exploitation of deep geothermal resources (at a depth of between approx.

[37] The German version of this chapter is available for download at: www.ta–swiss.ch/publikationen/2015

3000−6000m). In the case of a hydrothermal system, use is made of naturally occurring hot water passing through sedimentary rock in the subsoil. In the case of a petrothermal system, no naturally occurring water passes through sedimentary rock in the subsoil. The water reservoir must first be created artificially by pumping water into the rock at high pressure.

This **legal opinion** mainly deals with the **exploitation of geothermal resources within the meaning of exploiting deep geothermal energy** using hypothermal or petrothermal systems. Within this legal opinion, the term "subsoil" is meant to be understood as **the deep subsoil** which is not included in property protected under private law. The extraction of geothermal energy using probes or heat pumps up to a depth of approximately 500m can still be considered as the exercising of proprietary rights and does not include the exploitation of the deep subsoil.

7.2.1 Exploitation of the subsoil

7.2.1.1 Jurisdiction

7.2.1.1.1 The Swiss Federal State

The **division of authority** between **the Swiss federal state and the cantons** falls under **Art. 3 of the Federal Constitution**. In accordance with Art. 3 of the Federal Constitution, the cantons are sovereign, inasmuch as their sovereignty is not curtailed by the Federal Constitution. The cantons therefore exercise all the rights that have not been given to the federal state. Every responsibility that has not been assigned to the federal state by the Federal Constitution thus falls under the jurisdiction of the cantons. This type of breakdown of responsibilities between the federal state and the cantons is also called the "principle of single empowerment" ("Prinzip der Einzelermächtigung") (BIAGGINI, Art. 3 Federal Constitution, marginal no. 5) or "general subsidiary powers of the cantons" ("subsidiäre Generalkompetenz der Kantone") (TSCHANNEN, Staatsrecht, § 19, marginal no. 9).

Responsibilities that are **not assigned to the** federal **state through the Federal Constitution, namely under Art. 54-135 of the Federal Constitution**, therefore remain with the **cantons**, which are basically allowed to decide for themselves which responsibilities to take on as part of their subsidiary general jurisdiction. As a result, new responsibilities will automatically become the responsibility of the cantons, inasmuch and provided that no federal jurisdiction exists or is newly created (BIAGGINI, Art. 3 Federal Constitution, marginal no. 7). As opposed to the Swiss Federal State, the cantons do not need an explicit legal basis in their cantonal constitutions; the legal basis by statute assigning a responsibility to the canton is sufficient.

The **Federal Constitution mostly lacks provisions regulating the use of land and resources in the subsoil**:

Art. 89 of the Federal Constitution (Energy Policy) does not provide a basis for comprehensive federal powers. Section 1, according to which the state and the cantons, within the scope of their responsibilities, commit themselves to an environmentally friendly energy supply, stipulates no new federal powers as a target norm; it does not change the division of responsibilities between the federal state and the cantons. Its wording transcends their separate powers ("within the scope of their responsibilities") and "merely" makes certain demands as to how the federal state and the cantons should exercise their responsibilities. Its significance is largely programmatic (with regard to the whole article, see Federal Council Dispatch on the Energy Article, p. 375). Section 2 provides for the federal state to have the power to pass framework legislation for the exploitation of domestic and renewable energy sources and economical and efficient energy consumption. The power to pass framework legislation allows the federal state to create a legal framework for the exploitation of renewable energy carriers. In this context, the main aim is to increase energy production from renewable energy carriers (see also Art. 1 Energy Act). Sections 3−5 provide for a certain obligation for consideration (5) as well as the power to legislate and promote responsible energy consumption and the development of new energy technologies (3). All in all, Art. 89 of the Federal Constitution grants the federal state only limited legislative powers.

In accordance with **Art. 75 (1) of the Federal Constitution (Spatial Planning)**, the federal state establishes the basic principles of spatial planning (sentence 1). Their implementation is up to the cantons (sentence 2). Art. 75 (1) of the Federal Constitution only provides for the power to pass framework legislation, whereas Art. 75 (1) of the Federal Constitution does not exclude the possibility for the federal legislature to establish detailed rules to regulate specific issues (cf. in particular Art. 24 et seqq. Spatial Planning Act). According to Art. 1 (1) of the Spatial Planning Act, the Spatial Planning Act mainly regulates land use and the coordination of responsibilities related to spatial issues. The utilization of the subsoil has mostly been omitted. Regulation of the utilization or exploitation of the subsoil is left to the cantons. The Spatial Planning Act "merely" provides for cantons and communes to have a planning obligation with regard to projects that have extensive effects on existing rules on the use of land − such as the construction and operation of geothermal plants (see marginal no. 96 et seqq. below) (Art. 2 Spatial Planning Act), which is mainly exercised by means of cantonal structure plans and land-use planning.

In the same way, **Art. 76 (1) of the Federal Constitution (Water)** is limited to the establishment of certain principles: Pursuant to Art. 76 (1), the federal state, within the scope of its responsibilities, is concerned with the economical use and the protection of water resources as well as the defense against the harmful effects of water. Section 2 provides for its power to pass framework legislation. Pursuant to Section 3, comprehensive powers are provided for the federal state only in the areas of qualitative and quantitative protection of waters, hydraulic engineering, the safety of water retaining facilities, and interference with precipitations. It is essentially the cantons which have sovereignty over the waters (see Section 4 sentence 1). They can also determine if and how the groundwater found in deep sedimentary rock can be exploited.

According to Art. 91 of the Federal Constitution (Energy Transportation), the federal state has comprehensive powers which would enable it to establish a comprehensive monopoly on the transportation of energy, to control it by itself or to transfer that right to third parties (see BIAGGINI, Art. 91 Federal Constitution, marginal no. 3). The federal powers include the transportation of energy, irrespective of what primary energy source it is extracted from. The production of energy is not subject to federal jurisdiction (BIAGGINI, Art. 91 Federal Constitution, marginal no. 4).

According to **Art. 122 Federal Constitution** the federal state is competent to pass legislation in **areas of civil law**. The provisions of the Swiss Code of Civil Law however only describe the scope of land ownership (Art. 667 Swiss Civil Code) as well as the disposition of ownerless and public objects (Art. 664 Swiss Civil Code) (see in the following marginal no. 10 et seqq. [Art. 667 Swiss Civil Code] and marginal no. 19 et seqq. [Art. 664 Swiss Civil Code]).

To sum up, the Federal Constitution lacks an explicit provision for the exploitation of the subsoil. The jurisdiction largely lies with the cantons, which can themselves delegate the exploitation of the subsoil to the communes.

7.2.1.1.2 Cantons

Reservation of Art. 667 (1) Swiss Civil Code (Land Ownership)

In accordance with **Art. 667 (1) Swiss Civil Code**, **private ownership of land** extends upwards into the air and downwards into the ground to the extent determined by the owner’s **legitimate interest** in exercising his or her ownership rights. The provision of Art. 667 (1) of the Swiss Civil Code has a limiting function. The interest consequently determines the extension of land ownership in a vertical direction: With regard to the space above or below that, the Swiss Civil Code does not recognize private land ownership (Federal Supreme Court Decision 119 Ia 390 D. 5d).

How far upwards or downwards this extends cannot be determined in a universally valid manner but must be determined on a case-by-case basis according to the **specific circumstances** and the **legitimate interests of the owner** to either use or control the space themselves and defend it against penetration by others. The Swiss Federal Supreme Court has dealt with this norm in particular in connection with the **direct aerial traverse over land**. In doing so, it has always declined to make any general ruling with regard to the height that an aircraft may penetrate into the interest domain of land owners and thus into the property itself (see Federal Supreme Court Decision 134 II 49 D. 5, 131 II 137 D. 3.1.2, D. 3.2.2, and D. 3.2.3)

Actual direct aerial traverses, which a land owner can oppose based on Art. 667 (1) of the Swiss Civil Code, have been confirmed as unacceptable in the case of landing wide-bodied aircraft (jumbo jets) traversing residential areas at a height of 125m or below (see Federal Supreme Court Decision 131 II 137 D. 3.1.2). In the case of two land parcels situated in the immediate vicinity of the end of a runway, which are regularly traversed at a height of only 75m or 100m by wide-bodied aircraft, the Swiss Federal Supreme Court has confirmed a violation of land ownership rights (see comments in Federal Supreme Court Decision 123 II 481 D. 7 and D. 8). On the other hand, it has been noted that the aerial traverse of such aircraft at a height of 400m does not violate land ownership (Federal Supreme Court Decision 123 II 481 D. 8, 131 II 137 D. 3.2.2, and D. 3.2.3). Neither do individual flights, in particular by smaller aircraft at a height of approximately 220m or 250m, respectively (Federal Supreme Court Decision 131 II 137 D. 3.2.2). Likewise, flights at a height of above 500m cannot be said to constitute aerial traverse (Federal Supreme Court Decision 134 II 49 D. 5.5).

Similar considerations are relevant in the context of the **exploitation of the subsoil**. According to Federal Supreme Court jurisprudence, land ownership does not extend further into the ground as the land owner's claim to a legitimate interest in the land. The remainder of the terrestrial body, i.e. the actual subsoil, is under the jurisdiction of the canton (see in the following marginal no. 19 et seqq.). Legitimate interest should be determined based on the actual situation. The nature and economic function of the land in question, as well as the local situation and the possibilities to exploit it under public law must be taken into account (Federal Supreme Court Decision 134 II 49 D. 5.3, 129 II 72 D. 2.3, 122 II 349 D. 4a/cc).

A **legitimate interest** can only be said to exist with regard to a **specific area below ground** if the land owner can control that area and exercise any utilization rights that result from his or her ownership, or if measures by a third party affect the utilization of his or her land in that area. From an objective point of view, it must be technically possible and legally permitted to exercise such an interest. A legitimate interest cannot be said to exist if, e.g., a tunnel is excavated at a depth that would exclude the possibility of tremors, sagging foundations, or other effects. With Art. 667 (1), the Swiss Civil Code creates a legal barrier for the assertion of ownership rights, in particular concerning the ability for civil engineering tasks (such as the construction of tunnels or the laying of cables) to be carried out and for unjustified resistance by private land owners to be avoided (Federal Administrative Court, 25 November 2008, A-365/2008, D. 4.2).

In its **judgment 1C_27/2009 of 17 September 2009,** D. 2.5, the Swiss Federal Supreme Court held that the **interest of an owner of land parcels devoted to agricultural use** extends only a few meters below ground and that a tunnel whose roof extends to a level of 5m below ground already belongs to the ownerless subsoil which is the sovereignty of the state, and is thus no longer privately owned land. Accordingly, no expropriation is necessary to build a tunnel, and no railway or tunnel servitudes have to be established. This applies in any case as long as the tunnel does not cause any tremors, sagging, or similar problems.

In cases where a **railway tunnel crosses a development site at the relatively small depth** of 7−8m, the legal situation is a different one. The excavation of the tunnel needed to construct and operate the railway results in a situation where the subterranean utilization of a land parcel which is not actually restricted by building regulations is limited to a single subterranean level. Furthermore, in order to limit the load, any new structure would have to be built on a foundation platform which would have to be supported between and next to the tunnel tubes. For these reasons, a servitude has to be established for the construction of a railway tunnel and expropriation proceedings have to be conducted, if the easements needed for the construction and the operation of the railway cannot be privately obtained (Federal Supreme Court Decision 122 II 246 D. 4b).

Soil anchors to stabilize the subsoil which are installed at a depth of 20−43m and extend into neighboring soil do not affect the ownership rights of that neighbor, at least not to the extent to which he or she has an actual proven legitimate interest in the utilization of the subsoil, for instance the intention to build an underground car park (Supreme Court Decision 132 III 353 D. 4). A future interest of a land owner must only be accommodated if the project in question is technically possible and legally permitted, and if its realization is possible in the normal course of things and in the foreseeable future (Supreme Court Decision 132 III D. 2.1).

As a result of the **exploitation of geothermal resources** by means of **geothermal probes**, which can penetrate up to approximately 500m into the subsoil, the interest of land owners to utilize the subsoil has increased considerately. Such plants are directly linked to the exercising of ownership rights and can be said to constitute a legitimate interest. It can therefore be assumed that the interest of land owners can extend to several hundred meters into the subsoil. The installation of geothermal probes that reach that far into the ground does however not mean that the entire subsoil (below a piece of land) up to that depth becomes private property. Subsoil can only be considered as private if it is actually occupied by the geothermal probe.

Ownerless and Public Objects in Accordance with Art. 664 Swiss Civil Code

In accordance with **Art 664 (1) of the Swiss Civil Code**, **ownerless and the public objects** not regulated by Art. 667 (1) of the Swiss Civil Code are under the sovereignty of the state in which they are located. The deep **subsoil** within the meaning that is of relevance here − i.e. from a depth of approx. 500m − is considered, according to doctrine and jurisprudence, to belong either to the ownerless or the public objects in accordance with Art. 664 (1) of the Civil Code (Federal Supreme Court Decision 119 Ia 390 D. 5d; Federal Supreme Court of 17 Sept. 2009, 1C_27/2009, of D. 2.4 and D. 2.5; REY/STREBEL, Art. 664 Swiss Civil Code, marginal no. 13; SEILER, p. 317 et seq.). In other words, with regard to the exploitation of the deep subsoil the public bodies can in effect be said to have a monopoly. This public primacy reflects the cooperative and federalist foundations of our constitutional order and is an expression of the barriers to private ownership that result from social responsibility (Federal Supreme Court Decision 119 Ia 390 D. 4d).

Since the Swiss Civil Code only refers to land located within Swiss territory, the wording of Art. 664 (1) Swiss Civil Code however implies the existence of a multitude of "states" within this territory, it can be reasonably assumed that Art. 664 (1) Swiss Civil Code uses the term "states" to mean the **cantons** (Federal Supreme Court Decision 119 Ia 390 D. 5d; RENTSCH, p. 340; see also § 3 (1) of the Model Law, according to which the cantons have sovereignty over the subsoil, including its natural resources and all related rights of use and disposition).

Art. 664 (3) of the Swiss Civil Code also states that the exploitation of subsoil falling outside the private interest of an owner is subject to the authority of the cantons. In accordance with Art. 664 (3) of the Swiss Civil Code, cantonal law makes the necessary provisions pertaining to the appropriation of ownerless land, exploitation, and public use of public objects such as roads and open spaces, waters and river beds.

This is a **comprehensive power to set norms of public law** which allows the cantons to determine what objects are ownerless or public, respectively, what legal position can exist and can be claimed with regard to them (Rey/Strebel, Art. 664 Swiss Civil Code, marginal no. 23). As an expression of this comprehensive legal jurisdiction and power to set norms, the cantons also have the power to determine who should exercise these powers. A canton can therefore delegate its legal competence to the **communes**. Depending on the legal situation in a canton, the subsoil can thus be subject to cantonal or communal law. On the other hand, no canton in Switzerland has delegated the power to regulate the subsoil to its communes.

Basically the same rules apply for the **exploitation of geothermal resources from hot (deep) aquifers** as for the utilization of the subsoil. According to the Federal Constitution, the cantons have water sovereignty, i.e. the power of property under public law to control water resources (Art. 76 (4) sentence 1 Federal Constitution). They therefore have the power to define what constitutes public and private waters − as one of the aspects of water sovereignty − and to prescribe how and to what extent public waters may be utilized by third parties. They can therefore also determine if and how groundwater found in deep sedimentary rock can be exploited. In accordance with Art. 664 (1) of the Swiss Civil Code, the waters belong to the public objects. They are subject to the sovereignty of the canton, provided it has not delegated this power to its communes.

Certain **reservations by Swiss water protection legislation** must be taken into consideration: In the water protection areas A_u and A_o, no installations may be built which constitute a particular danger for a body of water (Appendix 4, Clause 211 (1) Water Protection

Ordinance). In the water protection areas S1 and S2 (Appendix 4 Clauses 222 and 223 Water Protection Ordinance), no installations are permitted which draw heat from the groundwater; according to Appendix 4 Clause 221 (1) lit. f. of the Water Protection Ordinance, this also applies to water protection area S3.

"Bergregal" (Mining Rights)

Another regulation of the deep subsoil is by means of the so-called "**Regalrechte**". The German term "Regal", which is related to the English term "regalia", is used for monopolies of historic origin. It goes back to the ownership-like sovereign rights of monarchs, especially with regard to land above and below ground (land and subsoil rights [in particular mining and salt extraction rights]) and in the area of hunting (hunting rights) and fishing (fishing rights) (Federal Supreme Court Decision 128 I 3 D. 3a, 124 I 11 D. 3b, 119 Ia 123 D. 2b, 114 Ia 8 D. 2b, 95 I 497 D. 2, and D. 3; cf. also HÄFELIN/MÜLLER/UHLMANN, RN 2560). Historically, "Regale" refer to limited natural resources or values which need to be distributed in an equitable manner (Federal Supreme Court Decision 119. Ia 390 D. 11b). Such a monopoly makes it possible for the state to exclude private parties from areas that are per se open to private enterprise and to commercially exploit such areas itself, thus putting them beyond the objective scope of economic freedom (Federal Supreme Court Decision 128 I 3 D. 3b, 125 II 508 D. 5b; see also the provisions in the Federal Constitution concerning "Regale" [Art. 94 (4) Federal Constitution], which mostly refers to historical monopolies such as hunting rights, fishing rights, mining rights, and salt extraction rights).

The "Regale" fall under the jurisdiction and sovereignty of the **cantons**. According to the Federal Constitution, the Swiss Federal State does not have any authority to regulate them. It is therefore the cantons that have the power to enact legislation on the "Bergregal" (hereinafter "mining rights"), and they can also grant such rights to its communes.

One of **the objective characteristics of historical land rights** derives from the fact that they concern previously existing, commercially valuable natural goods of limited availability which are ownerless and as such subject to the sovereignty of the canton (Art. 664 Swiss Civil Code; cf. Federal Supreme Court Decision 124 I 11 D. 3d, 119 Ia 390 D. 5d und D. 5e, D. 9 und D. 11b). Mining rights within the meaning of regalia therefore refer predominantly to the mining of natural resources rather than gravel, rocks, boulders, or soil (see, e.g., Art. 90 Introductory Act Swiss Civil Code/Schaffhausen, Art. 229 (1) Introductory Act Swiss Civil Code/Appenzell Ausserrhoden; Cantonal Council of Obwalden on 8 July 2003, in: Draft of Insurance Policies Act 2004/05 No. 1 D. 2.4 [marl mining]; of 15 Feb. 2000, in: Draft of Insurance Policies Act 1999/00 No. 1 D. 4 [commercial rock mining, in particular gravel]). Depending on the legal situation in a canton, mining rights typically include the exploitation of metal ore, salt, fossil fuels for heating and lighting such as mineral oils, coal, crude oil, and natural gas, as well as asphalt and bitumen. Quarries, soil, saltpeter, healing springs, peat, clay, sand, and other construction materials are not usually in the "Regale", and neither is the utilization of the subsoil in general.

Effectively, mining rights confer a nearly **unlimited power to legislate**. The Swiss Federal Supreme Court already recognized in 1918 that federal civil law must not stand in the way of the cantons if mining privileges were to be introduced, and that Art. 664 Swiss Civil Code is to be interpreted in such a way that the cantons are entitled to put exploitable deposits of minerals and fossils under special legislation that can deviate from Swiss Civil Code provisions, and that the Swiss Civil Code may not exclude cantonal “Regale” (see a summary of the jurisprudence in Federal Supreme Court Decision 119 Ia 390 D. 11b). The sovereignty over mining not only includes the right to exploit natural resources but also the right not to exploit them and the right to protect materials defined as “Regale” from being harmed (Federal Supreme Court Decision 119 Ia 390 D. 11c).

The **legal situation of the cantons** concerning **mining rights is** inconsistent: Some cantons (Basel-Stadt, Appenzell Innerrhoden, and Graubünden [that delegate it to the communes, which is why there is no cantonal regulation]) have issued no legislation on mining rights; other have adopted mining regulations into their cantonal Introductory Act to the Swiss Civil Code (Zurich [which however also has an old mining act], Zug, Schaffhausen, and Appenzell Ausserrhoden); most cantons have specific legislation pertaining to mining rights (Aargau, Bern, Luzern, Schwyz, Nidwalden, Fribourg, Solothurn, Basel-Landschaft, St. Gallen, Ticino, Vaud, Wallis, Neuchâtel, Geneva, and Jura). Individual cantons have expanded their legislation with regard to mining rights to include the exploitation of geothermal resources (see below). A factual necessity to treat geothermal energy the same way as metal ore or fossil fuel does however not exist since mining rights usually cover the exploitation of all natural resources found underground. On the other hand, the cantons are by and large free to define what they mean by "mining rights" and can therefore also subsume them to mean the utilization of the subsoil in general (for the whole topic, see also Section 7.2.1.1.3 et seqq. below).

7.2.1.1.3 Overview of cantonal regulations

In general, the **utilization of the deep subsoil** is only insufficiently regulated in the cantons. In some cantons, there is no specific legislation at all.

Others have explicitly placed the **exploitation of geothermal resources under mining rights** (Appenzell Ausserrhoden, Bern, Basel-Stadt, Glarus, and Thurgau). Some of the cantons that have extended the mining rights to include the utilization of the subsoil to extract geothermal energy have created a **constitutional basis** for this: In accordance with Art. 52 (1) lit. c of the Bern Cantonal Constitution, for example, mining rights also include the exploitation of geothermal resources; (also § 84 (1) Clause 4 Cantonal Constitution/Thurgau and Art. 47 (2) Abs. 2 Cantonal Constitution/Glarus).

Other cantons regulate the **use of the subsoil through Art. 664 (1) of the Swiss Civil Code** and consider the deep subsoil to be a public or ownerless object (i.e. the cantons of Aargau, Luzern, Uri, Schwyz, Nidwalden, and Ticino). Some cantons have an explicit basis for this in their cantonal constitution (see, e.g., § 55 (1) lit. g Cantonal Constitution/Aargau).

Utilization of the Subsoil in the Context of Mining Rights

Canton of Appenzell Ausserrhoden: In accordance with Art. 47 (1) lit. c of the Cantonal Constitution, the exploitation of geothermal resources falls under mining rights. These are regulated by the canton (Art. 229 Introductory Act Swiss Civil Code/Appenzell Ausserrhoden). All “Regale” are the responsibility of the Cantonal Council (Art. 229 (2) Introductory Act Swiss Civil Code/Appenzell Ausserrhoden). The Cantonal Council can issue exploitation permits for exploratory drilling or similar activities; the actual exploitation of geothermal resources is subject to a license (Art. 229 (3) Introductory Act Swiss Civil Code of Appenzell Ausserrhoden).

Canton of Basel-Stadt: In accordance with § 158 (1) of the Introductory Act to the Swiss Civil Code of Basel-Stadt, mining rights include the extraction of geothermal energy, with the exception of geothermal energy extracted for private use only by means of shorter geothermal probes. This right to grant such a permit is held by the canton; it can be transferred to a third party by means of a license (§ 158 Abs. 2 EG ZGB/BS). This is issued by the Cantonal Parliament (§ 158 Abs. 3 EG ZGB/BS). Licenses are also required for prospecting and drilling; these are issued by the Cantonal Council (§ 158 Abs. 3 EG ZGB/BS).

Canton of Bern: According to the **Bern Cantonal Constitution**, mining rights are cantonal privileges which also include the exploitation of geothermal resources if this is extracted from deep subsoil layers (Art. 52 Abs. 1 lit. c Cantonal Constitution/Bern). Accordingly, the canton, in accordance with Art. 2 Abs. 1 of the Act on Mineral Rights/Bern, has the right to exploit both mineral and geothermal resources from the deep subsoil layers. In accordance with Art. 3 Abs. 2 of the Act on Mineral Rights of the canton of Bern, the exploitation of geothermal resources from deep subsoil layers is defined as the extraction of geothermal energy from a depth of more than 500m. A party making the necessary preparatory measures to extract geothermal energy from deep subsoil layers only needs to obtain an exploitation permit (Art. 12 Act on Mineral Rights/Bern) This permit gives the holder the exclusive right to perform work such as exploratory drilling or other geophysical exploration within a specified area (Art. 12 Act on Mineral Rights/Bern).

The actual exploitation of geothermal resources is subject to a **geothermal energy license**, in accordance with Art. 14 (2) of the Act on Mineral Rights/Bern. There is **no legal entitlement** (Art. 14 (3) Act on Mineral Rights/Bern). However, a party already in possession of an exploitation permit takes precedence in obtaining a license if several parties are applying for one (Art. 15 (2) Act on Mineral Rights/Bern). Someone who has taken extensive preparatory measures should not be “overtaken” by a competitor submitting a license application (Message Act on Mineral Rights/Bern, p. 7).

Licenses are always limited to a **period of 80 years** (Art. 15 (4) Act on Mineral Rights/Bern). The obligation to acquire a license in accordance with Art. 14−18 of the Act on Mineral Rights/Bern only applies to the exploitation of geothermal resources from deep subsoil layers, i.e. below 500m. Accordingly, a homeowner wanting to use geothermal energy for heating purposes is not obliged to acquire a license; the provision does not apply since ordinary geothermal probes have a length of approx. 300−500m (cf. Message Act on Mineral Rights/Bern, p. 3). In addition, the extraction of heat from the groundwater using a heat pump is also not covered by the Act on Mineral Rights. This however is covered by water rights, which are regulated by the Act on Water Use.

Cantons of Glarus/Thurgau: In accordance with Art. 47 (2) of the Glarus Cantonal Constitution, mining rights also include the exploitation of geothermal resources. The mining law of the canton of Glarus was established in the 19th century. It provides for an obligation to obtain a permit to utilize the subsoil (Art. 1 Mining Act/Glarus). According to the Thurgau Cantonal Constitution, the canton has the exclusive right to utilize geothermal energy (Art. 84 (1) Clause 4 Cantonal Constitution/Thurgau). It can transfer this right to third parties (Art. 84 (2) Cantonal Constitution/Thurgau). There is no executive legislation at the cantonal level.

Canton of Obwalden: In accordance with Art. 38 of the Obwalden Cantonal Constitution, the utilization of mining rights is vested in the canton. There is no executive legislation at the cantonal level. Whether mining rights include the exploitation of geothermal resources from the deep subsoil has not been regulated.

The **cantons of Fribourg (1850), Ticino (1853), Wallis (1856), Basel-Landschaft (1876), Waadt (1891), St. Gallen (1919), Neuchâtel (1935), Geneva (1940), Jura (1978), and Nidwalden (1979)** all have some kind of mining legislation. These legislations do however not cover − at least not explicitly − the exploitation of the deep subsoil by means of geothermal technology but focus mainly on the extraction of resources such as ores, fuels, coal, or salt.

The **cantons of Schaffhausen (1911)**, **Zurich (1911), and Zug (1911)** have integrated their mining rights into their Introductory Act to the Swiss Civil Code, but specific provisions to regulate the exploitation of the subsoil by means of geothermal technology are missing. Their legislation does cover the commercial utilization of exploitable minerals.

The cantons of Appenzell Innerrhoden, Basel-Stadt, and Graubünden lack specific legislation.

Utilization of the Subsoil as an Ownerless or Public Object

Canton of Aargau: The canton of Aargau regulates the utilization of the deep subsoil and the extraction of natural resources in the same statute (Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). The utilization of the deep subsoil is understood to mean the utilization of subsoil outside of what is considered protected property under private law (§ 2 (2) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). Accordingly, the use of geothermal probes reaching a depth of 400 to 500m is not subject to a license in accordance with the Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau. A license is required to utilize the deep subsoil – i.e. from a depth of 500m − in accordance with § 7 (1) of the Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau. Anyone engaged in preliminary exploration with the aim to utilize the deep subsoil requires a permit by the relevant department (§ 4 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). In accordance with § 4 (2) of the Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau, this permit does not constitute an entitlement to be granted a permit. In accordance with Art. 2 (7) of the Message to the Act on the Utilization of the Subsoil and the Extraction of Natural Resources (Message ibid., p. 25), preliminary investigation permits are awarded without public tender. Licenses are issued for a period of no more than 60 years (§ 7 (2) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). In particular, they regulate the type, scope, and period of utilization (§ 10 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). These licenses are also awarded without public tender (Message Act on the Utilization of the Subsoil and the Extraction of Natural Resources, p. 26).

Canton of Nidwalden: In the canton of Nidwalden, ownerless land within the meaning of Art. 664 (1) Swiss Civil Code − and thus also the utilization of the deep subsoil − is vested in the canton, which has the exclusive power to dispose of it (Art. 83a (1) Introductory Act Swiss

Civil Code/Nidwalden). Utilization can be transferred to third parties by means of an award or a license (Art. 83b Introductory Act Swiss Civil Code/Nidwalden).

Canton of Schwyz: In accordance with § 72 (2) of the Introductory Act to the Swiss Civil Code/Schwyz, the canton has sovereignty over the subsoil. The Cantonal Council can therefore issue a Parliamentary Ordinance of formal legislative character to regulate the administration of the subsoil. Such an ordinance was issued by the Cantonal Council on 10 February 1999. As in the canton of Uri, the subsoil is defined as that part of the earth's interior that is not subject to mining rights or regulated by the Swiss Civil Code (§ 4 Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz). It is subject to the sovereignty of the canton, which has the exclusive right to dispose of it (§ 5 and 6 Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz). Its utilization can be transferred to third parties, in which case a license is required (§ 7 et seqq. Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz). Any preparatory measures taken with the aim to utilize the subsoil, such as exploratory drilling, require a permit (§ 9 lit. 1 on Mineral Regalia and Subsoil Use/Schwyz). If the heat extracted from the earth's interior does not exceed a thermal output of 5’000 kW, a permit is sufficient (§ 9 lit. c on Mineral Regalia and Subsoil Use/Schwyz). In the case of several license applications being submitted, § 10 of the Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz stipulates that precedence is to be given to the party which has already been granted a permit to implement preparatory measures. The licenses grants the holder the exclusive right to utilize the subsoil within a specified area as conceded by the license (§ 15 (1) Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz). A license is granted for a period of no longer than 50 years (§ 16 (1) Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz).

Canton of Uri: The Act on Mining Rights and Subsoil Use/Uri makes a distinction between actual mining rights (Art. 2 Mining Rights and Subsoil Use/Uri) and the utilization of the subsoil (Art. 3 Mining Rights and Subsoil Use/Uri). Both types of utilization are regulated by the same statute. According to Art. 3 of the Act on Mining Rights and Subsoil Use/Uri, the subsoil is defined as that part of the earth's interior that is not subject to the mining rights or regulated by the Swiss Civil Code, i.e. that is not covered by private ownership. The right to dispose of the subsoil is − in line with Art. 664 (1) Swiss Civil Code − subject to the sovereignty of the canton (Art. 5 Sentence 1 Act on Mining Rights and Subsoil Use/Uri). Anyone wanting to claim this right needs a license (Art. 6 (1) Act on Mining Rights and Subsoil Use/Uri), while preparatory measures such as exploratory drilling and other exploratory soil examinations only require a permit (Art. 6 (3) Act on Mining Rights and Subsoil Use/Uri). The licensing authority is the Cantonal Parliament (Art. 7 (1) Act on Mining Rights and Subsoil Use/Uri). If a project has a thermal output of less than 10’000 kW, it can be approved by the Cantonal Council (Art. 7 (2) Act on Mining Rights and Subsoil Use/Uri). A license grants its holder the exclusive right to utilize the subsoil in a specified area as conceded by the license (Art. 11 Act on Mining Rights and Subsoil Use/Uri). A license is granted for a period not exceeding 80 years (Art. 13 (1) Act on Mining Rights and Subsoil Use/Uri).

The **canton of Luzern** has completely revised its legislation concerning mining rights. The new statute is the Act on the Extraction of Natural Resources and Subsoil Use. It was introduced with effect from 1 January 2014. The new statute makes the distinction between the extraction of natural resources (formerly mining rights) and the utilization of the subsoil

(§ 2 Act on the Extraction of Natural Resources and Subsoil Use/Luzern). In accordance with the Act on the Extraction of Natural Resources and Subsoil Use, the canton has the right to dispose of natural resources and the subsoil (§ 3 Act on the Extraction of Natural Resources and Subsoil Use/Luzern). It can transfer this right to third parties by license (§ 3 (2) in conjunction with § 4 (2) Act on the Extraction of Natural Resources and Subsoil Use/Luzern). Whereas a license is required by anyone wanting to utilize the subsoil, such a license is not necessary for the extraction of geothermal energy in a depth of no more than 400m in accordance with the Act on the Extraction of Natural Resources and Subsoil Use/Luzern (§ 4 (2) and (3) Act on the Extraction of Natural Resources and Subsoil Use/Luzern). Those who want to conduct exploratory measures with the purpose to utilize the subsoil only require a permit (§ 4 (1) Act on the Extraction of Natural Resources and Subsoil Use/Luzern). If the utilization of the subsoil is in the overriding public interest, the competent department can issue a call for tender with regard to applications for exploration permits or licenses (§ 5 (1) Act on the Extraction of Natural Resources and Subsoil Use/Luzern). There is no legal entitlement to a license (§ 10 (2) Act on the Extraction of Natural Resources and Subsoil Use/Luzern). It is issued for a period not exceeding 40 years (§ 10 (3) Act on the Extraction of Natural Resources and Subsoil Use/Luzern).

7.2.1.2 Type of utilization

To the extent to which the subsoil is under the sovereignty of a canton or − depending on the canton's legal situation − a commune, the respective public bodies are competent to decide on the **type of utilization** (Federal Supreme Court Decision 135 I 302 D. 3.1).

In principle, **the same rules apply for the utilization of the subsoil as for the utilization of a public object in public use**. In this context, the distinction is made between three levels of intensity: ordinary public use, increased public use, and special use (Federal Supreme Court Decision 135 I 302 D. 3.1, 126 I 133 D. 4c).

The **scope of the respective levels of intensity** is not undisputed, however. To begin with, this distinction is relevant with regard to the question whether a specific type of utilization is permitted or whether a permit or license is required, and whether a utilization or license fee may be levied. Ordinary public use is always free, i.e. no permit or fee is required; a permit is sufficient in cases of increased public use, while in cases of special use a license is required, for which a license fee must be paid (Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 2.2).

In cases of **increased public use**, ordinary public use of a public object is usually only restricted **temporarily**, while in cases of **special use**, often in the context of construction projects, **third parties are permanently excluded**. Since the exploitation of geothermal resources is subject to the installation of structures such as drilling rigs, and since third parties are permanently excluded from utilizing the subsoil, it can basically be considered as a **special use** case − subject to a different interpretation by the relevant public bodies. It is subject to a license. The license entitles the holder to utilize the subsoil. In some cases, other permits such as a building permit or a land-clearing permit may have to be obtained (Moser, p. 278; concerning the various permits to be obtained in addition to a license, cf. Section 7.2.1.5 below).

Most cantons thus stipulate that any private party wanting to utilize the subsoil for a specific purpose which excludes its utilization for other purposes must obtain a **license**. Accordingly, the Act on the Utilization of the Subsoil and the Extraction of Natural Resources of the **canton of Aargau** provides that the utilization of the deep subsoil is subject to a license (§ 7 (6) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau; also Art. 6 (1) Act on Mining Rights and Subsoil Use/Uri; § 7 Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz). Similarly, the Act on the Extraction of Natural Resources and Subsoil Use of the **canton of Luzern** requires anyone wanting to extract natural resources or utilize the subsoil to obtain a license (§ 4 (2) Act on the Extraction of Natural Resources and Subsoil Use/Luzern, with the exception of the exploitation of geothermal resources at a depth of up to 400m [§ 4 (3) Act on the Extraction of Natural Resources and Subsoil Use/Luzern]). The license is issued by the cantonal council, and it is basically up to that body to decide whether to grant it or not (§ 10 (1) and (2) Act on the Extraction of Natural Resources and Subsoil Use/Luzern; also § 7 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). The Mining Act introduced by the canton of Glarus in the 19th century only specifies the need for a permit, which probably has mainly historical reasons (Art. 1 Mining Act/Glarus).

Some cantons specify the **need for a mere permit** in **cases of low intensity use**: In the canton of Schwyz, a license is required for the exploitation of geothermal resources with an output of 5’000 kW or more, while only a permit is needed if the output is below 5’000 kW (§ 8 lit. e and § 9 lit. c Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz). In accordance with § 5 lit. d of the Model Law, the extraction of 1’000 kW of geothermal energy or more is subject to a license. If the extraction of geothermal energy does not exceed a capacity of 100 kW to 1’000 kW, all that is needed is a permit (§ 4 (1) lit. d Model Law).

Continuous exploitation of water or extraction of heat exceeding ordinary common use constitutes a special use of water, which also requires a license (on the special legal situation of the canton of Glarus, cf. Federal Supreme Court, 11 July 2011, 2E_3/2009, D. 3): The canton of Glarus does have a derivative right to utilize hydraulic power; water rights are held by the owners of land and shoreland. (The canton does however have the right to exclude hydraulic power, provided the parties in question are fully compensated). Depending on a canton's legal situation, the threshold for public use without a permit or license is at 20 to 50 l/min, or in exceptional cases at 80 l/min (JAGMETTI, RN 7423 [incl. FN 202 and 203]).

Only a **permit** and no license is required for **preparatory or exploratory measures** (see also § 4 (1) lit. a Model Law): Someone who takes preparatory measures to extract geothermal energy from deep layers of the subsoil in the canton of Bern requires a so-called exploitation permit, which grants a holder the exclusive right to carry out work such as exploratory drilling or other geophysical exploration in a specified area (Art. 12 Act on Mineral Rights/Bern) and conditionally entitles him or her to being granted a license (Art. 15 (2) Act on Mineral Rights/Bern). Anyone engaged in preliminary exploration with the aim to utilize the deep subsoil requires a permit by the relevant department (§ 4 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). Such a permit does not entitle the holder to a license (§ 4 (2) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). Similarly, in the canton of Schwyz preparatory measures for the utilization of the subsoil, such as exploratory drilling, only require a permit (§ 9 lit. a

Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz; also Art. 6 (3) Act on Mining Rights and Subsoil Use/Uri).

A license must be granted **for a limited period** only. Most cantons that have regulated this issue stipulate periods of between 40 and 80 years. In order to stay abreast of future changes, in particular technological developments, the canton of Luzern limits its licenses to a maximum period of 40 years; in exceptional cases, a longer period may be granted (§ 10 (3) Act on the Extraction of Natural Resources and Subsoil Use/Luzern); also § 16 (1) Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz [50 years]; § 7 (2) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau [60 years]). The canton of Bern issues geothermal energy licenses for a period of 80 years (Art. 14 (2) in conjunction with Art. 15 (4) Act on Mineral Rights/Bern; also Art. 13 (1) Act on Mining Rights and Subsoil Use/Uri).

Public bodies can either use the special rights attached to the legal or factual monopoly themselves, arrange for them to be used by companies under their control, or by public enterprises, or they can transfer these rights to third, private parties by license. Thus, e.g., § 158 (2) of the Introductory Act of the Swiss Civil Code/Basel-Stadt specifies that the right to exploit geothermal resources is reserved to the canton, which can transfer it to third parties by license. In accordance with Art. 84 (1) Clause 4 of the Thurgau Cantonal Constitution, the exclusive exploitation of geothermal resources is reserved for the canton, who can transfer this right to third parties (Art. 84 (2) Thurgau Cantonal Constitution; see also Art. 83b Introductory Act Swiss Civil Code/Nidwalden; § 7 et seqq. Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz; § 3 (2) in conjunction with § 4 (2) Act on the Extraction of Natural Resources and Subsoil Use/Luzern). Also possible is a mixed system which allows public bodies or their own public enterprises to be active themselves in the monopolized area while at the same time also conferring that right to private third parties (WALDMANN, p. 5).

By being granted a license, a private party acquires a **position that is similar to ownership and protected by the right to property** (Federal Supreme Court Decision 119 Ia 154 D. 5c, 117 Ia 35 D. 3b; Federal Supreme Court, 1 June 2005, 1P.645/2004, D. 4.1). It is a situation of "**limited right to property"** which exists in the context of a right granted by license since the scope of the exploitation rights of the licensee is defined in the license (Construction Appeals Committee/Zurich of 21 Oct. 2008, in: Construction Law Decisions/Zurich 2009 No. 17 D. 4.1). In accordance with Art. 11 of the Act on Mining Rights and Subsoil Use/Uri, a licensee has the exclusive right to utilize the subsoil in the area specified in the license. His or her right to property therefore refers to a specific area. According to § 15 (1) Ordinance to the Federal Act on Mineral Rights and Subsoil Use/Schwyz, a license gives the holder exclusive utilization rights for a specified area within the scope and for the period of time specified therein.

In issuing a monopoly or special use license, therefore, a **vested right** is established whose essence is irrevocable and legally stable for reasons of legitimate expectations and which is protected by the right to property: The license itself has to identify as a vested right any rights that does not arise from a legal provision but has been created based on a voluntary agreement between the parties and which must be seen as an integral part of the license to be granted because anyone who is involved in the licensing relationship could not have been able to decide on the award of the license without them (Federal Supreme Court Decision 132 II 485 D. 9.5, 131 I 321 D. 5.3, 130 II 18 D. 3.1).

Every individual right to which the licensee is entitled as the holder of the license has to be reviewed in the light of whether it is a vested right or not. Once a **vested right** has been established, legislation that is introduced at a later date will not affect its **substance**, at least not without compensation (Federal Supreme Court Decision 131 I 321 D. 5.3, 127 II 69 D. 5a, 119 Ib 254 D. 5a, 107 Ib 140 D. 3a).

The applicant is **not entitled** to expect to be granted a license; the decision is made at the discretion of the competent authority (Federal Supreme Court Decision 128 I 295 D. 3c/aa [= Praxis des Bundesgerichts (Basel) 2003 No. 79]; Federal Supreme Court, 23 Oct. 2006, 2P.121/2006, D. 3.5). In awarding a license, similarly to the granting of a permit for the utilization of a public object, it is important not only to consider the prerequisites on the part of the applicant as a person but also local circumstances, in particular capacities. Since the rights that are transferable by license are usually limited, a selection must be made from among the applicants. By being granted a monopoly or special use license, the licensee is given a special legal position for the duration of the license which lies within the protected domain of the right to property and the principle of good faith (Federal Supreme Court Decision 132 II 485 D. 9.5, 131 I 321 D. 5.3, 127 II 69 D. 5b).

Accordingly, e.g., the **Act on Mineral Rights of the canton of Bern** explicitly provides that there is no legal entitlement to a license for the exploitation of geothermal resources from deep layers of the subsoil (a so-called geothermal energy license) (Art. 14 (2) Act on Mineral Rights/Bern; also § 10 (2) Act on the Extraction of Natural Resources and Subsoil Use/Luzern or § 7 (3) Model Law), whereas anyone who already has an exploitation permit would be given precedence in being granted a license if there is more than one applicant (Art. 15 (2) Act on Mineral Rights/Bern; § 7 (2) lit. b Model Law). The exploration or exploitation permit in the canton of Aargau in accordance with § 4 (2) of the Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau does however not provide for any (conditional) entitlement to a license.

A license fee must be paid in order to receive a license. This fee is a **causal tax** ("taxe causale"), since it is used to pay for a state monopoly or for the use of public land. It is not a mixed tax ("impôt mixte"), since usually there is no element of taxation involved (Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 4.1 [water use license]; Federal Administrative Court, 6 Jan. 2010, A-4116/2008, D. 4.2 [radio communications license]).

The **amount of the license fee** relates to the application of the relevant legal provisions or is − according to the maneuvering room left open − determined by the license document or regulated by means of an agreement. Depending on the circumstances, the fee amount may be a vested right (Federal Administrative Court, 6 Jan. 2010, A-4116/2008, D. 6.2 [radio communications license]; 19 March 2009, LI-3129/2008, [radio communications license]).

License fees are **never related to actual costs**, since the cost to the state − except for some small administrative expense in connection with issuing the license − is negligible compared to other fees that are levied (BGE 138 II 70 D. 5.3 und D. 6 [= Die Praxis des Bundesgerichts (Basel) 2012 Nr. 86], 131 I 386 D. 3.5, 131 II 735 D. 3.1 und D. 3.2). A fee for special use of public land or the use of a monopoly or of "Regale" does however have to follow the constitutional principle of **fiscal equivalence** (Federal Supreme Court Decision 138 II 70 D. 7.2 [= Die Praxis des Bundesgerichts (Basel) 2012 Nr. 86], 121 II 183 D. 4a; Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 4.2; 15 October 2009, 2C_329/2008, D. 4.2). In practice, fiscal equivalence also applies to licenses (Federal Supreme Court Decision121 II 183 D. 4a), at least in cases where they refer to a right to something that is basically supposed to be available to anyone (Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 4.2; 1 June 2005, 1P.645/2004, D. 3.4).

Its **value** is measured either by the economic benefit that it gives to those involved, or by the expense incurred by the actual use compared to the overall outlay of the administrative branch in question (Federal Supreme Court Decision 130 III 225 D. 2.3; Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 4.2). Since by issuing a license there is very little (administrative) cost to the state compared to the value of the license itself, expense-oriented considerations do not play a part and the amount must therefore be based on the economic benefit that the license has for the private party (Federal Supreme Court Decision 131 II 735 D. 3.1; Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 4.2).

The license fee must therefore be set based on the **special advantages conferred by the license**, in particular the benefit, the type and duration of the license, drawbacks to the public, its purpose, the volume of the public goods utilized, and in some cases − if it includes the use of waters − the value of the adjoining land (Federal Supreme Court, 2 June 2012, 2C_900/2011, D. 2.4 [water use license]; Federal Supreme Court, 1 June 2005, 1P.645/2004, D. 2.2 [use of public land]; High Court of Schaffhausen, 21 Aug. 2001, in: Amtliches Bulletin der Bundesversammlung 2001 p. 115 D. 4e [mooring fee]).

The **canton of Bern** specifies that no surface fees (for the exploitation permit) and no **license fees** (for the actual utilization of the subsoil) must be levied for the exploitation of geothermal resources (Art. 26 (2) Act on Mineral Rights/Bern). The reason for this can be found in the fact that the extraction of geothermal energy equals the exploitation of renewable energy sources and is thus worthy of support and in line with the objectives of the energy policy of the canton of Bern (see Message Act on Mineral Rights/Bern, p. 3). Similarly, no fee is due in the canton of Aargau for energy extracted from the subsoil for heating purposes (§ 19 (4) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau); merely a one-time administrative fee must be paid as an administrative charge in connection with issuing the license (§ 18 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau). In the canton of Luzern, the license fee for projects in the public interest can be reduced or waived altogether (§ 22 Act on the Extraction of Natural Resources and Subsoil Use/Luzern).

7.2.1.3 Procedure

In accordance with **Art. 2 (7) of the Internal Market Act**, the **transfer of the utilization of the monopolies of cantons and communes to private parties** has to be by **public tender** and must not discriminate in favor of persons resident or established in Switzerland. If the utilization of the subsoil is included in mining rights, a cantonal monopoly can be said to exist. Its transfer to third parties must therefore be by public tender. According to § 6 (1) of the Model Law, the license must be awarded by public tender and the selection from among the candidates should occur in accordance with the criteria set out in § 7 (1) and (2). The canton of Luzern does not prescribe the use of public tender. The responsible department can, in accordance with § 5 (1) of the Act on the Extraction of Natural Resources and Subsoil Use/Luzern, invite license applications by public tender if the utilization of the subsoil is an overriding public interest, which will usually be the case for larger power plants such as geothermal installations.

In the not undisputed **opinion of the Swiss Federal Supreme Court**, the requirement of public tender is primarily designed for constellations in which **public bodies are motivated themselves to carry out such a transfer of monopolies** (Federal Supreme Court, 16 Oct. 2012, 2C_198/2012, D. 6.2). If, however, the object is not the utilization of a monopoly, or if a private person becomes active on his or her own accord − by his or her own initiative − and the relevant public bodies agree to issue a license with regard to the project in question, no public tender is to be held within the meaning of Art. 2 (7) of the Internal Market Act (Federal Supreme Court, 16 Oct. 2012, 2C_198/2012, D. 6.2; left open in Federal Supreme Court Decision 135 II 49 D. 4.1 [= Die Praxis des Bundesgerichts (Basel) 2009 No. 75]). In following this interpretation by the Swiss Federal Supreme Court, a license for the utilization of the subsoil would not have to be subject to public tender, since the private person will usually become active on his or her own accord and at his or her own initiative.

Another question that is under dispute is whether **Art. 2 (7) of the Internal Market Act** should also be applied in the context of transferring **de facto monopolies**. If the subsoil is not included in mining rights, it is considered to be a public object, for which public bodies have a de facto monopoly, based on the actual circumstances and based on its ownership of public objects. According to recommendations by the Competition Commission, Art. 2 (7) of the Internal Market Act also applies to the use of de facto monopolies. Licenses for the utilization of public taxi stands, for instance, should therefore be awarded by public tender. The design of the licensing terms is essentially left up to the tendering authority. An analogous application of (inter-) cantonal provisions regarding public procurement would therefore be indicated (recommendation of Competition Commission of 27 Feb. 2012, in: Recht und Politik des Wettbewerbs 2012, p. 438 RN 58; also expert opinion by Competition Commission of 22 Feb. 2010 concerning the renewability of license agreements between Centralschweizerische Kraftwerke AG and the communes of Luzern about the use of public land and the supply of energy, in: Recht und Politik des Wettbewerbs 2011 p. 345 RN 26 et seqq.; overview also in KUNZ, p. 34 et seqq., in particular p. 37 et seqq.; TRÜEB/ZIMMERLI, p. 113 et seqq.; also Aargau Administrative Court of 25 June 2012, in: Aargau Court and Administrative Decisions 2012 p. 176 E. 3.2).

Selection Criteria: Irrespective of any public tender, in cases where there are several interested parties for the same area the selection decision of the competent authority has to comply with the general **principles of the rule of law (Art. 5, 8, and 9 Federal Constitution)** and the **fundamental rights**, in particular economic freedom and the principles of the competitive neutrality of constitutional action as well as the (procedural) equal treatment of competitors (Federal Supreme Court Decision 132 V 6 D. 2.3.2 [with unsuitable reference to Federal Supreme Court Decision 128 I 136 D. 4.1; this judgment concerns the use of public land in increased public use]; also Zurich Administrative Court of 23 Aug. 2007, VB.2007.00105, D. 4.1; of 20 June 2002, VB.2001.00404, D. 3b).

In this context, the principle of **competitive neutrality of constitutional action** does **not specify a particular type of procedure**. A procedure must however be designed in a manner that becomes more formalized the greater the respective economic benefit is (Zurich Administrative Court of 23 Aug. 2007, VB.2007.00105, D. 4.1, with reference to SCHMID/UHLMANN, p. 345). The selection of the type of procedure and the criteria for the licensing decision, provided these are based on reasonable, objective reasons, is however largely up to the authority making the licensing decision (Zurich Administrative Court of 23 Aug. 2007, VB.2007.00105, D. 4.1).

The **issuing of licenses to private parties** does **not** fall under the scope of a **tendering procedure**. As opposed to a public tendering procedure, in issuing a license the state mainly acts as a provider, while the private party is mainly the demander who has to pay a fee for receiving something in return from the state (Federal Supreme Court Decision 125 I 209 D. 6b [= Die Praxis des Bundesgerichts (Basel) 2000 No. 149]). The mere fact that the state allows a private party to perform a specific activity does not constitute public procurement since the state does not initiate a public duty or acquires a good but merely acts in its capacity as the sovereign state in arranging, and in some cases regulating, a private activity (Federal Supreme Court Decision 125 I 209 D. 6b [= Die Praxis des Bundesgerichts (Basel) 2000 No. 149]; Federal Supreme Court, 16 Oct. 2012, 2C_198/2012, D. 5.1.3).

Public procurement can only be said to exist if public bodies acting as demanders in the free market acquire the means they need to perform their public duties against payment of a price (Federal Supreme Court, of 16 Oct. 2012, 2C_198/2012, D. 5.1.2). In this context, the public bodies are the "consumers" of a service and the private enterprise is its "producer" (Supreme Court Decision 135 II 49 D. 4.3.2 [= Die Praxis des Bundesgerichts (Basel) 2009 No. 75], 128 I 136 D. 4.1, 126 I 250 D. 2d/bb, 125 I 209 D. 6b [= Die Praxis des Bundesgerichts (Basel) 2000 No. 149]). A prerequisite for public procurement is always a legal transaction for a consideration, whereby the public contractor receives a service, and the provider of the service receives a consideration (Federal Supreme Court, 16 Oct. 2012, 2C_198/2012, D. 5.1.2). Such a consideration can also be said to exist in cases where the public contractor and private parties carry out an action together whereby both sides provide certain benefits and receive certain benefits in return ("public private partnership"; Federal Supreme Court, 16 Oct. 2012, 2C_198/2012, D. 5.1.2; 10 October 2007, 2C_116/2007 D. 4.4).

A similar situation exists whenever **the award of a license is subject to benefits rendered in return** that have a certain significance − such as the supply of energy to public bodies by the owner of an energy plant − which can usually be the sole object of public procurement (Federal Supreme Court Decision 135 II 49 D. 4.4 [= Die Praxis des Bundesgerichts (Basel) 2009 No. 75]; Federal Supreme Court, 16 Oct. 2012, 2C_198/2012, D. 5.1.3). Such procurement in the context of a license was recognized by the Federal Supreme Court in Federal Supreme Court Decision 135 II 49 D. 5.2 where the public bodies issued a special use license, tying it to the condition that a certain number of rental bicycles would have to be provided for public use. The decisive fact in this case was that the public bodies were involved, at least in part, in a public function which was to be met by means of the license − i.e. the distribution of posters − and the condition tied to the license, i.e. the provision of rental bicycles, a task which could be the object of public procurement (Supreme Court Decision 135 II 49 D. 5.2.2 [= Die Praxis des Bundesgerichts (Basel) 2009 No. 75]).

In the case of **supplementary benefits of lesser importance**, which in themselves cannot be the object of public tender, such as the obligation of a potential holder of a license for the distribution of posters to develop a concept for said distribution, the regulation concerning the issuing of public contracts does not, according to the Federal Supreme Court, apply to all such benefits (BGE 125 I 209 D. 6b [= Die Praxis des Bundesgerichts (Basel) 2000 No. 149]).

With the exception of the special cases mentioned above, **the analogous application of the law governing the submission of tenders** is also rejected in practice (Federal Supreme Court Decision 125 I 209 D. 9d/bb [= Die Praxis des Bundesgerichts (Basel) 2000 No. 149]). Even in the case of a procedure similar to that of the submission of tenders, the applicability of the law governing the submission of tenders does not follow: Only to the extent that public bodies actually refer to individual submission of tender provisions in their tender documentation, or formulate specific conditions for the submission of offers, the decision to issue a license must be reviewed according to the principles of good faith. Outside these specific tendering conditions, an analogous application of procurement law is not required (Zurich Administrative Court, 20 June 2002, VB.2001.00404, D. 3b).

7.2.1.4 Planning obligation

In accordance with **Art. 2 (1) of the Spatial Planning Act**, the federal state, the cantons, and the communes develop their own plans for any activity that has a spatial impact and coordinate these plans with each other where necessary ("nötig"). In this context, and in connection with the relationship between **exemptions and regular land-use planning**, the Federal Supreme Court has repeatedly dealt with the term "necessary" ("nötig") (HÄNNI, p. 106 et seqq.). The issuing of an exemption must not affect the planning procedure.

Exemptions from land use according to the zoning plan have to take into account the underlying **planning structure**. For buildings and installations which due to their nature can only be sufficiently dealt with in the context of a planning procedure, no exemptions may be issued. A project that does not meet zoning requirements or has a significant effect on the existing rules of land use must only be approved after the zoning map has been adapted accordingly. Whether or not a project meets the planning obligation in accordance with Art. 2 Spatial Planning Act depends on the principles and objectives of planning (Art. 1 and 3 Spatial Planning Act), the cantonal structure plan, and the significance of the project in light of the arbitration rules set out in the Spatial Planning Act and in cantonal law (Federal Supreme Court Decision 124 II 252 D. 4a, 120 Ib 207 D. 5).

According to Federal Supreme Court jurisprudence, the fact that an installation requires an **environmental impact assessment**, is a weighty indication that the project can only be approved on the basis of a land-use plan (Federal Supreme Court Decision 124 II 252 D. 4a, 120 Ib 436 D. 2d, 119 Ib 439 D. 4b). Nevertheless, each case must be assessed individually and its effect on the rules of land use taken into account: The greater the effect is, the greater the need for a specific project to require land-use planning. Deep geothermal projects with a power of more than 5 Megawatt thermal (MWth) require an environmental impact assessment (cf. Clause 21.4 Appendix to the Federal Environmental Impact Assessment Ordinance of 19 October 1988; Classified Compilation of Federal Legislation 814.011). It can therefore be assumed that such plants are subject to planning obligation.

Other decisive factors determining the extent of a planning obligation include the geographic scope of the project, the extent of the effects to be expected, the need to coordinate activities with other activities having spatial impact, the accessibility situation, the location of the buildings, or − as previously stated − the fact that an environmental impact assessment is required (HÄNNI, p. 106 et seq.).

In recognition of these principles, the Federal Supreme Court has recently approved a **planning obligation for bigger dismantling and landfill projects** and rejected the possibility of implementing such projects by means of an exemption (Federal Supreme Court 120 Ib 207 D. 5, 119 Ib 174 D. 4; left open in Federal Supreme Court Decision 124 II 252 et seqq.). With regard to the **building of golf courses**, the Swiss Federal Supreme Court handed down a similar decision (Federal Supreme Court Decision 114 Ib 312 D. 3b). **Multicomponent**

landfills where, on the one hand, gravel and rocks are mined and, on the other, construction waste is deposited, are also subject to planning (Federal Supreme Court Decision 120 Ib 207 D. 5).

Because a drilling rig system as a whole can require a large area (St. Gallen: approximately 18’000m ^{2}), and since leveling and sometimes backfilling are necessary, it must be assumed that the **construction of a geothermal plant is subject to planning obligation** and cannot be approved by means of an exemption. Therefore, a land-use plan must first be created, or existing land-use plans must be modified. Whether land-use planning should be **cantonal or communal** is determined by cantonal law.

Further, it must be clarified if the (cantonal or regional) structure plan must also be modified. **Structure plans** co-ordinate activities that have a spatial impact by determining one planning objective in particular, i.e. the future use of a particular area and its prospective exploitation. A structure plan has not the status of a statute; it neither grants any rights to natural or legal persons, nor does it impose any obligations on them that do not already have a basis in the provisions of legislative or constitutional law. In accordance with Art. 9 (1) of the Spatial Planning Act, structure plans are “only” binding on authorities and communes, and in this context especially for land-use planning (Federal Supreme Court, 10 April 2012, 1C_181/2012, D. 1.1; 21 Jan. 2010, 1C_415/2009, D. 2.1). The structure plan does provide binding guidelines for compliance with legally prescribed discretionary power and for the definition of indefinite legal terms, which is why its binding effect on the scope of applicable law remains limited.

In accordance with Art. 6 (3) lit. b of the Spatial Planning Act, the structure plan also has to provide details of the state and development to be achieved with regard to **supply**. A structure plan should give information on requirements for an entire area with regard to satisfying supply demands and measures to be taken to adapt and supplement existing supply installations as well as the sites of new plants and land-fills. **The fundamental guidelines on the subject area of supply further cover the existence of groundwater and other natural resources as well as the state of their utilization, including any installations planned for the future. The cantonal structure plan should therefore include the suitable** sites for deep geothermal plants and list the sites of already implemented plants. In some cases, a distinction is made according to plant capacity: In the canton of Zurich, plants with a capacity exceeding 10 MWh per year must be registered in the cantonal structure plan, with a capacity of 5−10 MWh in a regional structure plan.

7.2.1.5 Permits in accordance with the Spatial Planning Act, Nature and Cultural Heritage Act, and Water Protection Ordinance

7.2.1.5.1 Building permits and exemptions (Art. 22 and Art. Spatial Planning Act)

The erection or modification of buildings and installations is subject to permission by the authorities (Art. 22 (1) Spatial Planning Act). The cantons regulate competences and procedures (Art. 25 (1) Spatial Planning Act). For all construction projects outside a construction zone requiring an exemption (Art. 24 Spatial Planning Act), a cantonal authority determines whether they are in line with zoning requirements or whether an exemption may be granted (Art. 25 (2) Spatial Planning Act). Building permits and exemptions must take into account the underlying planning structure. If a project has a considerable effect on existing rules of land use, it must only be approved if new rules of land use are created or existing rules amended. In some cases, the structure plan may also have to be modified (see Section 7.2.1.4 above).

Building Permit (Art. 22 (1) Spatial Planning Act)

In accordance with **Art. 22 (1) of the Spatial Planning Act,** the erection and modification of buildings and installations is subject to permission by the authorities. A pre-requisite for being granted a permit is also that the building or installation meets zoning requirements ((2) lit. a) and that the land is accessible ((2) lit. b).

In accordance with **Art. 22 (1) of the Spatial Planning Act**, buildings and installations are artificially created facilities, intended for permanence and firmly connected to the ground, which are able to affect the perception of how land use is to be practiced, be it by radically changing the space around them or by having an adverse effect on spatial development or on the environment. The key issue in determining whether a structural project is substantial enough to warrant a building permit procedure, is if the realization of the building or installation, in the ordinary course of events, has spatial consequences that are big enough to be of interest to the public or to neighboring parties and therefore require that the project should first be evaluated. Consequently, the building permit obligation should enable the authorities to review the construction with regard to its spatial consequences prior to its execution in order to confirm that it complies with the rules of spatial planning and any other applicable legislation (Federal Supreme Court Decision 139 II 134 D. 5.2, 123 II 256 D. 3).

According to Federal Supreme Court practice, buildings ("Bauten") are also understood to mean movable structures which are used in one place for not inconsiderable periods of time. With regard to preparatory actions for a project affecting the environment, such as exploratory drilling, these pre-requisites are in any case to be considered as met if they take on a considerable volume in terms of communal or regional planning, such as held by the Federal Supreme Court in the context of an exploratory drilling project at a prospective site for storing radioactive waste that took some 12 months to complete (Federal Supreme Court Decision 111 Ib 102 D. 6). In the case of geotechnical explorations, the pre-requisites mentioned above can be said to be met if any required changes to the terrain have a considerable effect on the environment and remain visible for a longer period of time (left open in the outcome, in Federal Supreme Court Decision 118 Ib 1 D. 2c). The building permit obligation can however also refer to mere changes in the use of land which do not result in significant changes to the terrain but can have an adverse effect on the environment (cf. Federal Supreme Court Decision 119 Ib 222 D. 3a, concerning a hang-gliding landing site).

Projects not requiring a permit in accordance with Art. 22 (1) of the Spatial Planning Act include **small projects** of low impact that affect neither public nor neighborly interests. These include, e.g., structural changes to the interior of buildings, or tents or mobile homes installed for a short period of time. Key issues in determining whether a small structure is subject to a permit or not are the type and susceptibility of the environment in which the project is to be carried out.

According to Federal Supreme Court jurisprudence, the **obligation to obtain a drilling permit** depends on its spatial consequences in a specific situation. Having said that, it is significant in this context whether or not the effects a drilling project has on the area and on the environment are substantial enough that an assessment prior to the start of the work would be in the interest of the public or a neighboring party; other issues of key significance for the assessment of the spatial consequences of a project also include the type of environment and its susceptibility to being affected. Usually, drilling work to extract geothermal energy has a substantial adverse effect on the environment, which is why such projects are subject to a building permit.

In accordance with Art. 22 of the Spatial Planning Act, another pre-requisite for being granted a building permit is the need for a building or installation to correspond with the **purpose of the utilization zone** ((2) lit. a). Plants for the supply of energy are infrastructural buildings. In principle, it is a matter of cantonal (or communal) law and land-use planning to determine in general what zones are available for what types of infrastructural buildings, and where might an exemption be granted.

Based on the fundamental principle of spatial planning with regard to the separation of construction and non-construction areas, it can be deduced that **plants to develop or supply a settlement** should basically be erected **inside and not outside a construction zone**. The Federal Supreme Court has adopted this principle to stipulate that infrastructural buildings that are necessary to supply a specific zone are permitted to be built in that zone, provided that there is a direct functional relationship to the site on which they are to be built, and that the land they cover is mainly in a construction zone. An infrastructural building can sometimes also be said to meet zoning requirements if it is a facility that serves to supply the construction zone as a whole, not just a specific part of a construction zone (Federal Supreme Court Decision 138 II 173 E. 5.3, 133 II 321 D. 4.3.2).

As an interim conclusion it can thus be confirmed that infrastructural buildings in construction zones can meet zoning requirements, in which case they do not require an exemption in accordance with Art. 24 of the Spatial Planning Act (see in the following), but "merely" a building permit in accordance with Art. 22 of the Spatial Planning Act.

Since **drilling to extract geothermal energy** usually does not take place in a construction zone but in a **forest or agricultural area**, there is a need for an **exemption in accordance with Art. 24 of the Spatial Planning Act**, and therefore also for a planning obligation (see Section 7.2.1.4 above). The building and installation concept used in Art. 24 of the Spatial Planning Act is based on the meaning of Art. 22 of the Spatial Planning Act. Thus, the application of Art. 24 of the Spatial Planning Act presupposes the existence of a building or installation for which a permit is required in accordance with Art. 22 (1) of the Spatial Planning Act. Essentially, building permits and exemptions differ "merely" in terms of compliance with zoning requirements.

Exemption (Art. 24 Spatial Planning Act)

In accordance with Art. 24 and deviating from Art. 22 (2) lit. a of the Spatial Planning Act, permits can be issued for the erection of buildings and installations or for altering their purpose if the purpose of the buildings and installations requires them to be built on a site that is outside a construction zone (lit. a) and there are no overriding interests (lit. b). Art. 24 of the Spatial Planning Act − from a geographic perspective − therefore only applies to buildings and installations situated outside building zones and in substance for exceptions from the need to comply with zoning requirements (HÄNNI, p. 200).

Site Dependency (lit. a): In order to qualify for an exemption, the purpose of a construction project has to require it to be situated outside a construction zone. According to Federal Supreme Court practice, site dependency can only be confirmed in cases where a structure depends on a site outside a construction zone due to technical or economic reasons or due to surface conditions ("positive site dependency"). In this context, the pre-requisites are evaluated according to objective criteria and neither subjective ideas and wishes of individual parties nor personal practicability or convenience can be taken into account (Federal Supreme Court Decision 136 II 214 D. 2.1, 129 II 63 D. 3.1, 124 II 252 D. 4a 117 Ib 266 D. 2a, 116 Ib 230 D. 3a).

Relative site dependency suffices: It is not necessary for there to be no other site available; on the other hand, there have to be particularly important, objective reasons which make the proposed site appear much more advantageous compared to other sites within the construction zone (Federal Supreme Court Decision 136 II 214 D. 2.1, 133 II 409 D. 4.2).

In addition to this "positive site dependency", **Art. 24 of the Spatial Planning Act** also recognizes the concept of **"negative site dependency"** (HÄNNI, p. 221). According to Swiss Federal Supreme Court jurisprudence, negative site dependency must be assumed to exist in only a few situations, such as when a plant produces emissions which would exclude its erection in a building zone (Federal Supreme Court Decision 115 Ib 295 D. 3c, 114 Ib 180 D. 3c, 111 Ib 213 D. 3b). Such site dependency is commonly found in the case of large infrastructural buildings such as plants for the extraction of natural resources, landfills, or wastewater treatment plants. Negative site dependency has also been confirmed by the Federal Supreme Court in the context of animal husbandry (further references in HÄNNI, p. 221).

Infrastructural installations such as plants for the extraction of geothermal energy are often tied to a specific site. In this regard, positive site dependency can be assumed to be the norm. Furthermore, due to their emission levels, they are not suitable for settlement areas (negative site dependency).

Balancing of Interests (lit. b): In addition, no overriding interests should exist against such site-dependent structures. In balancing the interests, all spatial planning concerns in accordance with Art. 1 and Art. 3 of the Spatial Planning Act making reference to the case must be taken into account (Federal Supreme Court Decision 134 II 97 D. 3.1). It must be determined, for instance, whether or not there are environmental factors which could be held against the project, since spatial planning measures must safeguard natural resources such as the land, the air, the forests, and the landscape (Art. 1 (2) lit. a Spatial Planning Act). These all form part of the natural environment whose protection is safeguarded by Art. 74 of the Federal Constitution on the Protection of the Environment as well as by special protective orders (e.g. water conservation and protection, the protection of natural and cultural heritage, and the protection of animals [Art. 76−80 Federal Constitution]) which make them the responsibility of the state (Federal Supreme Court Decision 134 II 97 D. 3.1). In conducting a comprehensive review of all interests, these requirements should be taken into account (cf. Federal Supreme Court Decision 129 II 63 D. 3.1, 115 Ib 472 D. 2e/aa).

In accordance with **Art. 3 (1) of the Spatial Planning Act**, authorities with the authority to act in the context of carrying out and confirming activities that have a spatial impact must determine all interests involved, assess them individually, and in particular consider whether they, and any effects they may have, are compatible with future spatial development, and, based on their assessment, take into account the interests as fully as possible in making their decision; this balancing of interests must be described in the reasoning (Art. 3 (2) Spatial Planning Act). In accordance with the considerations set out above, the key benchmark for the balancing of interests to be conducted are the planning goals and principles of the Spatial Planning Act (Art. 1 and Art. 3 Spatial Planning Act). To the extent to which positive constitutional and legislative law regulates individual aspects balancing different interests, it must be determined first whether or not the project is in line with these provisions. Only after this has been confirmed can the weighing of all relevant interests be coordinated and carried out (Federal Supreme Court Decision 134 II 97 D. 3.1).

7.2.1.5.2 Special land-clearing permit (Art. 5 Forest Act) and special permit for the detrimental use of forest land (Art. 16 Forest Act)

Depending on the location, a project may also be subject to a land-clearing permit or a special permit for the detrimental use of forest land.

Special Land-Clearing Permit (Art. 5 Forest Act)

The purpose of the **Forest Act** is the conservation and protection of the forest. It aims to ensure that the forest can perform its silvicultural functions (Art. 1 Forest Act). In this context, the forest is also meant to include all forest roads (Art. 2 (2) lit. b Forest Act). Construction projects which permanently or temporarily use forest land for their own purposes are subject to a land-clearing permit (Art. 4 Forest Act). In forests, land-clearing is generally prohibited (cf. Art. 5 (1) Forest Act).

In accordance with **Art. 5 (2) of the Forest Act**, an **exemption or special permit** may be granted if the applicant can provide important reasons for the need to clear the land which override the need of forest conservation and if the project also meets the following conditions: The plant for which land is to be cleared is dependent on the proposed site (lit. a); The plant meets the objective spatial planning requirements (lit. b); The clearing of the land does not constitute an environmental risk (lit. c). Furthermore, the protection of natural and cultural heritage must be taken into account (Art. 5 (4) Forest Act). Less important reasons include financial interests such as that the land use be as profitable as possible or the cheap acquisition of land for non-agricultural purposes (Art. 5 (3) Forest Act). Every land-clearing permit therefore constitutes an exemption, and the granting of such exemptions is tied to the strict adherence to legal requirements (Federal Supreme Court Decision 119 Ib 397 D. 5b).

According to Federal Supreme Court jurisprudence, an **overriding interest in the clearing of a forest site** for a public plant can only be confirmed if it has at least been reviewed and approved as a general project by the competent authority (Federal Supreme Court Decision 119 Ib 397 E. 6a). The proper application of **Art. 5 of the Forest Act** requires the evaluation of a **project as a whole**; it excludes the possibility of individual issues of importance for the balancing of interests being subjected to separate procedures. In particular, in accordance with Art.5 (2) lit. a of the Forest Act, a plant for which an exemption under the Forest Act is being sought must be dependent on the proposed site. Site dependency is not to be understood in an absolute sense, since there is almost always a certain flexibility of choice and since the question of site dependency is only one of the perspectives to be taken into account in a comprehensive balancing of the interests in a given case in accordance with Art. 5 of the Forest Act. Decisive is whether the reasons for a proposed site override the interests of forest conservation. Another condition for relative site dependency to be confirmed however is that a comprehensive evaluation of alternative sites has taken place (Federal Supreme Court Decision 120 Ib 400 D. 4c, 119 Ib 397 D. 6a).

The **use of forest land for forest buildings and installations** as well as for **small non-silvicultural buildings and installations** does not constitute land-clearing in accordance with Art. 4 lit. a of the Forest Ordinance and does therefore not constitute an alternative use of forest land. Accordingly, underground cables and small antenna systems do not count as land clearing. On the other hand, non-silvicultural construction projects, with the exception of small buildings and installations, must be considered an alternative use of forest land. They therefore require a land-clearing permit and, like all forest construction projects, a building permit in accordance with the Spatial Planning Act (for the whole issue, Supreme Court Decision 134 E. 6.2, 123 II 499 E. 2). Being granted a land-clearing permit does not exempt the holder from obtaining a building permit in accordance with Art. 22 or Art. 24 of the Spatial Planning Act (cf. Art. 11 (1) Forest Act). The respective procedures should be coordinated (see Section 7.2.1.6). If a land-clearing project is being discussed in the context of creating a specific land-use plan, the spatial planning and forest police procedures have to be coordinated (Federal Supreme Court Decision 119 Ib 397 D. 6a; see also Art. 12 Forest Act).

The **authority for the granting of exemptions** is regulated by Art. 6 (1) of the Forest Act. According to this, land-clearing permits are issued either by the federal state or by the canton, depending on whether it is a federal or a cantonal authority that decides on the erection or modification of a plant for which land is to be cleared (see also WALDMANN/HÄNNI, Art. 25a Spatial Planning Act, RN 27). In this particular situation – the utilization of the subsoil by a geothermal plant – it is a cantonal authority, which therefore also has to decide on whether or not to grant a land-clearing permit, if such a permit is requested. What has to be taken into consideration is that in accordance with Art. 6 (2) of the Forest Act the respective cantonal authority, before it can decide on whether or not to issue an exemption, has to consult with the Federal Office for the Environment if the area to be cleared exceeds 5'000 m^2 (lit. a) or if the forest in which clearing is to take place, extends across several cantons (lit. b).

Exploratory drilling, like the final **erection of a geothermal plant**, does not serve a silvicultural purpose and thus constitutes an alternative use of forest land. The sole exception to this would be a one-time, short-term, isolated use of forest land. The use of forest land for a period of four weeks can still be considered “temporary” (Federal Supreme Court Decision 139 II 134 D. 6.3). If the forest area in use does not exceed 100 m^2, and if the utilization period is limited to a maximum of four weeks, a planned exploratory drilling project is assumed to constitute an isolated use of forest land, which does not affect the stand structure of the forest and is therefore not subject to a land-clearing permit in accordance with Art. 5 (2) of the Forest Act (Federal Supreme Court Decision 139 II 134 D. 6.3). In contrast, it can be assumed that an exploratory drilling project in the context of exploiting geothermal resources, an operation which usually takes far longer than four weeks, is subject to an exemption.

Detrimental Use of Forest Land (Art. 16 Forest Act)

Detrimental use of forest land that does not constitute **land clearing** is generally prohibited. It can however be permitted by the cantons under certain conditions and with certain requirements, if there are valid reasons (Art. 16 Forest Act). Detrimental use of forest land includes isolated or insignificant instances of forest land use for small non-silvicultural buildings and installations such as modest rest areas, campfire sites, sports and nature trails, underground cables, and small antenna systems, none of which affect the stand structure of the forest. On the other hand, non-silvicultural buildings and installations are not subject to a land-clearing permit because they do not actually constitute cases of alternative use of forest land. Since these are however detrimental for the forest, they are still subject to an exemption to be granted by the canton in accordance with Art. 16 (2) of the Forest Act. And because they are not completely in line with the silvicultural purpose of the forest due to their detrimental nature, a building permit in accordance with Art. 24 of the Spatial Planning Act (Federal Supreme Court Decision 139 II 134 D. 6.3) is also required.

7.2.1.5.3 Water protection permits

In cases where heat is extracted from groundwater sources, public water, in this case groundwater, is generally used to an extent that exceeds ordinary public use, which in accordance with Art. 29 lit. b of the Water Protection Act is subject to a permit, which is granted by the cantons. Furthermore, Art. 19 (2) of the Water Protection Ordinance requires a cantonal permit for buildings, installations, as well as excavations, earth-moving projects, and similar work in particularly endangered areas if these might harm the waters (see also Art. 32 Water Protection Ordinance).

7.2.1.5.4 Natural habitat and wetland protection (permit under the Nature and Cultural Heritage Act)

The erection of geothermal plants can also be in conflict with the protection of natural habitats provided in Art. 18a et seqq. of the Nature and Cultural Heritage Act or with wetland protection as regulated in Art. 78 (5) of the Federal Constitution:

In accordance with **Art. 18 (1) of the Nature and Cultural Heritage Act**, the extinction of species of animals and plants is to be prevented by means of the conservation of large natural habitats and other suitable measures. Art. 18 (1)^{bis} of the Nature and Cultural Heritage Act lists the natural habitats that are in particular need of protection: Shorelines, reed beds and marshes, rare forest habitats, hedges, copses, dry meadows, and other sites which have a balancing function in an ecosystem or which provide a particularly beneficial environment for biotic communities.

Federal legislation contains certain provisions on **natural habitats of national significance** (cf. Art. 18a Nature and Cultural Heritage Act, Art. 16 and Art. 17 Nature and Cultural Heritage Ordinance). Federal law does not define the term “natural habitat” in any detail. The requirements of Art. 18 of the Nature and Cultural Heritage Act do not apply to all biotic environments which provide relatively stable conditions to animal and plant communities. The concept of the natural habitat in federal legislation on the protection of natural and cultural heritage refers to a sufficiently large home territory with a specific task (Federal Supreme Court Decision 121 II 161 D. 2b/bb, 116 I b 203 D. 4b).

In addition, the **cantons** are required to provide protection and maintenance for natural habitats of **regional and local significance** (Art. 18b Nature and Cultural Heritage Act). In this regard, they have to specify sufficiently large natural habitats worth protecting (cf. Art. 14 (3) Nature and Cultural Heritage Ordinance). In doing so, they have a wide margin of discretion since – unlike in the case of forest protection – federal law does not provide for the protection of all natural habitats (Federal Supreme Court Decision 121 II 161 D. 2b/bb, 118 I b 485 D. 3a, 116 I b 203 D. 4b and 5g).

Federal law does not require the cantons to have a special permit procedure – such as for land-clearing permits within the meaning of Art. 5 of the Forest Act – in cases where the realization of a structure or plant might harm a protected habitat. The balancing of interests required in accordance with Art.18 (1)^{ter} of the Nature and Cultural Heritage Act can be conducted in the course of an ordinary approval procedure (Federal Supreme Court Decision (Federal Supreme Court Decision 121 II 161 D. 2b/bb; cf. also Art. 14 Abs. (6) Nature and Cultural Heritage Ordinance).

In accordance with **Art. 78 (5) of the Federal Constitution, marshes and marshland of particular beauty and national significance** are protected by law. Both the erection of plants and alterations to the land are prohibited. The only exceptions are installations which serve to protect marshes and marshland or have hitherto served to exploit them agriculturally. Art. 78 (5) of the Federal Constitution therefore provides for an absolute ban on changes both for marshes and for marshland and permits exceptions only if they would serve to protect an area or have hitherto served to exploit it agriculturally. Art. 78 (5) of the Federal Constitution gives absolute precedence to the protection of marshes and marshland and does not leave any room for balancing other interests in individual cases (Federal Supreme Court Decision 138 II 281 E. 6.2, 117 Ib 243 E. 3b). Only in setting the boundaries of individual areas do the competent authorities have a certain scope of discretion (JAGMETTI, RN 2241).

The marshes and marshland thus protected are listed in the appendices of the Highland Marsh Ordinance, Lowland Marsh Ordinance, and Marshland Ordinance. In addition, Art. 78 (5) of the Federal Constitution is directly applicable (i.e. also if there is no specific executive legislation or a relevant inventory) if the marsh or marshland has particular natural beauty and national significance (HÄNNI, p. 414).

Art. 23d (1) of the Nature and Cultural Heritage Act permits the development and utilization of marshland areas provided this does not contradict the preservation of features that are characteristic to marshland. This replaces the criterion of protection target compliance with that of protection target compatibility (Federal Supreme Court Decision 138 II 281 E. 6.1, 124 II 19 E. 5c). Under these conditions, Art. 23d (2) of the Nature and Cultural Heritage Act declares certain uses as acceptable (agricultural and silvicultural utilization; the maintenance and renovation of legally erected buildings and installations; measures for the protection of the population from natural disasters; infrastructural buildings necessary for the application of letters a-c). In this regard, there is no absolute ban on alterations in marshland areas but it must be evaluated in each individual case whether or not a project is compatible with the protective targets. A balancing of interests is however not permitted either in this case: If a project is not in line with protective targets, it is not permitted, regardless of the weighting of other relevant interests (Federal Supreme Court Decision 138 II 281 D. 6.2).

Wetland protection not only applies to surface installations but also subterraneous ones such as tunnels constructed in the context of surface mining. Such infrastructural measures, which also include installations to extract geothermal energy, are not in line with the targets of wetland protection and thus not permitted within the perimeter of a marsh (Federal Supreme Court Decision 138 II 281 E. 6.4).

7.2.1.5.5 Other permits provided under cantonal law

Cantonal law can provide for other permits such as permits related to water protection, for the use of forest roads, or the utilization of the subsoil.

The **canton of Glarus** requires a special permit, i.e. a special permit procedure, for all energy production plants of a certain size. In accordance with Art. 5 (1) of the Glarus Energy Act, the erection of a new plant for the production of electrical energy with a thermic capacity of more than 1’000 KW is subject to a permit by the Cantonal Council. In accordance with (2), all types of energy production are subject to this provision, in particular subterranean energy extraction. Prior to granting a permit, the permit authority consults with the commune in which the proposed site is located; any requirements that are in the public interest are integrated into the permit. A permit is granted if the plant is in line with the objectives of this legislation and if there are no overriding public interests (3). The permit is issued for a specific period of time, which must not exceed 80 years (4).

The **canton of Jura** has a special procedure for private plants built for the production of energy on behalf of third parties. This procedure is conducted in addition to that for obtaining a building permit. However, it has to be coordinated with the latter, whereby it remains unclear whether or not this special procedure replaces the need for a license in the cantons of Jura or Glarus. In cantons that do not have any special energy-related permit, compliance with the provisions of energy legislation must be reviewed in the context of the building permit or licensing procedure.

7.2.1.5.6 Environmental impact assessment

An **environmental impact assessment** is required for plants which might adversely affect some areas of the environment (Art. 10a (2) Environment Protection Act). Based on Art. 10a (3) of the Environment Protection Act, the Federal Council of Switzerland uses the Environmental Impact Assessment Ordinance to specify which plants are subject to an environmental impact assessment. Deep geothermal projects with a capacity of more than 5 Megawatt thermic (MWth) require an environmental impact assessment (cf. Clause 21.4 Environmental Impact Assessment Ordinance).

With the provisions of **Art. 10a to Art. 10d of the Environment Protection Act**, legislators **did not intend to introduce an additional, independent procedure**. The prescribed assessments are to be carried out within the framework of existing decision-making procedures (Federal Supreme Court Decision 117 Ib 135 D. 2b). In accordance with Clause 21.4, the procedure to be employed is to be determined by cantonal law. Whether or not a project is subject to an environmental impact assessment or an environmental impact report is usually best reviewed in the context of a planning, building, or licensing procedure.

In determining whether or not a plant might seriously contaminate the environment (Art. 10a (2) Environment Protection Act), it is immaterial whether or not there are already other effects emanating from other plants, and how these will develop in future. Any preexisting contamination of the environment and any contamination expected to remain after the new plant has been completed must be established or estimated within the framework of the environmental impact assessment itself (Art. 10b (2) Environment Protection Act); they are therefore the subject of the assessment and not criteria of the obligation to carry out the assessment per se.

If the Appendix to the Environmental Impact Assessment Ordinance provides for a **multi-level assessment** in different procedural steps – which does not apply here – the assessment is carried out for every procedural step to the extent to which the effects of the project on the environment are known for the decision to be made (Art. 6 Environmental Impact Assessment Ordinance). A multi-level environmental impact assessment can also be required under cantonal law, for example if a special use plan is not sufficiently detailed to enable a final evaluation of the project to be made but still regulates certain decisive questions with regard to the volume, site, or equipment of a plant which cannot be queried at a later stage of the building permit (Federal Supreme Court Decision 120 Ib 436 E. 5d/aa).

What needs to be taken into account is that in accordance with **Art. 55 (1) of the Environment Protection Act** any national environmental protection organization in existence for more than 10 years can object against orders issued by competent authorities with regard to the planning, erection, or modification of permanent plants subject to an **environmental impact assessment**. The organizations are obliged to make use of the cantonal legal remedies available, otherwise they lose their right to object (Art. 55a and Art. 55b Environment Protection Act).

7.2.1.5.7 Permit for preparatory measures

Depending on cantonal law, a **special permit for preparatory or exploratory measures** (exploratory drilling, excavation, or other soil exploration) – in addition to the actual license for the permanent utilization of the subsoil – is required. Such preparatory or exploratory measures are activities which are undertaken with a view to the future extraction of natural resources or the utilization of the subsoil. They include, in particular, seismic explorations or exploratory drilling which serve to clarify geological and geothermal conditions.

Anyone who wants to conduct exploratory measures in the cantons of **Aargau, Bern, Luzern, Schwyz, and Uri requires** a **permit** (§ 4 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau, § 4 Abs. 1 Act on the Extraction of Natural Resources and Subsoil Use/Luzern; Art. 6 (3) Act on Mining Rights and Subsoil Use/Uri; § 9 lit. a Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz). The right to the actual extraction of natural resources or utilization of the subsoil is granted by means or issuing a license. The **canton of Bern** provides for an exploitation permit which must be obtained before taking preparatory measures for the extraction of geothermal energy from deep layers of the subsoil (Art. 12 (1) lit. b Act on Mineral Regalia/Bern). This exploitation permit exclusively entitles the holder to carry out work such as exploratory drilling and other exploration within a specified area (Art. 12 (2) Act on Mineral Regalia/Bern. The application is made public and objections can be raised against it (Art. 13 (1) Act on Mineral Regalia/Bern).

Besides this exploitation permit, no other building permit is required in the **canton of Bern**; the **exploitation permit "consumes" the building permit** (Message Act on Mineral Regalia/Bern, p. 6). Such projects do however require a water protection permit and in some cases additional permits (Message Act on Mineral Regalia/Bern, p. 6). If several permits are needed, the leading procedure in accordance with the Bern Coordination Act is the exploitation permit procedure (Message Act on Mineral Regalia/Bern, p. 6)

Depending on the legal situation in a canton, the **exploitation permit** grants to the holder a **"conditional right"** to **being granted a license** (for the permanent utilization of the subsoil). Art. 15 (2) of the Act on Mineral Regalia/Bern states that whoever is in possession of an exploitation permit is given precedence in being granted a so-called geothermal energy license (Art. 14 (2) Act on Mineral Regalia/Bern) if several persons are applying for the same license (also § 10 Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz or § 7 (2) lit. b Model Law), while in the canton of Aargau, the permit does not give the holder any right to expect a license to be granted (§ 4 (4) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau).

7.2.1.5.8 Expropriation procedures

Depending on the location of a plant and who is the operator, private ownership rights are to be withdrawn against full compensation or the owner be given to limited material rights. Of some significance in the context of energy law is the withdrawal of land ownership as well as its limitation by the imposition of easements (right of conduits to traverse land, right to erect pylons, etc.). In some circumstances, neighboring parties lose the right to object to being affected by a plant, with the effect that neighbors have to bear the emissions from a plant. Most cantons have their own expropriation legislation. In the energy sector, federal law is applied for expropriation by the state or for purposes that are recognized by federal law, such as the utilization of hydraulic power, the storage of radioactive waste, and the construction of electrical installations and pipe systems (see for the issue, JAGMETTI, RN 2108 et seqq.).

Usually, the **licensing authority issues the expropriation right with regard to the material rights required for the construction or the operation of the installations at the same time as the license** (for the exploitation of geothermal resources) itself, provided private acquisition of land ownership or sufficient easements (e.g. the right to build) are not possible and the license is necessary to meet requirements of the common good (cf. e.g. Art. 6 (1) Act on Mineral Regalia/Bern). In such cases, or rather in cantons where the expropriation right is granted at the same time as the license, a separate expropriation procedure is not necessary (cf. Message Act on Mineral Regalia/Bern, p. 4). Similarly, the canton of Luzern grants the expropriation right together with the license if the private acquisition of the required rights is not possible on a contractual basis and the project is in the public interest (§ 14 Act on the Extraction of Natural Resources and Subsoil Use/Luzern; similarly Art. 23 (1) Act on Mining Rights and Subsoil Use/Uri, § 11 (1) Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz, § 11 (1) Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau).

Expropriation of the Rights of Neighboring Parties in Particular: The rights of neighboring parties regulated by the Swiss Civil Code prohibit a land owner from exceeding his or her own ownership rights (Art. 679 Swiss Civil Code) and from excessively affecting the property of a neighbor (Art. 684 Swiss Civil Code). This provision only applies conditionally if the encroachment emanates from a piece of land which constitutes a public plant, since the right of a neighbor under civil law to object to being affected is not allowed to lead to a situation where the implementation of installations in the public interest is prevented or severely impeded. This always applies only under the condition that the encroachment is **inseparably** and **unavoidably** tied to the intended operations of the public plant.

If these conditions are met, the private neighbor of a public plant can, in accordance with federal court jurisprudence, assert his or her rights as a neighbor in the case of **excessive emissions** and demand a formal expropriation of his or her rights as a neighbor. Excessive emissions of a public plant can only be said to exist if they cause serious damage to the neighbor which could not be foreseen when the property was acquired, rented, or leased, or when the building was erected, and which are affecting said neighbor in a specific way. If one of these conditions does not apply, no claim can be said to exist for compensation due to withdrawal of neighbor rights (with regard to the whole issue, Häfelin/Müller/Uhlmann, RN 2086 et seqq.).

7.2.1.6 Coordination of procedures

7.2.1.6.1 Multiple permits

The approval procedure for the exploitation of geothermal resources can – depending on the legal situation of a canton – be a two-step procedure (see, e.g., for the utilization of hydraulic power WEBER/KRATZ, § 6, RN 59):

Step 1:

- Cantonal Right: issuing of a monopoly or special use license
- Water Protection Act: permit to extract water or exploit the groundwater
- Spatial Planning Act: establishing a plan, perhaps an exemption
- Forest Act: land-clearing permit
- Environment Protection Act: environmental impact assessment, 1st level
- Nature and Cultural Heritage Act: permit
- Environmental impact assessment (within the framework set out by the plan)

Step 2:

- Spatial Planning Act: building permit (zoning requirements must be met)
- Employment Act: operating permit
- Cantonal expropriation act: expropriation
- Environmental impact assessment: 2nd level (if necessary)
- Other cantonal permits

7.2.1.6.2 Harmonization

If the same federal provisions are to be applied for a project in several cantonal and/or communal procedures, constitutional law provides for effective **substantive and procedural coordination** to be carried out. From the perspective of procedural law, the principle applies that cantonal law cannot be formulated or applied in such a way as to block, prevent, or seriously impede the carrying out of federal law. If a project – as applies here – requires several permits, or if several federal provisions must be complied with, and if different authorities are involved, these different edicts must be processed by the various authorities in a coordinated manner. The need for coordination also exists in cases where both cantonal and federal edicts need to be applied and applies to both administrative procedures and appeal procedures. The purpose of coordination is to achieve a uniform outcome. Otherwise, there is a risk of substantively uncoordinated, perhaps even contradictory decisions to be made or of federal law being blocked, which contradicts the principle of the derogatory power of federal law and could lead to materially untenable outcomes (fundamentally Federal Supreme Court Decision 116 Ib 50 ff.; on the whole issue, WALDMANN/HÄNNI, Art. 25a Spatial Planning Act, RN 8 et seqq.).

In accordance with jurisprudence, under certain conditions the application of the law must however be substantively coordinated, i.e. be conducted by coordinating content. This is the case if for the realization of a project different provisions under substantive law have to be applied and if such a **close relationship between issues** exists in these provisions that they cannot be applied separately or independently from each other (fundamentally, Federal Supreme Court Decision 117 Ib 35 D. 3e). It is however not sufficient for different procedures to concern one and the same plant (HÄNNI, p. 458 et seq.).

If therefore – which is frequently the case – **different authorities** are in charge of evaluating individual legal issues which need to be substantively coordinated, these authorities have to coordinate the application of the law as if one authority were to decide on all issues requiring coordination. If an overall decision at first instance does not occur, the whole procedure may, for example, be carried out by means of a **leading procedure** coordinated by the leading authority to ensure consistency. This involves several, separately made decisions which, to ensure substantive coordination, are subject to the reservation that the other permits are granted.

These **coordination principles, i.e. the obligation to coordinate procedures**, were developed by the **Federal Supreme Court** and later embedded in **Art. 25a of the Spatial Planning Act by federal legislators**. In doing so, the federal legislators followed two different strategies: On the one hand, they used the Spatial Planning Act to regulate the minimum requirements in terms of coordination by the cantonal authorities if the erection or modification of a building or installation requires orders from several authorities. As the legislators did not wish to interfere too strongly into cantonal organizational autonomy, the cantons merely have to designate an authority to take on the task of providing sufficient coordination (acc. to the so-called **coordination model**). The authority in charge of this task issues the required procedural orders, ensures that the documentation of the various approval procedures is publicly available as a whole, consults with all cantonal and federal authorities involved and requests detailed feedback with regard to the proposed project, and coordinates their input while ensuring that the various rulings by the different offices are issued jointly or simultaneously (see Art. 25a (2) Spatial Planning Act). The rulings must not be contradictory in content (Art. 25a (3) Spatial Planning Act).

An additional strategy was followed by the federal legislators for the erection and modification of **buildings that are approved by the federal authorities**. They enacted a collective piece of legislation (Federal Act of 18 June 1999 on the Coordination and Simplification of Decision-Making Procedures) which introduces the so-called **concentration model** at the federal level. This model unites the decision-making powers in one single authority which in a particular case issues one ruling which replaces all other rulings. This authority acts as the leading authority as well as the authority of first instance. This model best guarantees effective coordination and prevents contradictory decisions from being made.

Plants for the **production of energy** – with the exception of electrical installations (for the transportation and supply of electrical power) and nuclear power stations – are approved by **cantonal or communal authorities**. Art. 25a of the Spatial Planning Act is therefore applied. The cantons are at the very least required to designate an authority in charge of ensuring sufficient coordination (Art. 25a (1) Spatial Planning Act), whereby the cantons can choose freely between the coordination model and the more advanced concentration model. Accordingly, they are also entitled to decide on the details of the model they have chosen within the scope of federal law, or in accordance with the minimum requirements set out in Art. 25a of the Spatial Planning Act. As a result, mixed forms are also permissible. Although this is not expressly mentioned in Art. 25a of the Spatial Planning Act., the Federal Supreme Court did not drop the requirement of a close relationship between issues (above see Section 7.2.1.6.2) with its introduction of the new Art. 25a of the Spatial Planning Act.

The **responsibilities** which the federal state assigns to the cantonal coordination authorities are set out in **Art. 25a (2) of the Spatial Planning Act**. The responsibilities thus assigned constitute minimum requirements. Furthermore, the cantons are free to enact special coordination provisions. In particular, the coordination authority has to coordinate the formal requirements of the various approval procedures (publication, public display, joint and simultaneous issuing of rulings, objection procedures, etc.) as well as the various substantive objectives (requests for feedback from the authorities involved, drafting a coordination proposal, etc.). The federal state also requires the cantons to provide for a uniform legal remedy against the coordinated rulings (Art. 33 (4) Spatial Planning Act). Only if one complaints authority is able to review all objections in one overall decision, is it possible in cases where there the issues are closely related to guarantee and achieve an appropriate application of substantive law (see Federal Supreme Court Decision 118 Ib 381 E. 4a).

The objective of a coordinated procedure is however to prevent contradictory content in the individual rulings and achieve one **overall outcome as if only one authority had been involved** which had only issued a single ruling. Contradictions constitute discrepancies between individual rulings. However, no contradiction can be said to exist if a particular piece of legislation allows the proposed project (e.g. the granting of a building permit) while another piece of legislation does not allow this (e.g. the refusal to grant a land-clearing permit). If a negative decision is issued in such a context, no permit can be issued for that particular project. Such decisions are also referred to as “killer decisions”. A killer decision is issued when an authority that is competent to rule recognizes that the proposed project cannot be realized under any circumstances in a legally compliant manner. Accordingly, it will inform the applicant by means of a rejection letter, a so-called “letter of obstacles”. This “negative” decision cannot however be seen as a contradictory decision. No contradiction can be said to exist either if different authorities review the same subject matter from the perspective of different legal aspects, for it is possible that a subject matter must satisfy different (legal) requirements in a cumulative manner. A contradiction can, on the other hand, be said to exist if the same legal question is answered differently.

Most **cantons** have implemented the **coordination model** required under Art. 25a of the Spatial Planning Act. Only some cantons have introduced the **concentration principle** (such as the canton of Bern). Conceivable options include **mixed models**: In such a model, the authority which has the lead collects all cantonal permits into an overall decision (concentration model) and coordinates this with any communal permits (coordination principle). In some cases, special provisions were introduced that reflect the concentration principle in regulating subsoil use, which − with regard to Art. 25a of the Spatial Planning Act − is completely valid: In accordance with § 11 (2) of the Act on the Extraction of Natural Resources and Subsoil Use/Luzern, the licensing procedure is to be coordinated with other procedures such as the building permit procedure. According to a Federal Council Message, this provision implements the so-called concentration principle. The licensing decision should also contain all other permits and rulings by communal and cantonal authorities − including the building permit (Message Act on the Extraction of Natural Resources and Subsoil Use/Luzern, p. 11). The canton of Luzern thus realizes the so-called concentration model in this subject area.

The **procedure involving the so-called coordination model** is relatively unwieldy: In a first step, the coordinating authority has to obtain comprehensive feedback from the authorities issuing the required rulings. This feedback is a decisive criterion for the decision to be made by the coordinating authority. In a second step, the coordinating authority must use the feedback to prepare a coordination proposal. In a third step, the coordination proposal is returned to the authorities making the rulings. In a final step, they have to adapt their respective rulings in line with the coordination proposal in order to achieve an outcome with no contradictions, i.e. as if one authority had issued all the rulings. The outcome of the procedure therefore has to have the same quality as if only one authority had been in charge. In order to achieve such a result, a relatively complicated procedure has to be completed.

The **coordinating authority or leading authority can either be a cantonal or a communal one**. In fact, certain provisions under federal law − such as Art. 6 (1) lit. b of the Forest Act or Art. 12 (2) of the Water Protection Act − explicitly provide for a cantonal authority to take over the coordination required. Otherwise, the relevant leading procedure within the meaning of Art. 25a of the Spatial Planning Act is regulated by cantonal or communal law. Individual cantons such as St. Gallen or Bern have enacted their own cantonal coordination legislation. In accordance with § 34 (2) of the Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz, for example, coordination − at least to the extent that no land-use plan is issued for activities requiring a license − is handled through the building permit procedure; only where such a building permit is not necessary will the coordination be carried out in the context of the licensing procedure.

These principles basically apply whenever the afore-mentioned situations arise, both in the context of **projects requiring an environmental impact assessment and those that do not**, whereby the lading procedure in the case of a project requiring an environmental impact assessment basically corresponds to the relevant procedure within the meaning of **Art. 5 of the Environmental Impact Assessment Ordinance**. If a planning procedure has to be conducted, this is to be considered as the relevant procedure (Art. (3) Environmental Impact Assessment Ordinance).

7.2.2 Liability

The state is liable for damaging actions or omissions in the context of **official activities** regulated by public law if the licensee fulfills **public responsibilities** (cf. for the state, Art. 3 Government Liability Act). On the other hand, liability falls under **private law** to the extent that the licensee fulfills private responsibilities and acts as a subject under private law.

7.2.2.1 State liability

Liability under Swiss public law is structured federally. It is regulated by federal law insofar as damage is caused by persons who have been appointed by the state to hold a public office (Art. (1) Government Liability Act). In all other cases, the provisions of the respective cantonal liability laws apply, which are, inter alia, also valid when officers of the cantons or communes cause damage in the act of enforcing federal law, which they are legally required to do.

In accordance with **Art. 61 (1) of the Swiss Code of Obligations**, **the state and the cantons can set up liability rules under public law** that **deviate from civil law** for (extra-contractual) damage arising in the course of performing public duties. Liability in the case of state activities that do not have official character but are by nature issues of private law or commercial law, is decided according to the rules of private law (Art. 61 (2) Swiss Code of Obligations). Most cantons have taken advantage of the opportunity granted by Art. 61 (1) of the Swiss Code of Obligations to enact standards of responsibility that deviate from federal private law. Only the canton of Appenzell Innerrhoden refers to the Swiss Code of Obligations with regard to the right to compensation.

A **reservation** only comes into play in **state activities with an official character**. In differentiating between “official” and “commercial” activities, it must be considered whether or not **state responsibilities** are being fulfilled. In the administration of services, the term “fficial responsibility” refers, in particular, to the provision of public services, while “commercial responsibility” includes the operation of installations that has not been assigned to the state as an unescapable duty, i.e. where there is a certain discretionary margin. It must be established whether the performance of a responsibility by the state is done in the common interest or whether the state actually has an obligation. Voluntary responsibilities, i.e. activities with a discretionary margin, should probably be considered as commercial in the context of liability law (on the whole issue, Federal Appeals Committee Decision on State Liability of 18 March 2005, in: Administrative Case Law of the Federal Authorities 2005 No. 78 D. 2a/cc). If an officer or employee of a public administration **does not act within the scope of his or her responsibilities** but in a private interest, he or she is considered to act as a private person; in such a case, liability is regulated in accordance with **Art. 41 et seqq. Swiss Code of Obligations** (Federal Supreme Court Decision 130 IV 27 D. 2.3.2).

The **operation of an agricultural institute**, for example, aims to improve the vocational education of farmers and enhance the utilization of the land; it can therefore be assumed to be a **state responsibility**. The fact that an agricultural institute may also be organized under private law does not change this (Federal Supreme Court Decision 128 III 76 D. 1a; cf. for hospitals: Federal Supreme Court Decision 133 III 462 D. 2.1, 122 III 101 D. 2 a). Similarly, activities by or on behalf of **the Swiss Armed Forces** are also considered to be state responsibilities. A service, or official, activity is therefore any activity carried out by citizens called up to do military service for or on behalf of the Swiss Armed Forces. Service activity also includes the military life of service personnel, i.e. eating or sleeping while serving in the Swiss Armed Forces (Federal Administrative Court, A-7385/2006 of 6 July 2007 D. 3.2).

The **supply with electricity** is still understood by most cantons as a service which is the **responsibility of the state** and/or which is provided by the state or by public or private companies on behalf of the state (WEBER/KRATZ, § 8, RN 11 and RN 25 et seqq.). Accordingly, the monopolization of the electricity supply would be admissible. In the opinion of the Swiss Federal Supreme Court, such a communal or cantonal monopoly does not violate superordinate legislation, in particular not Art. 94 (4) of the Federal Constitution. The issue here is that the supply as well as the distribution and consumption are guaranteed in accordance with principles of efficiency; in addition, the focus must be on the development of renewable energy sources and environmental protection. Furthermore, a monopoly also turns out to be appropriate. In an economy with free competition, a monopoly system can safeguard that the objectives set by the cantonal constitution for the benefit of its citizens can actually be implemented. It can do this in a manner that is safe, more efficient, and more cost-effective for consumers than previous permit systems (Federal Supreme Court Decision 132 I 282 D. 3 [= Die Praxis des Bundesgerichts (Basel) 2007 No. 75]).

In the context of electricity supply, the state only has an **obligation to guarantee that the service is provided ("Gewährungsverantwortung"), not the obligation to provide the service itself** ("Erfüllungsverantwortung"). This applies in any case as long as no specific power plant has been awarded a contract to supply specific communes or cantons with electricity (= obligation to provide a service, i.e. assignment to fulfill a public responsibility). If, on the other hand, licenses are awarded to private providers, without the added obligation to provide a service, such third parties do not represent the extended arm of the administration as is typical in the case of state responsibilities being assigned. Instead, licensees act in their own, private interests, on their own behalf, for themselves, and at their own risk. Against this background, any damage caused by the licensee in carrying out his or her licensed activity cannot be attributed to the state (WALDMANN, p. 16). Typically, services rendered by private parties are not compensated by the state − such as is characteristic in the case of fulfilling an obligation to provide a service. Instead, the licensee is allowed to make a profit or a loss and pays taxes.

This interpretation is confirmed in the constitutional order. In accordance with Art. 91 (1) of the Federal Constitution, the state enacts provisions with regard to the transportation and delivery of electrical energy. Such a power to legislate in itself does however not imply that the state has to fulfill a responsibility. In the area of nuclear energy, where Art. 90 of the Federal Constitution gives the state the (unlimited) power to legislate, the construction and operation of nuclear energy is the undisputed domain of private enterprises. On the other hand, the Constitution is clear on cases where the state is given the obligation to provide a service. Art. 63 (1) of the Federal Constitution regulates that it is the responsibility of the state to operate the Swiss federal institutes of technology. Thus, the Constitution provides the basis for an − as yet indefinite − obligation by the state to provide services (cf. also Art.

83 (2) Federal Constitution, according to which the state builds, operates, and maintains national roads). In addition, the Swiss economic constitution is supported by a fundamental regulatory decision in favor of a competition-oriented private economy (cf. Art. 94 Federal Constitution). Due to a lack of a clear transmission of the responsibility to operate energy enterprises to the state − or to another sovereign authority − it is the obligation of the private energy sector to safeguard universal service (cf. WEBER/KRATZ, § 8 RN 212−216; Federal Administrative Court 2013/13 D. 5.4.4).

As a result, the operation of plants for the extraction of energy is in the public interest, which means that a legal monopoly (mining rights) or a de facto monopoly (subsoil and the land-use rights) is used for the purpose; it does not mean the assignment of a state responsibility, however. A private person who utilizes the subsoil to extract energy therefore does not act in a sovereign manner, and neither does he or she have any authority to issue rulings. The legal relationship between the operators of the plant and any third parties is regulated under private law and it is the responsibility of the parties themselves to define the fundamentals of this relationship. The fact that due to legal provisions little room is sometimes left to the parties to specify the details of their legal relationships under private law does not change anything (see also Federal Administrative Court 2013/13 D. 5.5).

For the reasons described above, the cantons therefore usually provide for **liability on the part of the licensee**: In accordance with Art. 25 of the Act on Mining Rights and Subsoil Use/Uri, for example, the licensee, i.e. the operator of the power plant, is liable for any damage caused by the construction and the operations of the plant (also, § 12 Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz).

This also applies in cases where the **licensee is obliged to take on certain obligations that lie in the public interest** (e.g. the obligation to supply a service). If the holder of a license − in addition to his or her basically private commercial activity − has to meet certain obligations that lie in the public interest, said license can be said to be a **public service license** (cf. e.g. Federal Supreme Court Decision 135 II 49 et seqq. [= Die Praxis des Bundesgerichts (Basel) 2009 No. 75]: Connection of a special use license [license to distribute posters on public land] with a duty to provide a "service public" in the form of an additional service at the expense of the licensee [provision of self-hire bicycles]; Federal Supreme Court, 14 Dec. 2012, 2C_401/2010, D. 2.3.3 [Connection of a gas supply contract and a special use license for the utilization of public land for laying gas lines]). Licensees are required to guarantee the public service with which they have been entrusted (a so-called obligation to provide a "service public"). This does however **not constitute the fulfillment of a state responsibility**, even though the licensee also has to safeguard public interests. Accordingly, licensees act on their own behalf and for themselves, and their liability is strictly private. Only if a license were also to be awarded in conjunction with an actual administrative responsibility, could a state liability be said to exist.

7.2.2.2 Extra-contractual liability under private law and the Environment Protection Act

7.2.2.2.1 Land owner's liability in accordance with Art. 679 of the Swiss Civil Code

If private licensees exceed the power given to them under civil law, their liability is basically regulated in accordance with the general principle of objective liability of **Art. 679 of the Swiss Civil Code**. As a land owner, a power company is liable based on Art. 679 of the Swiss

Civil Code for any injury or damage caused to its neighbors as a result of **a breach of ownership rights**, in particular due to excessive emissions. A land owner's liability in accordance with Art. 679 of the Swiss Civil Code constitutes an objective liability, which is a no-fault liability.

A pre-requisite for the applicability of Art. 679 of the Swiss Civil Code is the need for **two separate properties to be involved and for an excessive breach of land use on one property to have an adverse effect on the other**. The issue here is an unlawful breach of ownership rights through positive or negative emissions. Further, land owner's liability in accordance with Art. 679 of the Swiss Civil Code also implies that there is a causal link between the breach of property rights and the damage that occurs.

Liability in accordance with Art. 679 of the Swiss Civil Code can even said to occur if the "land owner" in question has only a limited right in rem, or even only an indirect right (i.e. through a lease), to use a plot of land. Owners with a limited right in rem, or "indirect" owners, are liable in accordance with Art. 679 of the Swiss Civil Code for any behavior by which they breach their rights and cause damage to a neighboring property. This extension of passive legitimization is valid inasmuch as Art. 679 of the Swiss Civil Code focuses on the use of property or rather on its excessive use, and not on the ownership position.

Besides, since the ratification of **Art. 679a of the Swiss Civil Code** unlawfulness is no longer an absolute requirement. Where a land owner temporarily causes excessive and unavoidable disadvantages to a neighbor while managing his or her parcel of land lawfully, in particular by building, and thus causes damage, said neighbor can at least claim damages from the land owner in accordance with Art. 679a of the Swiss Civil Code. Art. 679a of the Swiss Civil Code aims to cover any damage that is unavoidable and therefore acceptable, e.g. during the construction of a building. A neighbor can therefore do nothing to stop related emissions; he or she can merely claim damages. Managing a property is permitted and lawful if a legally binding permit or license has been obtained for a purpose which temporarily causes damage to a neighboring property.

7.2.2.2.2 Liability of the Owner of a Construction in Accordance with Art. 58 of the Swiss Code of Obligations

The operator of a power station is liable as the owner of a construction in accordance with Art. 58 of the Swiss Code of Obligations if damage occurs as a result of faulty construction, erection, or insufficient maintenance. The liability of the owner of a construction in accordance with Art. 58 of the Swiss Code of Obligations is an objective liability that is a no-fault liability. However, the damage must be attributable to a construction defect (within the meaning of a defective installation) or to insufficient maintenance of the construction, which can be difficult to prove.

Whether or not a **construction has a defective design or whether it has been insufficiently maintained** depends on the purpose which it has to fulfill. A construction defect can be said to exist when a plant does not provide sufficient security when it is used according to its purpose (Federal Supreme Court Decision 130 III 736 D. 1.3, 126 III 113 D. 2a/cc, 123 III 306 D. 3b/aa). The basic principle is that a construction should not be put to improper use. Whether or not a construction is free from defects is determined by objective factors and in accordance with what could conceivably occur at the site in question (Federal Supreme Court Decision 122 III 229 D. 5a/bb).

Whenever special measures are indicated to guarantee the necessary level of safety for the erection or maintenance of the constructions, the **criterion of appropriateness** has a special significance. Owners must make all provisions that can reasonably be expected from them, taking into account the probability that an accident could occur as well as the severity of such a potential accident, the technical possibilities, and the cost of the measures that could be employed (Federal Supreme Court Decision 126 III 113 D. 2a/cc). Another barrier in terms of the obligation to provide safety is **personal responsibility**. Owners of constructions are not obliged to prevent every conceivable danger. They may disregard risks that users of the construction or persons involved in the construction could avoid by exercising a minimum of precaution (Federal Supreme Court Decision III 736 D. 1.3).

If the conditions of Art. 58 of the Swiss Code of Obligations and Art. 679 or rather of Art. 679a of the Swiss Civil Code are met, both liabilities are applicable concurrently, whereby the liability under Art. 58 of the Swiss Code of Obligations is detrimental to the extent that the claimant must prove the existence of a construction defect. In applying Art. 679 of the Swiss Civil Code, merely a breach of ownership rights has to be proven.

A liability in accordance with Art. 58 of the Swiss Code of Obligations basically only occurs after the construction has been completed, not while it is being erected. The liability towards third parties during the erection of a construction is in accordance with Art. 41 of the Swiss Code of Obligations or Art. 679 of the Swiss Civil Code.

7.2.2.2.3 Environmental liability in accordance with Art. 59a of the Environment Protection Act

In accordance with Art. 59a of the Environment Protection Act, the owner of an operation or installation that poses a risk to the environment is liable for any damage caused by exposure to any actual risk. Art. 59a of the Environment Protection Act contains an increased causal liability. This applies in cases where an installation constitutes a particular environmental risk. In this context, such a particular risk may be the employment of a drilling or simulation procedure with a residual risk of tremors (cf. TRÜEB/WYSS, p. 10 et seq.). This generally applies irrespective of whether in an individual case an earthquake caused by a drilling procedure has only an insignificant impact on the environment. In accordance with Art. 59a of the Environment Protection Act, the liability includes all damage by environment-relevant exposure (TRÜEB/WYSS, p. 11).

7.2.3 Summary

In general, the **legal situation in the cantons** is favorable for more intensive exploitation of geothermal resources. In each individual procedure, it should therefore be established whether or not the necessary requirements are met and whether or not a license can be awarded for the utilization of the deep subsoil.

The **current legal situation in the cantons is however somewhat confusing and unsatisfactory**: Individual cantons have enacted some regulations, either based on the “Bergregal” (mining rights), or on their sovereignty over the deep subsoil. Some cantons, such as Basel-Stadt, Appenzell Innerrhoden, or Graubünden have no relevant regulations at all. Others have created a constitutional foundation, although in some instances, such as in the canton of Thurgau, there is no executive legislation. Some cantons have integrated the utilization of the subsoil into their Introductory Act to the Swiss Civil Code (Basel-Stadt, Appenzell Ausserrhoden, Nidwalden, Zug, and Schaffhausen). This frequently does however regulate subsoil use only rudimentarily. Yet another group of cantons have created mining legislation, however without explicitly amending their mining rights by regulating the aspect of the utilization of the subsoil. In some cases, the original laws were written in the 19th century. Individual cantons have adapted their laws to the new circumstances (Bern, Aargau, Uri, Schwyz, and Luzern). These cantons regulate subsoil use, in some cases in great detail.

The **utilization of the subsoil** is generally **subject to the same rules that apply to the use of a public object**. Permanent subsoil use to the exclusion of third parties, e.g. by a geothermal power station, constitutes special use or the use of a monopoly (mining rights), which in most cantons is subject to a license. This license grants the holder the exclusive right to utilize the area of the subsoil specified in the license. Accordingly, the cantons that have regulated the utilization of the deep subsoil require that this utilization is subject to a license (§ 7 Act on the Utilization of the Subsoil and the Extraction of Natural Resources/Aargau, Art. 6 (1) Act on Mining Rights and Subsoil Use/Uri, § 7 Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz, § 4 Abs. 2 Act on the Extraction of Natural Resources and Subsoil Use/Luzern). By obtaining a license, the private person moves into an ownership-type position. A vested right is given a foundation whose substance must not be infringed – at least not without compensation.

For **preparatory and exploratory measures** such as exploratory drilling, a mere permit usually suffices. Such a permit does not give the holder the right to expect to be granted a license. In the canton of Bern, the revised Act on Mineral Regalia provides for someone who is already in possession of an exploitation permit to be given precedence in cases where there is more than one applicant (Art. 15 (2) Act on Mineral Regalia/Bern; also § 10 Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz as well as § 7 (2) lit. b Model Law).

Licenses are usually not awarded by public tender; According to Federal Supreme Court practice, **Art. 2 (7) of the Internal Market Act** is designed for constellations where the public bodies themselves wish to award monopolies. In the present constellation, a private person acts in his or her own interest and by his or her own initiative, which means that according to not undisputed Federal Supreme Court practice there is no need for a public tender. In the canton of Luzern, the competent department can, in accordance with § 5 (1) Act on the Extraction of Natural Resources and Subsoil Use/Luzern, issue a public call for tender if the utilization of the subsoil is in the overriding public interest. In deciding between different parties interested in a special use license, the competent authority must observe the general principles of the rule of law. A special procedure is usually not required.

A **geothermal plant** is generally subject to a **number of different permits**. To avoid decisions with contradictory content, the cantons have to designate an authority in accordance with Art. 25a (1) Spatial Planning Act which ensures sufficient coordination (Art. 25a (1) Spatial Planning Act: coordination model). The coordinating authority issues the necessary procedural instructions, arranges for public disclosure of the application documentation, and collects comprehensive feedback on the project from all cantonal and federal authorities involved; it ensures that contents are coordinated and that rulings are issued jointly and simultaneously (Art. 25a (2) Spatial Planning Act). Rulings must not contain any contradictions (Art. 25a (3) Spatial Planning Act). What is not necessary, at least not according to federal law (cf. Art. 25a Spatial Planning Act), is for the cantons to designate an authority to issue decisions which contain all permits or licenses. Some cantons have realized such a concentration principle voluntarily.

Overall, it can be said that with regard to the utilization of the subsoil the legal situation as it exists today is unsatisfactory for several reasons: **First,** many cantons lack provisions that set out how and in what form the subsoil should be utilized. It is difficult for the potential operator of a geothermal power station to predict which legal obstacles might possibly stand in the way of a future project. **Second,** cantons requiring a permit for exploratory drilling and similar projects do not provide for a conditional entitlement to a license. Potential operators of power stations need more investment security. They need to be able to know in advance whether or not they will be awarded a license. Only a few cantons provide for such an entitlement. **Third,** it has not yet been sufficiently clarified if the cantons need to issue their licenses by public tender in order to enable different persons to be able to apply for them, and how such procedures should be handled in cases where an exploration or exploitation permit has already been granted. **Fourth**, although the individual public interests existing are taken into account by means of a multitude of permits and in some cases − depending on the size of an installation − in the form of an environmental impact assessment, federal law merely requires the cantons to follow the so-called coordination model, according to which individual permits must be coordinated in terms of content to prevent contradictions. However, individual permits can be issued by different authorities. This is inconvenient for the potential operator of a power station and does not really help to expedite procedures.

7.3 Outlook on 2050 Energy Strategy

On 4 September 2013, the Federal Council of Switzerland issued its message on a first package of measures for the 2050 Energy Strategy. The **cantons** − with the support of the federal state (cf. in particular Art. 12 Draft Energy Act) – are required to create a new **concept for the development of renewable energy sources** (Art. 11 (1) Draft Energy Act; Message 2050 Energy Strategy, p. 7662 et seq.). In these concepts, the cantons are to designate areas which are generally suitable for the exploitation of renewable energy sources (Art. 11 (2) Draft Energy Act). The concept constitutes a type of planning and includes − in addition to an explanatory report − a map depicting suitable areas; these can be outlined and do not have to be assigned to exact land parcels (Message 2050 Energy Strategy, p. 7662 et seq.). This planning may also include the possibility of excluding certain areas from utilization by renewable energy sources (so-called negative planning; cf. Message 2050 Energy Strategy, p. 7662). In accordance with Art. 11 (3) lit. a of the Draft of the Energy Act, the concept should already take into account conflicting concerns, in particular protection concerns. Further, Art. 11 (5) of the Draft of the Energy Act requires cantons to submit their concept to the Federal Council of Switzerland for approval.

The concept is binding on the federal state and the cantons to the extent that in fulfilling their spatial responsibilities it must be taken into consideration in all areas (Art. 11 (6) Draft Energy Act; Message 2050 Energy Strategy, p. 7663). In particular, the concept enables the cantons to transfer the areas suitable for utilization to their structure plan (Art. 13 (1) Draft Energy Act); the federal state, for its part, will consider the concept in approving these structure plans (Art. 13 (3) Draft Energy Act).

The cantons are obliged to reserve certain areas in their structure plans (Art.13 (1) Draft Energy Act; Message 2050 Energy Strategy, p. 7664). Only this will ensure that plans are set out that are binding on the communal and cantonal authorities (Message 2050 Energy Strategy, p. 7664). The cantons can decide to vary their structure plan from their concept. They ensure that the cantonal and communal authorities create the land-use plans based on the structure plan, which is binding on the authorities, or that they adapt existing land-use plans, if necessary.

Further, in accordance with Art. 16 (1) of the Draft of the Energy Act the cantons have to provide for speedy approval procedures for the construction of installations for the exploitation of renewable energy sources. In the case of individual permits that are the responsibility of the state, of if the state has to provide feedback, an administrative unit at state level must be designated to coordinate the processes (Art. 16 (3) Draft Energy Act; Message 2050 Energy Strategy, p. 7667). This leading authority will act as the contact person for cantonal and communal authorities (exception: expert opinions of the committees under the Nature and Cultural Heritage Act; the committees are contacted by the cantonal permit authorities in accordance with Art.16 (2) of the Draft Energy Act).

7.4 Recommendations

Federal Powers: Autonomous federal powers to regulate the utilization of the subsoil to exploit deep geothermal resources – in line with those in place for nuclear energy – would allow the creation of a single a permit under federal law (the so-called "planning approval") to replace, or incorporate, all other permits. From a political perspective, it does however seem rather unlikely that such an authority will be created. In addition, there are different types of subsoil use, which would make it difficult to separate the utilization of the subsoil to exploit geothermal resources from other forms of utilization.

The **cantons** are therefore authorized to issue **regulations concerning subsoil use**. In general, such regulations should contain the following provisions: responsibility, type of use, expropriation, exploitation permit, procedure, human and material resources, liability, coordination with other permits, charges, enforcement, and legal protection. In particular, the following aspects would have to be regulated: conditional entitlement to being granted a license for holders of an exploitation permit; a public invitation to tender for the exploitation permit, if necessary also for the actual license, as well as the establishment of procedural principles and award criteria; introduction of the concentration principle for installations for the production of geothermal energy and respective expropriation rights to be awarded along with the license.

The spatial planning laws of the federal state are generally the suitable vehicle in which to enshrine the policies and fundamental principles of subsoil law. Basically, the well-established instruments of spatial planning can easily be adapted to include the subsoil. In doing so, the federal state sets out superordinate objectives and policies in the Spatial Planning Act and, jointly with the cantons, issues measures for the implementation of these objectives. The main **cantonal instrument** for this purpose is the **cantonal structure plan**, already provided for under Art. 6 et seqq. of the Spatial Planning Act. A cantonal structure plan has to indicate the land areas that are suitable for geothermal exploitation (see Art. 6 et seqq. Spatial Planning Act). In addition, the federal state may make recommendations concerning subsoil planning, which are however not legally binding on the cantons. In addition to spatial planning regulations, the **creation of an inventory** of existing and prospective subsoil use is an important instrument of subsoil planning. In their structure plans, the cantons can also create inventories of areas where the deep subsoil is already utilized today or might be utilized in the foreseeable future.

Exemption of Cantonal Land Use and Protected Areas: In the context of its "2050 Energy Policy", the Federal Council of Switzerland has proposed that the cantons should issue plans for the use and protection of their land which would have to be ratified by the Federal Council (Art. 13 Draft Federal Energy Act). Such plans would create more transparency and enable future investors to see which land areas are actually available for the exploitation of renewable resources; among other things, the plan would help to expedite procedures (cf. LEHMANN, p. 804). Based on cantonal structure planning, cantonal and communal authorities have to update their land-use plans. Where the communes are in charge of land-use planning in the respective areas − as designated by the cantons − the implementation of plans can be affected by delays. The cantons must retain the power to instruct their communes to produce land-use plans for the respective areas (Lehmann, p. 804).

National Structure Plan/Sectorial Plan: The Bourgeois Motion of 15 June 2011 asked for the federal state to review whether it would be in accordance with federal law to issue a national structure plan listing locations suitable for deep geothermal exploitation. The Federal Council of Switzerland gave the following answer (Opinion of 7 September 2011): In accordance with Art. 75 of the Federal Constitution, spatial planning lies within the competence of the cantons. The structure plan as a spatial planning measure is therefore an instrument of the cantons, not of the federal state. The Spatial Planning Act does not provide for a federal structure plan; such a plan would actually not be in line with the Spatial Planning Act. The spatial planning tool of the federal state is the sectorial plan. The creation of a sectorial plan is however only provided for in areas in which the federal state itself is spatially active, i.e. where it fulfills federal state responsibilities which have a spatial impact. The construction of geothermal plants does not belong to the responsibilities of the federal state, even though the federal state enacts policies and objectives with regard to the supply of energy (cf. Art. 89 Federal Constitution) and provides funding to cover construction costs by means of so-called supply payments ("Einspeisevergütungen"). The federal state merely has an obligation to guarantee the supply of energy, not the obligation to provide it. The cantons are however required to confirm their structure plans with neighboring cantons (Art. 6 (4) Spatial Planning Act), which ensures regional coordination, at least. Even where a project has a substantive justification, it is therefore the cantons which are in charge of structural planning and of including information on suitable geothermal sites in their structure plans.

Structural/Land-Use Planning vs. Art. 24 of the Spatial Planning Act: The mandate of a conscious allocation of areas to a specific zone based on democratic principles must not be undermined by the fact that geothermal plants, which are usually planned for sites that are not part of an official construction zone, are approved by means of an exemption. If a project that is not compliant with zoning requirements would have a significant impact on existing land-use planning due to its volume or its nature, which is usually the case for geothermal plants, the respective land-use plan first has to be amended. Based on the updated plan, a building permit in accordance with Art. 22 of the Spatial Planning Act may be awarded, provided the respective requirements have been met.

Award of Licenses and Exploration Permits by Public Tender: According to the Federal Domestic Market Act, a transfer of the exploitation of a cantonal monopoly must be awarded by public tender. Although the Swiss Federal Supreme Court has considerably amended Art. 2 (7) of the Internal Market Act, this principle must be upheld. With regard to the procedure to be employed, the existing regulations applying to public tendering procedures might be adapted for this purpose. The utilization of the subsoil frequently requires detailed investigation on the part of the applicant. Depending on a canton's legal situation, such preliminary investigations are subject to a permit. Since the actual license is usually awarded to the person who has already carried out the necessary preliminary exploration, permits to conduct preliminary exploration should also be published in the official gazette with an announcement that any parties that are also interested in the same area can also submit an application. In this context, it is conceivable that several applicants could be granted a preliminary investigation permit. It is also conceivable for the area in question to be divided into lots in order to utilize the area to the full extent and provide an additional opportunity for competition.

Expediting Approval Procedures in General: Especially with regard to the use of alternative energy sources, measures to expedite approval procedures seem to be essential. Procedures can, for example, be expedited by introducing processing deadlines. However, it must also be remembered that geothermal plants use complex, highly technological processes with a certain risk potential. This requires thorough balancing of interests, which somewhat limits the extent to which the procedure can be expedited. Furthermore, justifiably rigorous environmental protection and spatial planning requirements must be met. It must also be kept in mind that the procedures are not an end unto themselves but generally suitable instruments that serve the public interest. Nevertheless, the Federal Council could pass recommendations to expedite approval procedures in the whole of Switzerland.

Expediting Approval Procedures in Particular: The construction of large installations is frequently subject to multiple permits which need to meet a range of different requirements. Since plants with the purpose to extract geothermal energy from the subsoil also have a considerable (spatial) impact on the surface, it is important to create a legal framework for planning them. In addition to a land-use plan, such projects also have to be included in the structure plan. Next, the building permit is issued on the basis of the land-use plan; The licensing procedure is carried out either simultaneously or subsequently: Such a project has to be subjected to licensing, planning, and building procedures which must comply with different legal requirements and protect the interests of different stakeholders, requiring a complex, intensive process of weighing different interests against each other. This necessarily makes these procedures time-consuming (LEHMANN, p. 801). One way to expedite procedures would be to combine planning permission and licensing procedures and grant the building permit at the same time as the license. Preferably, this should be handled by one authority in line with the concentration model. On the other hand, the federal state cannot impose additional regulations on the cantons − beyond Art. 25a of the Spatial Planning Act. It is therefore up to the political will of each individual canton to create the legal framework for streamlining and expediting procedures.

Federal Act on the Coordination of Approval Procedures for Renewable Energy Projects (Grunder Motion): The Grunder Motion proposes to coordinate and streamline procedures required in the context of renewable energy sources at the communal, cantonal, and perhaps also federal level and to introduce an approval authority (see Grunder Motion of 17

June 2011). However, with Art. 25a of the Spatial Planning Act the federal state has required the cantons merely to introduce the so-called coordination model. If the cantons were also to be asked to introduce the concentration model, Art. 25a of the Spatial Planning Act would have to be amended accordingly. In the case of most installations for the exploitation of renewable energy, the federal state has no wide-reaching authority, which is why issues concerning procedures and/or competence fall within the regulatory jurisdiction of the cantons. The federal state does not have the power to impose a single federal authority on the cantons to approve all applications. At most, it could amend Art. 25a of the Spatial Planning Act to include the need to use the concentration model, which would require the cantons to provide for only one authority to issue permits and licenses.

Introducing the Concentration Model: According to such a model, the decision to grant a license also includes all permits and rulings by other authorities. This solution is effective and convenient. After all, in processing a license application many issues regularly need to be addressed that also affect other permits. In accordance with § 11 (2) of the Act on the Extraction of Natural Resources and Subsoil Use/Luzern, for instance, the licensing decision made by the Cantonal Council also has to incorporate all other permits and rulings by communal and cantonal authorities − such as the building permit (Message Act on the Extraction of Natural Resources and Subsoil Use/Luzern, p. 11). Such a model serves to expedite procedures and facilitates communication with those to whom a ruling is addressed. It should however be kept in mind that even with the concentration model, other authorities are still entitled to comment in the context of reporting procedures.

General Land-Use License: An interesting instrument to expedite procedures and ensure investment security is used by the canton of Schwyz: Whenever a cantonal or communal land-use plan is to be issued, a decision regarding a general land-use license must be made at the same time (§ 34 (1) Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz). This general land-use license must regulate important aspects at the preliminary stage (§ 35 (1) Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz). This general land-use license could also include a permit for exploratory measures or preliminary investigations for which an additional permit is currently necessary in the canton of Schwyz. In awarding the actual license, the competent authority is bound by the content of the general land-use license, provided the circumstances have not changed (§ 35 (2) Ordinance to the Federal Act on Mineral Regalia and Subsoil Use/Schwyz).

7.5 Literature, Legislation, Materials

7.5.1 Literature

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7.5.2 Legislation

7.5.2.1 The Swiss Federal State

Bundesverfassung der Schweizerischen Eidgenossenschaft (BV) vom 18. April 1999, SR 101.

Bundesgesetz über den Binnenmarkt (Binnenmarktgesetz, BGBM) vom 6. Oktober 1995, SR 943.02.

Energiegesetz (EnG) vom 26. Juni 1998, SR 730.0.

Fernmeldegesetz (FMG) vom 30. April 1997, SR 784.10.

Bundesgesetz über den Schutz der Gewässer (Gewässerschutzgesetz, GSchG) vom 24. Januar 1991, SR 814.20.

Gewässerschutzverordnung (GSchV) vom 28. Oktober 1998, SR 814.201.

Bundesgesetz über den Natur- und Heimatschutz (NHG) vom 1. Juli 1966, SR 451.

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Bundesgesetz über die Raumplanung (Raumplanungsgesetz, RPG) vom 22. Juni 1979, SR 700.

Raumplanungsverordnung (RPV) vom 28. Juni 2000, SR 700.1.

Bundesgesetz über den Umweltschutz (Umweltschutzgesetz, USG) vom 7. Oktober 1983, SR 814.01.

Verordnung über die Umweltverträglichkeitsprüfung (UVPV) vom 19. Oktober 1988, SR 814.011.

Bundesgesetz über die Verantwortlichkeit des Bundes sowie seiner Behördenmitglieder und Beamten (Verantwortlichkeitsgesetz, VG) vom 14. März 1958, SR 170.32.

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7.5.2.2 Cantons

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Gesetz über die Nutzung des tiefen Untergrunds und die Gewinnung von Bodenschätzen (GNB/AG) vom 19. Juni 2012, SAR 671.200.

(2) Appenzell Ausserhoden

Verfassung des Kantons Appenzell A.Rh. (KV/AR) vom 30. April 1995, bGS 111.1.

Gesetz über die Einführung des Schweizerischen Zivilgesetzbuches (EG ZGB/AR) vom 27. April 1969, bGS 211.1.

(3) Appenzell Innerhoden

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(4) Basel-Landschaft

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(5) Basel-Stadt

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(6) Bern

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(7) Freiburg

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(8) Genf

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(10) Graubünden

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(13) Neuenburg

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(14) Nidwalden

Verfassung des Kantons Nidwalden (KV/NW) vom 10. Oktober 1965, NG 111.

Gesetz über die Einführung des Schweizerischen Zivilgesetzbuches (Einführungsgesetz zum Zivilgesetzbuch, EG ZGB/NW) vom 24. April 1988, NG 211.1.

Gesetz über die Gewinnung mineralischer Rohstoffe (Bergregalgesetz) vom 29. April 1979, NG 852.1.

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(15) Obwalden

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(16) Schaffhausen

Gesetz über die Einführung des Schweizerischen Zivilgesetzbuches (EG ZGB/SH) vom 27. Juni 1911, SHR 210.100.

Wasserwirtschaftsgesetz vom 18. Mai 1998, SHR 721.100.

(17) Schwyz

Einführungsgesetz zum schweizerischen Zivilgesetzbuch (EG ZGB/SZ) vom 14. September 1978, SRSZ 210.100.

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(18) Solothurn

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(19) St. Gallen

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(20) Tessin

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(21) Thurgau

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(22) Uri

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(25) Zug

Gesetz betreffend die Einführung des Schweizerischen Zivilgesetzbuches für den Kanton Zug (EG ZGB/ZG) vom 17. August 1911, BGS 211.1.

(26) Zürich

Einführungsgesetz zum Schweizerischen Zivilgesetzbuch (EG ZGB/ZH) vom 2. April 1911 (LS 230).

7.5.3 Materials

7.5.3.1 The Swiss Federal State

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Botschaft zu einem Bundesgesetz über Walderhaltung und Schutz von Naturereignissen (Waldgesetz, WaG) vom 29. Juni 1988, BBl 1988 173 ff. (zit. Botschaft Waldgesetz).

Botschaft zum Energiegesetz vom 21. August 1996, BBl 1996 1005 ff. (zit. Botschaft Energiegesetz).

Botschaft zum ersten Massnahmenpaket der Energiestrategie 2050 vom 4. September 2013, BBl 2013, S. 7561 ff. (zit. Botschaft Energiestrategie 2050).

7.5.3.2 Cantons

Botschaft des Regierungsrates des Kantons Luzern an den Kantonsrat zum Entwurf eines Gesetzes über die Gewinnung von Bodenschätzen und die Nutzung des Untergrundes vom 18. Dezember 2012, B 60 (zit. Botschaft LU).

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Vortrag des Regierungsrates des Kantons Bern an den Grossen Rat zum kantonalen Energiegesetz vom 1. Juli 2009.

Vortrag des Regierungsrates des Kantons Bern an den Grossen Rat betreffend das Bergregalgesetz (BRG, Totalrevision des Bergwerkgesetzes) vom 22. Januar 2003 (zit. Botschaft BRG/BE).

7.5.3.3 Miscellaneous

Bundesamt für Raumentwicklung ARE, Weshalb sich die Raumplanung um den Untergrund kümmern muss, Bericht der Arbeitsgruppe «Raumplanung im Untergrund», April 2011 (zit. Bericht der Arbeitsgruppe).

Die Nutzung des geologischen Untergrunds in der Schweiz, Empfehlungen des Schweizer Geologenverbands CHGEOL zur Harmonisierung von Verfügungshoheit, Sachherrschaft und Nutzungsvorschriften vom Februar 2013 (zit. Empfehlungen Geologenverband)

8 WP7: Public Opinion

WP7 investigated the attitudes and positions towards geothermal energy of the Swiss stakeholders and citizens in a broader social context.

The analysis was carried out in close cooperation with Michael Stauffacher, Corinne Moser and Nora Muggli (ETHZ) who had analysed the public debate in Swiss public media. Working closely together, with the aim to integrate our approaches and look for common interpretations, we thoroughly and gradually exchanged ideas, concepts and intermediate results.

8.1 Focus Groups

Christina Benighaus (DIALOGIK and University of Stuttgart), Ludger Benighaus (DIALOGIK), Ortwin Renn (DIALOGIK and University of Stuttgart)

A focus group is a qualitative research method where participants representing specific interests are encouraged to provide information and opinions on a specific topic in a discussion round (Henseling *et al*., 2006; Kruger and Chasey, 2008, Schulz *et al*., 2012).

Focus groups respond to a stimulus, develop specific arguments around this stimulus and reflect their validity and applicability. Questions are asked in an interactive group setting where participants are free to talk and exchange information with other group members (Benighaus and Benighaus, 2012). The interaction and discussion in the focus groups help to illustrate perceptions of and attitudes towards geothermal energy.

Focus groups, just by the small number of people involved, cannot be representative for the whole population of a canton or Switzerland. But they give valuable and broad indications of the patterns of attitudes, opinions and reactions to a given topic that is expected to come up.

Focus groups – contrary to representative surveys – often give the opportunity for a deeper understanding of the public and provide impulses for further research.

In this project it was intended to conduct four focus groups. The goal was to get a reasonable impression of the public opinion in Switzerland. We tried to consider the administrative situation of Switzerland and invited stakeholders and citizens from different cantons. Over the course of this project we have discussed the concept of the focus groups with the advisory board set up for this project and experts from the ETH.

As a result of the brainstorming process we considered it suitable for the project to compare the arguments before and after the installation of geothermal energy production in communities in Switzerland. Therefore we tried to include at least one community, which was at the time in the phase of planning or installing deep geothermal energy, and one, which had attempted to or had already installed geothermal energy.

This analysis has helped to understand the argumentation and especially the factors, which underlie the participants' risk perception. Based on this analysis we are now better prepared to derive ideas of how we can communicate with the people and thus involve them in the planning process in a more productive way. For instance, we invited either the head or the deputy of each community, project partners, authorities or chairpersons of citizen groups, NGOs, and other individuals who were interested to speak for their communities and/or on behalf of the citizens.

8.1.1 Catalogues of questions

The following central questions served as a guideline in each community's focus group(s):

Topic 1: Renewable energy and geothermal energy

- How do you describe geothermal energy in the context of energy transition (Energiewende)?
- What do you think about the idea that geothermal energy will be part of the renewable energy mixture in Switzerland?
- How do you evaluate geothermal energy in comparison to other renewable energy sources?

Topic 2: Benefits, challenges and risks

- What are the arguments to develop and install deep geothermal energy, what speaks against geothermal energy?
- What kind of benefits do you associate with this form of energy?
- Which kinds of risks do you see?

Topic 3: Deep geothermal energy in your community

The focus groups took place in local communities in which geothermal energy plants are planned, under construction or operating. The questions were modified and adapted according to the specific prerequisites of each community.

What are the needs of a community when planning, installing deep geothermal energy in a community?

Table 40 summarizes the programme of the focus groups with the three different input phases and the focus group's final discussion.

Table 40: *Programme of the focus groups.*

	0.30	**–**	**0.00**	**Welcome & Coffee**
1	**0.00**	**–**	**0.20**	**Round of introduction, details of the project** *Moderation: Uni Stuttgart/Dialogik*
2	**0.20**	**–**	**0.30**	**Heating and Power in Switzerland** *Warm-up und discussions*
3	**0.30**	**–**	**1.00**	**Input 1: Renewable energy and deep geothermal energy** *Perspectives of the participants of the energy mix in Switzerland*
4	**1.00**	**–**	**1.30**	**Input 2: Challenges, benefits and risks** *Working with different case studies from Switzerland, Germany*

	1.30	**–**	**1.45**	**Coffee break**
5	**1.45**	**–**	**2.30**	**Input 3: Deep Geothermal Energy in *(Name of the community)*** *Particular needs of the communities in the phase of planning, drilling or installation/production*
6	**2.30**	**–**	**3.00**	**Recommendation for the Canton** *Concluding discussion*
	3.00			**End of the focus group**

(Note: the time slots can vary while conducting a focus group, but the overall duration of 3 hours is fixed)

8.1.2 Catalogue of input material

During the focus group sessions the facilitators exposed the participants to information, communication materials and questionnaires to which the group was asked to respond. This discussion informed us about the level of knowledge and − in addition to that − showed the usability and effectiveness of different information materials.

Warm-up for Topic "Heating and Power in Switzerland"

To ensure a smooth and quick start of the session the facilitator asked the participants to give a brief introduction, state their name and profession or affiliation and to answer the warm-up question "What comes to your mind when you hear the words "geothermal energy" or "geothermal power"?"

In order to get a quick impression of what the participants associate with the energy mix in Switzerland and what they wish for in the future with respect to deep geothermal power the facilitators showed and explained the actual energy mix in Switzerland. Then they handed out an empty pie chart with the working question "Consumption of energy 2030, what do you think? How should this look?" All participants were asked to individually fill out this chart.

Video and Questionnaire for "Input 1: Renewable energy and deep geothermal energy"

We had produced a short video of around 13 minutes in total, which we screened during the first phase in order to introduce deep geothermal energy to the group, whose task was to later evaluate the information displayed in the videos. The interview partners were:

- **Prof. Dr. Stefan Wiemer,** ETH Zurich, Director of the Swiss Seismological Service and Professor of Seismology (SED)
- **Prof. Dr. Ernst Huenges,** GFZ German Research Centre for Geosciences Potsdam, Head of Section Reservoir Technologies and the International Centre for Geothermal Research

Both experts had agreed to participate and to be interviewed. The videos were recorded in mid-November 2013. We had approached Prof. Wiemer and Prof. Huenges because they are both experts in deep geothermal energy and seismic events and had also been working in this area for many years. In addition, both researchers had gathered broad expertise in various countries, including Switzerland and Germany. They are affiliated with independent institutes and involved in a huge number of projects concerning geothermal energy.

In the interview the two experts discussed the following questions:

- Why is geothermal energy important?
- How do you define Deep Geothermal Power? How would you describe it in a few words?
- What is the status quo of Deep Geothermal Power today?
- Advantages – which are the positive aspects from your perspective? And the disadvantages?
- Please explain the risk of earthquakes relating to drilling and running a power plant. What does the science say?
- How will deep geothermal power and the technology develop by 2020 and beyond?

After the participants had watched the video of Prof. Huenges and Prof. Wiemer they completed a questionnaire.

Case studies for Input 2: Challenges, Benefits and Risks

Concerning the material for input 2, the participants were asked to comment on case studies from different regions − e.g. St. Gallen, Riehen (near Basel), Basel and Unterhaching (Germany). The knowledge and background experience varied from group to group, so that not all case studies were handed out to all focus groups.

Questionnaires based on the media analysis (served as material for Input 3)

The results from WP5 “Risk Perception” including the content media analysis served as additional material. We used material that explained the different arguments and in particular the four mental frames titled: “Energy Transition”, “Risk”, “Technology” and “Costs”. We asked the participants to evaluate the pro and con arguments and frames in the focus groups. In addition, we elicited additional concerns.

Closing Question

To terminate the session, the facilitators asked the closing question: “Concerning Geothermal power − what do you recommend that the government or the people in charge at the cantonal level should do?” The final answers to this question then provided further insights to what the participants expected from the official institutions and the decision makers.

For each focus group up to 15 people were invited and the group sessions lasted around 150 to 180 minutes. The discussions were recorded and systematically analyzed.

8.1.3 The selection process of communities

In autumn 2013 we started asking public officials in charge of selecting communities and companies with the support of Dr. Gunter Siddiqi, Chairman of the Project Advisory Board of the TA-SWISS project. Our first impression was that many communities had second thoughts about their initial drilling plans in their community and were not sure how to react sensibly to the St. Gallen incident in July 2013. Most of them had gone through extensive and continuous internal discussions about risks and how they should proceed. It was often articulated that it was better to wait to see what will happen in St. Gallen before making final decisions. In this phase of uncertainty and ambiguity most of the communities wanted to wait and have no external discussion about their community's geothermal energy plan before the end of winter 2013, or even as late as the end of spring 2014.

In the end we found four communities that agreed to participate in the project and supported the conduct of a total of five focus groups (compare **Table 41**):

Table 41: *Communities and regions in which focus groups were conducted.*

Number	Community	Canton/City	Status production geothermal energy	Focus group and participants
1	Sursee-Mittelland	Luzern	Plan for 2017	1 focus groups in 1/2014, 12 participants Mostly decision makers and members from working groups involved in regional development, partly citizens
2	Sursee-Mittelland	Luzern	Plan for 2017	1 focus groups in 1/2014, 14 participants Some decision makers and mostly members from working groups involved in regional development, partly citizens
3	Riehen	Basel-Stadt	Installed 1989	1 focus group in 2/2014, 12 participants Citizens from Riehen interested in energy issues
4	Tiefencastel	Graubünden	No plans	1 focus group in 2/2014, 9 participants Members of a working group involved in energy
5	Neuchâtel	Neuchâtel (French)	Plans in the wider canton	1 focus group in 3/2014, 9 participants Young researchers, PhD-candidates and master students, all qualified in geology and hydrology
		4 different regions	All phases covered	5 focus groups with 56 participants

The first community was from the region of Sursee-Mittelland where the project on geothermal energy project is in a very early stage. Installation is planned to begin in 2017. At this location two focus groups were conducted in January 2014, the first one with 12 and the second one with 14 participants.

The second participating community was the city of Riehen where a hydrothermal energy plant has already been installed (see Section 3.4.2) and used since 1989. This facility has been producing geothermal heat since 1994. The community participated with one focus group in the project in February 2014 and 12 participants joined the group.

Third, a focus group in Tiefencastel was organized in March 2014. Tiefencastel is a community where there are no concrete plans for harvesting deep geothermal energy in the next years. Here we interviewed 9 persons from Tiefencastel and some other communities nearby.

Fourth, an additional focus group was conducted in the city of Neuchâtel in the French-speaking region of Switzerland where deep geothermal energy is planned in the wider realm of the canton within the next years. There we were in contact with Dr. François-David Vuataz of the University of Neuchâtel. He introduced us to a member of the students' associations of the University's institute. Young researchers, PhD-candidates and Masters students, all qualified in geology and hydrology, participated in our investigation. Here, we conducted the focus group in English and provided the inputs, case studies and questionnaires in English, and to a lesser extent in French. The facilitator showed the video of the two experts, and translated the most important messages into English. All questionnaires were formulated in English, and the participants were asked to complete them either in English, German or French. In spite of the language variation, the results of this focus group can be compared to the results of the other German speaking focus groups.

In summary, we found one community without geothermal plans, one in the early planning phase and another one with an already installed plant that produces geothermal energy in Switzerland. Furthermore we were able to get some insights from a city with a French-speaking population.

We covered a broad range of arguments and gathered information about the main issues from different cantons, based on five focus groups with 56 persons in total.

8.1.4 Results of focus groups

Focus groups stimulate expressions of opinions and attitudes from a limited number of persons involved and interested in a specific topic under consideration, here the technical issue of geothermal energy. It should be mentioned that the results are not representative: They are not suitable to reflect the opinion or attitude of the whole community, canton or the whole population of Switzerland.

However, focus groups reveal thoughts, opinions and even emotions that often trigger decisions and behaviour, and readers learn more what is "behind the scenes". The main advantage of focus groups is that they stimulate intense debate among the participants and provide evidence for the strength of arguments and positions that survive such a debate.

We illustrate the broad spectrum of comments and opinion with selected citations from all five focus groups here.

Citation Focus Group Neuchâtel

« Toutes les notions sont intéressantes, les prix, les séismes, la durée de la mise en place de ce genre de progresse. Cela montre bien toutes les chemins qu'il reste à faire. »

"All these concepts are interesting, the costs, earthquakes, the duration of the implementation of this kind of progress. This shows all the work that remains to be done."

« L'énergie produit localement réduit la dépendance énergétique de l'étranger. »

"Locally produced energy will reduce our energetic dependence on foreign countries."

« La technologie a un grand potentiel et peut couvrir toute l'énergie du monde complètement renouvèle. Mais il ya les risques de pollution et des séismes. »

"This technology has a great potential and could cover the whole world's energy consumption. But there are risks of pollution and earthquakes."

Citation Focus Groups 1 and 2 in Sursee

«Pioniere braucht es für neue Technologien.»

"Pioneers are needed for new technologies."

«Unerschöpflich ja, die Herausforderung ist, diese gefahrlos zu nutzen.»

"Yes, inexhaustible, the challenge is to use this without risk."

Citation Focus Groups Riehen

«Pionierrolle hat Riehen, aber zu wenig erkannt.»

"Riehen holds the pioneering role, but it remains hardly known."

«Standort Glücksfrage.»

"Location is a matter of luck."

Citation Focus Group Tiefencastel

«Die genauen Auswirkungen auf das Erdbebenverhalten sind ungenügend bekannt.»

"The exact effects on earthquake incidents are inadequately known."

«Es braucht jedoch schon mehr Forschung, damit die Risiken sinken.»

"More research is needed so that risks decrease."

Renewable energy and geothermal energy

The first exercise focused on the viewpoint of the participants about the energy mix in Switzerland and their opinion on what should be changed in the future. The facilitator showed a simple pie chart on the actual energy mix in Switzerland, and explained the different energy sources briefly. The participants were told that energy from renewable sources covers roughly 20%, and that this is nearly the same as in Germany. The facilitator noted that even energy experts' opinions vary significantly on how the share of the renewable energies will develop. There is no doubt that Switzerland will produce energy in form of an energy mix but how the composition will change in the future is contested.

The groups' participants were asked to fill out an empty pie chart, entitled with the question: "How should the energy mix look like in 2030? What do you think?"

The responses showed a broad acceptance of all sources of renewable energy. **Figure 133** shows that in all focus groups renewable energy should make up a high percentage, starting at more than 60 % in the first focus group in Sursee-Mittelland, up to 90% in Riehen, which consisted of citizens with an interest in energy. Please note that the participants were asked to state their opinion, not what they think is realistic in the future.

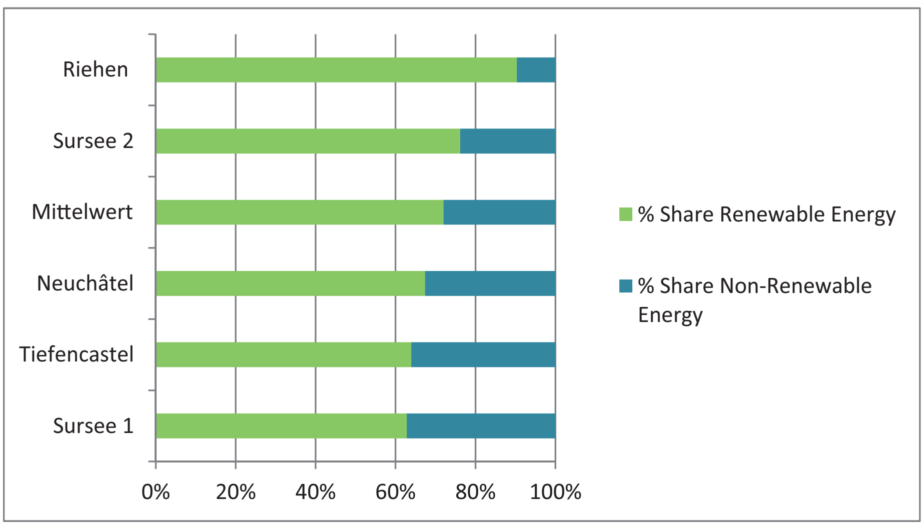


Figure 133: *Responses of all participants (5 focus groups, N = 56) to the question: How should the energy mix look in 2030?*

The material was then analyzed with a focus on the attitude towards geothermal energy. The working question was: "What share of total energy production should geothermal power have in the future?"

A further differentiation between the different types of geothermal technology were not pursued since many respondents had little or no knowledge about the various types of geothermal energy production and would probably provide mere guesses. Many participants accepted the idea that geothermal power should play a role in the future energy mix in Switzerland, but only to a small percentage of 4.4 % of total energy production on average.

The highest acceptance was expressed by the second focus group in Sursee-Mittelland (nearly 13 %), the lowest in Neuchâtel with nearly 2% (**Figure 134**).

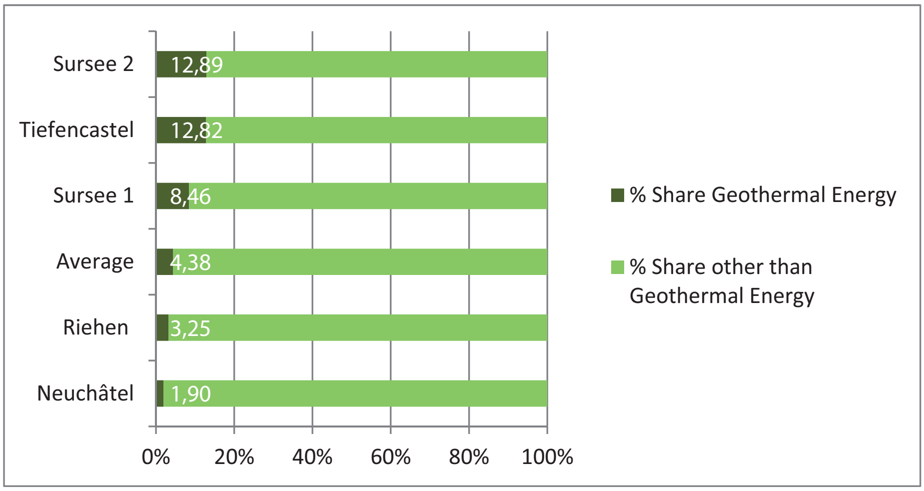


Figure 134: *Share of geothermal energy among all renewable energies in 2030 in Switzerland, according to participants' answers in five focus groups (N=56).*

Summing up, geothermal power benefits from a slightly positive attitude in general.

Benefits, Challenges and Risks

This part was based on selected results of the media analysis mostly carried out by ETH. The main objective was to investigate whether participants share arguments – pro and contra – with newspaper reports or not.

As described in Section 6.4.2 ETHZ analyzed 200 newspaper articles from the NZZ and Tages-Anzeiger, which were published in the last couple of years, and which covered the topic of deep geothermal power. Here the researchers counted the number of arguments (pro and con), and grouped them in different classes. DIALOGIK then developed a questionnaire, and asked all participants to state their degree of agreement with several pre-formulated statements. First, the participants rated six arguments in favour of deep geothermal power that the journalists often raised. Secondly, the participants were confronted with seven contra arguments also derived from the media analysis. All arguments were accompanied by a direct quote from one the newspaper articles.

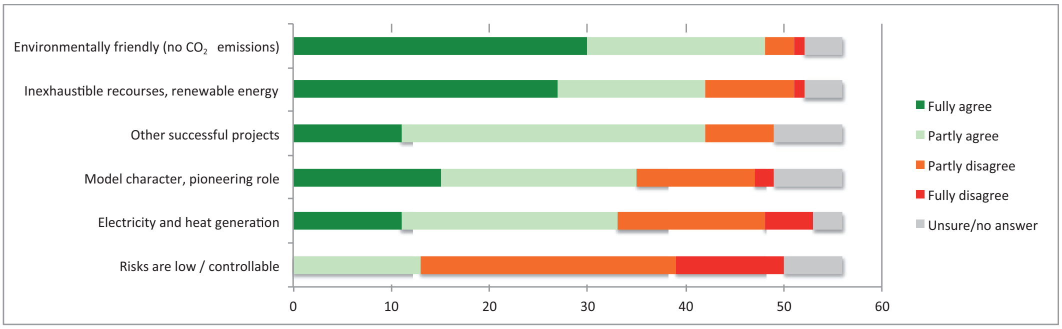


Figure 135: *Agreement on various pro arguments for deep geothermal energy, according to participants' answers in five focus groups (N=56).*

Very high agreement was found for two arguments "Environmentally friendly and no CO_2 emissions" and "Inexhaustible resources and renewable energy". The statement "Risks are low/can be controlled" is not shared by the majority of the participants. 37 of the participants out of the 50 partly disagree or fully disagree (**Figure 135**).

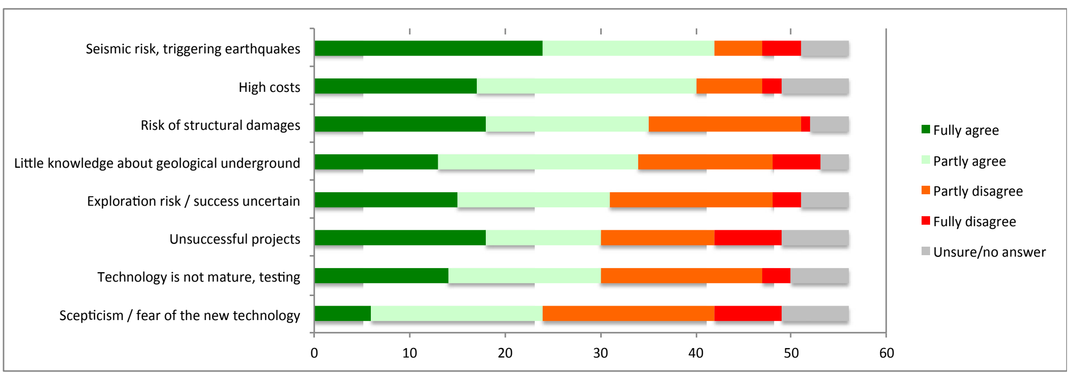


Figure 136: *Agreement on various contra arguments against deep geothermal energy, according to participants' answers in five focus groups (N=56).*

Looking at the contra arguments, most of the participants agree with the seven counter-arguments. The highest share of agreement concerns the risk of seismic incidents and earthquakes triggered by deep geothermal energy. Here, 42 out of 51 participants fully agree or partly agree. The majority of the participants (40 out of 49 participants) perceive high costs as a negative aspect, and they are concerned about the risk of structural damages (35 out of 52, **Figure 136**).

In conclusion, the opinion spectrum shows that geothermal energy is clearly associated with both risks and benefits. Most people are aware that trade-offs are necessary to find a viable solution that navigates between benefits and risks. It is interesting to note, following the insights of many perception studies, that the idea that people tend to resolve cognitive conflicts by either downplaying the risks or the benefits is not true for our focus groups members. Both risk and benefits received high ratings. These people are aware of the conflicts between having benefits and risks at the same time.

Frames of deep geothermal power according to specific topics

Similar to the reflection of pro and contra arguments, the questionnaire also contained questions about frames of presenting geothermal energy. As an introduction, the facilitator explained that, based on the findings of the ETH media studies, deep geothermal energy has been framed in terms of four overarching themes, each of them linked with specific pro and contra arguments.

- Energy Transition
- Risks
- Technology
- Costs and expenses

We included these four frames in the questionnaire accompanied by one contra argument and one pro argument for each frame. The participants were asked to state their opinion on each frame and report their agreement with the pro and con argument. They were also given the opportunity to add comments.

Looking roughly over the results of the answers, a clear cluster becomes visible, as summarized here:

- A significant shift took place towards the pro arguments, specifically with respect to “Contribution to energy transition” and “Technology”, followed by “Risks are under control”.

- However, a high proportion of participants preferred the middle range, specifically with respect to “Costs and expenses”, but also the others. We assume that these participants did not yet make up their opinion, and that some balance the positive and negative sides as well as the result of the evaluation of the pro and con arguments outside of the frames.

Aspect 1: Contribution of deep geothermal power to energy transition

Topic Energy Transition (48 answers)						
Contra:	-2	-1	0	1	2	Pro:
Deep geothermal energy is not a realistic option for the upcoming energy transition, there are more promising alternatives.	6	1	9	19	13	Deep geothermal energy is the way to go in the upcoming energy transition and to substitute for nuclear power.

Figure 137: *Topic Energy Transition, agreement or disagreement on various issues to deep geothermal energy, according to participants’ answers in five focus groups, number of answers (N=56).*

Written comments and suggestions, taken from the questionnaire:

- Bis diese Technologie reif ist, muss die Energiewende geschafft sein
  Until this technology is mature, the Energy Transition must be mastered successfully
- Die Geothermie kann an der EW teilnehmen, kann aber niemals die Nuklearenergie ersetzen
  Geothermal energy can participate in the Energy Transition, but can never replace nuclear energy
- Es bestehen wirklich gute Chancen, mit dieser Technologie bestehende Technologien abzulösen
  There really is a good chance to replace existing technologies with this technology
- Nur Geothermie wird meiner Meinung nach als Ersatz nicht ausreichen
  In my opinion geothermal energy alone will not suffice as a substitute
- Ist ein Teil der Energiewende, jedoch nicht „die" Wende / nur auf eine Technologie zu setzen, ist langfristig ungünstig; was ist, wenn diese wegfällt oder aufgegeben werden muss?
  It is a part of the Energy Transition, but not "the" Energy Transition itself / to fully rely on only one technology is unfavourable in the long-term − what if it fails or must be discarded?
- Man sollte darüber nachdenken, wie man den Energiemix anders zusammensetzt, so dass Kernenergie nicht mehr gebraucht wird
  One should think about how to make up the energy mix differently, so that nuclear energy is no longer neccessary
- Es kann zwar Atomenergie nicht ersetzen, aber es kann daran teilhaben, Nuklearenergie zu ersetzen
  Although it cannot replace nuclear energy, it can replace part of it
- Die vielen positiven Aspekte der Geothermie können nicht negiert werden (Bandbreite, CO_2-neutral, unendlich, s. ökologisch)
  The many positive aspects of geothermal energy cannot be negated (bandwidth, CO_2-neutral, sustainable, see ecological)
- Noch zu jung, zu wenig erprobt
  Too young, too little tested

Aspect 2: Risk and Deep Geothermal Power

Topic Risk (48 answers)						
Contra: Deep geothermal energy is too risky.	-2	-1	0	1	2	Pro: The associated risks with deep geothermal energy are under control.
	3	11	10	19	5	

Figure 138: *Topic Risk, agreement or disagreement on various issues to deep geothermal energy, according to participants' answers in five focus groups, number of answers (N=56).*

Written comments and suggestions, taken from the questionnaire:

- Es gibt viele Risiken, z.T. kennt man diese noch nicht
  There are many risks, partly they are not yet known
- Haben sich unsere Vorfahren diese Frage bei Ölbohrungen gestellt?
  Did our ancestors ask these questions when they began drilling for oil?
- Risiko ist gering, aber nicht vollständig unter Kontrolle
  The risk is low, but not fully controllable
- In Anbetracht des Risikos atomarer Energie ist dieses Risiko völlig akzeptabel!
  Considering the risks of nuclear energy this risk is fully acceptable!
- Es gibt immer Risiken – Kernenergie ist wesentlich schlimmer. Für einige Länder ist ein Erdbeben Stärke 3,4 lachhaft!
  There are always risks – nuclear energy is much worse. For many countries a earthquake on the scale of 3.4 is ridiculous.

Deep Geothermal Power and Technology

Topic Technology (48 answers)						
Contra: The technology of deep geothermal energy has handicaps and is unsuccessful	-2	-1	0	1	2	Pro: The technology of deep geothermal energy has benefits and is successful.
	2	3	11	23	9	

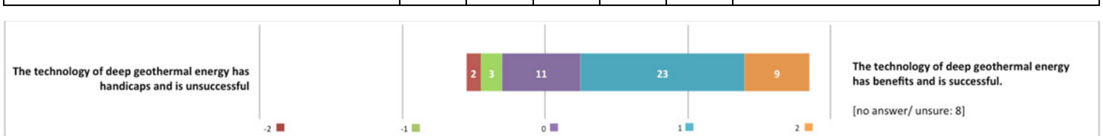


Figure 139: *Topic Technology, agreement or disagreement on various issues to deep geothermal energy, according to participants' answers in five focus groups, number of answers (N=56).*

Written comments and suggestions, taken from the questionnaire:

- Vieles unklar, Erfolg erst langfristig
  Many things are uncertain, the success will only be visible in the long run
- Die Technologie ist noch in der Anfangsphase
  The technology is still in the beginning phase
- Über Erfolge wird nicht berichtet, nur Unfälle werden erwähnt
  There is no media coverage of successes, only about accidents
- Es könnte erfolgreicher sein, benötigt aber mehr Forschung und Entwicklung
  It could be more successful, however more research and development are neccessary

Deep Geothermal Energy and Costs

Topic Expenses (47 answers)						
Contra: Deep geothermal energy is too expensive.	-2	-1	0	1	2	Pro: Deep geothermal energy is economic.
	4	9	19	12	3	

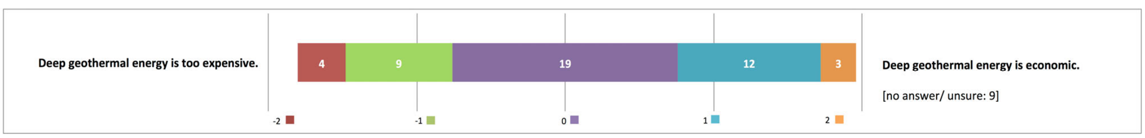


Figure 140: *Topic Expenses, agreement or disagreement on various issues to deep geothermal energy, according to participants' answers in five focus groups, number of answers (N=56).*

Written comments and suggestions, taken from the questionnaire:

- Braucht 30 Jahre mehr
  Needs thirty more years
- Schwer abschätzbar
  Hard to estimate
- Informationen fehlen
  Information is lacking
- Ich weiß nicht, wie diese Technologie im Vergleich zu anderen Energiegewinnungs-technologien dasteht
  I don't know how this technology performs in comparison to other energy technologies
- Tiefengeothermie kostet viel, wird sich aber lohnen, sie ist gut für die Umwelt
  Geothermal energy is expensive but this will pay off, it is environmentally friendly

8.1.5 Conclusions focus groups and recommendations

The last section includes some recommendations that are drawn from the insights of the five focus group study in Sursee-Mittelland, Riehen, Tiefencastel and Neuchâtel, and the results of the media analysis, including social media.

Conclusions

- While the changes of the energy transition in Switzerland and the shift to a bigger share of renewable energy are generally welcomed, the attitudes towards deep geothermal power vary from "full rejection" to "full acceptance". No clear pattern of acceptance or rejection emerges from the data.
- The participants see a potential that geothermal power might contribute to the present and future energy mix, but its share is expected to be relatively low compared to hydro, solar or wind.
- A majority of the participants associate positive aspects with deep geothermal power. Positive associations include "endless energy from the ground", "chance that geothermal power could contribute to the renewable energies", and "low impact on environment".
- However, the participants of the focus groups raised many critical issues, for example "financial risks if the water temperature in the deep is too low for sufficient production of heat and power", "technical and environmental risks that first need to be researched", and "potential damages to houses and infrastructure".
- In line with the results of the media analysis, the participants were well aware of the incidents of St. Gallen and Basel, and were concerned about the financial and technical risks including seismic incidents.

Policy recommendations

- For geothermal energy to be accepted a neutral to quite positive attitude by citizens and stakeholders is beneficial. The citizens should at least tolerate these activities and acknowledge that geothermal energy could play a part in the future energy portfolio of Switzerland. Such a tolerance is dependent on four conditions:
    - *Acknowledgment of the necessity of the contribution of geothermal energy to the overall energy mix:* This cognitive aspect includes the insight that the proposed geothermal facilities are going to deliver the service in terms of the envisioned contribution to the energy mix and that the concomitant risks can be managed by the societal institutions.
    - *Benefit to oneself, to others for whom one cares and/or the common good:* Residents need to be convinced that the proposed geothermal installations will have a benefit either for themselves or for others for whom they care. If the common good is invoked it needs to be articulated in form of concrete advantages to those who will need the additional energy source. Abstract promises such as: "it will improve the competitiveness of the country" are insufficient to serve this objective.

  - *Assurance of self-efficacy:* People tend to reject changes in their environment if they believe that their personal range of options or their personal freedom is negatively affected. Loss of sovereignty or the perception of being dominated by others, are powerful threats to self-efficacy. In the case of geothermal energy this criterion is probably met when it comes to planning a geothermal power project.
  - *Emotional identification:* Changes in one's environment always include interventions into one's livelihood. If these changes are seen as something alien in people's neighbourhoods they are likely to be rejected. A good example is the ownership. If the geothermal installations are owned by a distant company, people often feel that they do not fit into the landscape in which they live. However, if the people in the community own the facilities themselves, they feel that these installations seem to match the community's self-image.

- As a means to meet these four conditions for tolerance, improved communication and public participation programs are essential from an early stage of the project. Communication and participation do not guarantee the success and acceptance of the project but they make it more likely that the planning process will be successful, in particular if the concerns of the various constituencies are acknowledged and included in the respective policies. Public participation should be implemented in a transparent process with open outcome; if there are no options available the authorities and the proposer of the project should engage in a convincing communication program. Participation is a viable option only if there are several alternatives from which the participants can make their choice.
- In some cases, the acceptance might decrease with more public participation: people are then better informed also about risks and problems, and they might see them as more substantial than the benefits. It is also possible that people start to believe that other alternatives constitute better options for the society and for themselves. Such a learning process towards rejection needs to be respected. Yet it is equally possible that participants will learn more about the benefits and potential merits of this technology. In contrast to controversies such as nuclear energy, the study here clearly shows that people do not polarize in their opinions and give credit to both risks and benefits. This provides an excellent starting position to help people making rational and value-based tradeoffs between risks and benefits.
- A clear, easy to understand, and well-balanced information campaign including a state-of-the-art assessment of benefits and risks with respect to deep geothermal power is essential for gaining trust and public support. This should especially cover the policy choices and developments in the energy sector, information about risks of earthquakes triggered by stimulation and daily operations, a clear assessment of financial benefits and estimation of the consequences if a project fails.

Recommendations for further research and research questions

- There is still much to learn about the underlying factors affecting acceptance of geothermal energy. Future research may produce more insights about the main components of tolerating and accepting a project of deep geothermal energy.

- There is a need for the Swiss government to combine the political and strategic planning process with public participation in different cantons and communities. Research is needed to investigate the concerns of the various stakeholders and public groups and to design appropriate communication and participation strategies.
- The design and process of communication programs about geothermal energy production are still not well developed. Research is necessary to test different designs and to compose communication guidelines that promise to be effective, efficient, responsive and fair.
- Furthermore, there is a need for legal scholarship to propose improved legislation for integrating strategic energy planning with regional and local participation.

8.2 Social web analysis

Christina Benighaus, Ortwin Renn (DIALOGIK and University of Stuttgart)*, Aleksandar Jovanovic (University of Stuttgart)*

Ideally the patterns revealed by focus groups should be transferred into a quantitative survey of the Swiss population. Such a survey would reveal the distribution of these images in the population. However, such surveys are rather expensive and are also methodologically problematic since the topic is not well known to the respondents.

Another option to gain more insight about the attitudes of Swiss citizens and stakeholders is to perform an automatic web search on the topic of geothermal energy in various social media platforms (Ebersbach *et al*., 2010). The social web analysis can reveal the main issues and arguments that dominate the debate among the Internet community and can shed some more light on the content of social web sites such as internet, forums, discussion communities, e.g. the quantitative results can serve as an indicator on the distribution of arguments and positions in the population. Yet they are less reliable than systematic surveys. For example, a small number of users of social media can influence the results by providing a high number of contributions.

Within the constraints of the budget, however, this instrument of measuring public preferences provides sufficiently valid and reliable results for determining the main trends in argumentation and positioning of the Swiss population.

8.2.1 Twitter social network

In April 2013 we decided to analyse the service of Twitter as one of the most popular social networking media. “In February 2011, Twitter had more than 20 million visitors a day and was thus the fourth most popular social media service in the world,” (statista 2011). In Twitter one can post up to 140 characters, which can be followed by comments by other people immediately. It is often used to “post private and social stories and trending topics,” (statista 2011). In summary, Twitter is a “news and social network medium” that can help researchers to detect popular or breaking news. Therefore it is an instrument for identifying upcoming trends, critical issues and risks in the technological sector by measuring the frequency of topics.

In Switzerland 8.2% of the Internet users use Twitter (compare **Figure 141**), which is not as much as in other European countries such as Spain, Turkey or Great Britain. If we assume that in 2011 around 77.5% of the Swiss people above 14 years use the Internet regularly (Bundesamt für Statistik 2013), then we can calculate around 5.2 million Swiss Internet users and around 426’000 Swiss Twitter users[38]. No scientific or official data are available about who is using Twitter in Switzerland, but Google Ad Planner (Alike 2012)[39] says that the typical person using Twitter in Switzerland is male (76%), older than 35 years old (58%) and often employed in the business sector. But especially in Switzerland a lot of the Twitter users are companies and organizations.

[38] We assume that 2011 we had around 6.75 million people over 14 years old in Switzerland.

[39] Google Ad Planner is only an instrument to estimate rough data by extrapolating it.

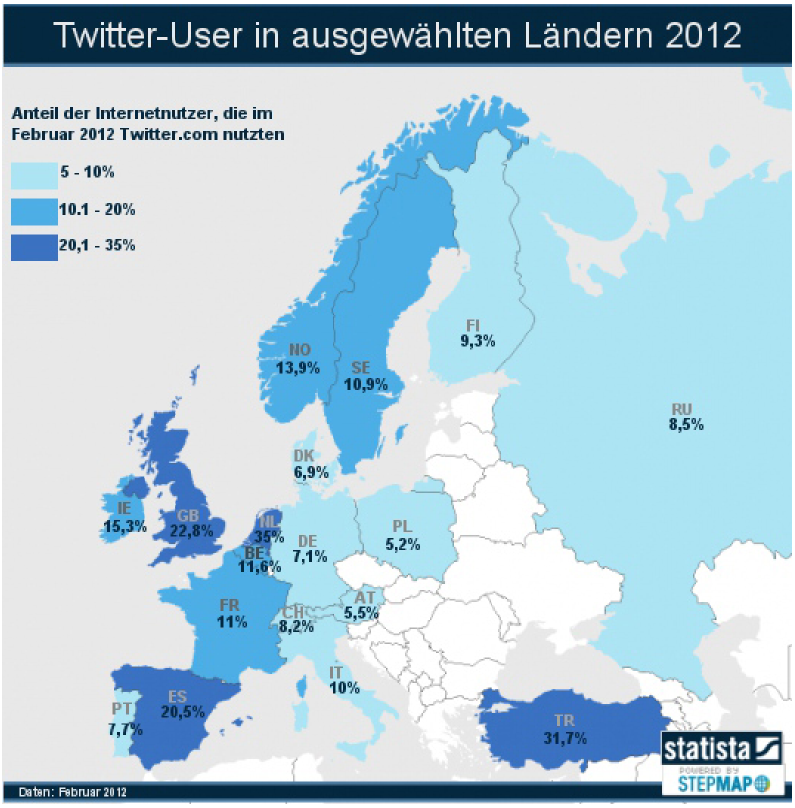


Figure 141: *Twitter use in selected countries 2012 (Source: Statista (2012) http://www.statista.com/statistics/223177/twitter-reach-in-selected-countries/ und www.stepmap.de Landkarten-Editor).*

A typical screenshot of Twitter.com is shown below (**Figure 142**) from November 2, 2013 with the topic: "St. Gallen will use both gas and hot water." News is shared not only by writing characters, but also by posting links from important websites. In this example the links from Spiegel Online and Ad-hoc-News are posted and shared with followers.

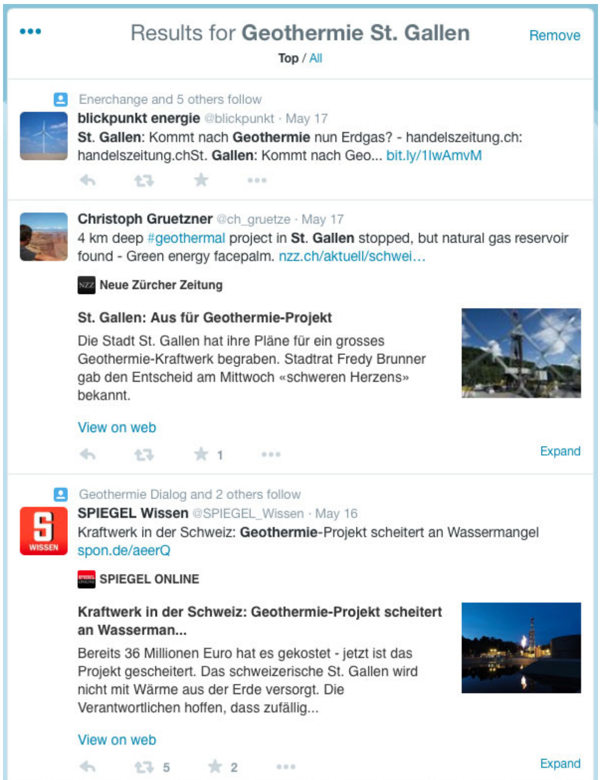


Figure 142: *Screenshot of Twitter.com from October 27, 2014, on the topic "geothermal energy in St. Gallen."*

8.2.2 Counting Tweets with RiskRadar

In April 2013 we began quantitative counting of Twitter tags on the web using the data processing tool included in the RiskRadar from the project iNTeg-Risk[40] (compare Jovanovic and Renn 2012, Jovanovic *et al*. 2012). RiskRadar is a software programme that analyses data from three different sources:

- Expert knowledge (RiskEars)
- Social media streams (RiskTweet)
- Google search volume

We only used the module RiskTweet, which analyses the social media stream from Twitter.

8.2.3 RiskTweet

Since April 2013 each day RiskTweet counts the number of tweets in Twitter with the different keywords "Erdwärme or Geothermie", and compares this number to the average volume over a larger period of time. These are the same keywords that are analysed in the

[40] iNTeg-Risk (Early Recognition, Monitoring, and Integrated Management of Emerging, New Technology related Risks) is a EU financed project of the FP7 call, www.integrisk.eu-vri.eu (access March 2014)

content media analysis by WP 5 (see Section 6.4.2) so that we can compare the results from newspapers and new media. We faced many technical challenges in the beginning with analysing and counting the entries. The software tools first counted all tweets from all languages. But we are only interested in counting entries in the German language in Twitter.

Another problem occurred mid of June 2013 when Twitter relaunched its tool with new functions and changed its system. Therefore we missed consistent data from mid-June until mid-August until the relaunching was finalized. So in the end we got mostly European data from April to mid-June 2013 and from mid-August 2013 until March 2014 data from the German speaking tweets containing tweets from Germany, Switzerland, the Netherlands, Belgium, Finland, Great Britain and France. The reason is that the other languages such as Dutch or French have nearly the same spelling of the keyword “Geothermie,” so that the analysis counts French and Dutch entries too. From this bundle we were, however, able to separate the Swiss tweets in the last working step by countries.

8.2.4 Traffic in Twitter, monitoring the risk activity

The software tool RiskTweet measures the traffic for single keywords. Each day the tool RiskTweet counts the number of Tweets with the keywords “Erdwärme or Geothermie” and compares this number to the average volume over a longer period of time so we can assess peaks of tweeting activities dealing with geothermal energy and geothermal power.

Table 42: *Monitoring the risks activity in Twitter.*

activity	-1	tweeting is low at all time
	0	tweeting is at the average volume
	+1	tweeting is high at all time

If we have low traffic all the time we will get a negative value under 0, tweeting in the average volume would result in values around 0 and tweeting with high traffic produces positive values (compare **Table 42**). The results of the last year show that the activity is with -0.1 on a low activity level for the whole observation period for the German-speaking language areas of Germany and Switzerland. If we look at the daily volume over a longer time period from mid-August 2013 to March 2014 we can on average count 2 to 7 tweets per day in the German speaking areas of Europe (**Figure 143**).

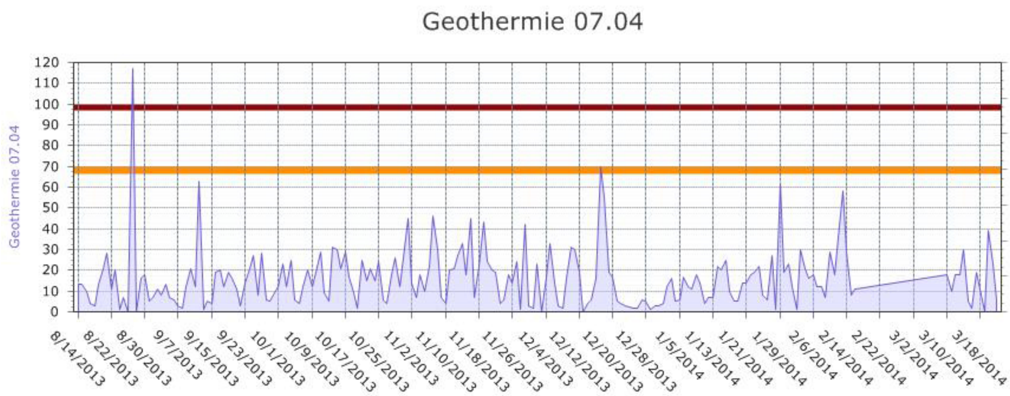


Figure 143: *Daily volume of tweets over a longer time period from mid-August 2013 until March 2014 in Twitter with the Keyword "Erdwärme und Geothermie." The red line is the Alarm-Level and the orange Line the Alert-Level.*

This means we have around 20 to 50 tweets a month dealing with geothermal energy in the European countries with the keywords. These frequencies are clearly below an "Alert-Level" and "Alarm-Level." The program calculates and displays whether the topic gets more popular as part of an intensive discussion in the social web. If we look at the breakdown of countries, we can say that we have less than one-eighth of the entries from Switzerland (**Figure 144**). That accounts to 4−6 tweets per month.

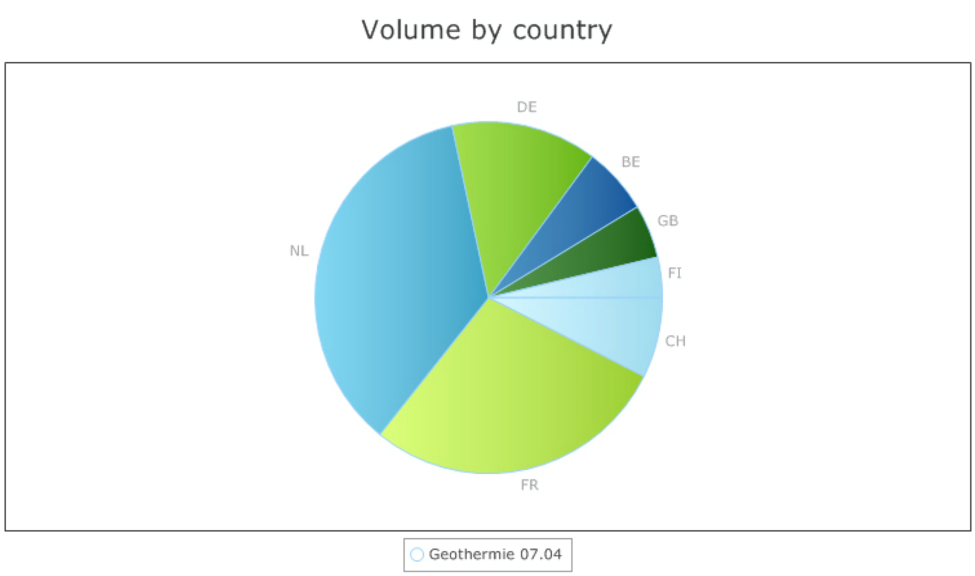


Figure 144: *Tweets counted in Twitter with the keywords "Erdwärme und Geothermie", separated according to European countries (period 7. April till end of March 2014).*

In summary we have a low traffic of tweets in Switzerland and Germany, a little bit more in French- and Dutch-speaking countries. Only a small community using social media is talking about geothermal energy in these countries and it is not a popular topic in the social media at the moment. The same situation holds true for all of Europe.

These values are lower than the corresponding numbers derived from the analysis of the printed and online media of the newspapers (see Section 6.4.2) where we were able to retrieve around 10 articles per newspaper dealing with geothermal energy per month in the last years in Switzerland and Germany. Twitter is less influenced by local events than the newspapers at the present time. We assume that the lack of international or trans-regional attention is the reason for the low level of activities in Twitter about this subject.

8.2.5 Positive and negative sentiments towards geothermal energy

The software tool allows analysis of retrieved texts about positive and negative sentiments to show a positive or negative association with the issues at hand. Therefore the retrieved text passages were broken down into single words and the most frequent words (for example "the", "a", "is"…) are removed. The lists of keywords are then compared with a lexicographic compilation of terms and phrases that allow an automatic diagnosis of positive and negative sentiments.

Figure 145 shows the tracking of sentiments during the last year. From April 2013 until March 2014 "Geothermie" is often considered in a neutral way. They vary between moderately positive and moderately negative sentiments. If we look at the second period from August 2013 to the present time we can see a moderately positive tendency with a few spikes of highly sceptical statements. Thus most twitters demonstrate positive and neutral sentiments with the issue. We found an overall moderately positive attitude about geothermal energy at the moment in Switzerland as part of the German speaking countries.

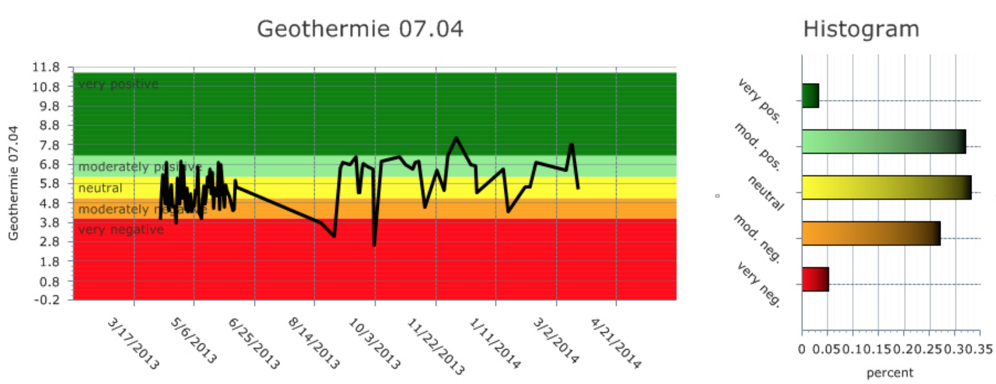


***Figure 145:** Sentiments of the issue "Geothermie" and "Erdwärme" from April to November 2013 in twitter.com.*

8.2.6 Criticality

The software tool also measures if the issue is currently undergoing major shifts or changes in behaviour, which is called criticality. An issue is high ranked in criticality if it has high traffic (volume) at the moment of measuring and shows an increasing trend of traffic. The closeness to the red cluster, centre of the radar, shows the criticality of an issue (**Figure 146**). The green clusters contain no critical issues at the moment. If the issues are located closer to the centre in the red and orange area, the issue is often posted in the social media with a tendency to trigger more activity. The topic of geothermal energy has low traffic and no increasing trend and therefore we find the issue in the green/yellow outer cluster of the radar in November 2, 2013 (**Figure 146**, left) and in the green cluster of the radar in March 2014 (**Figure 146**, right). That means that trend is weak and decreasing with smaller activities.

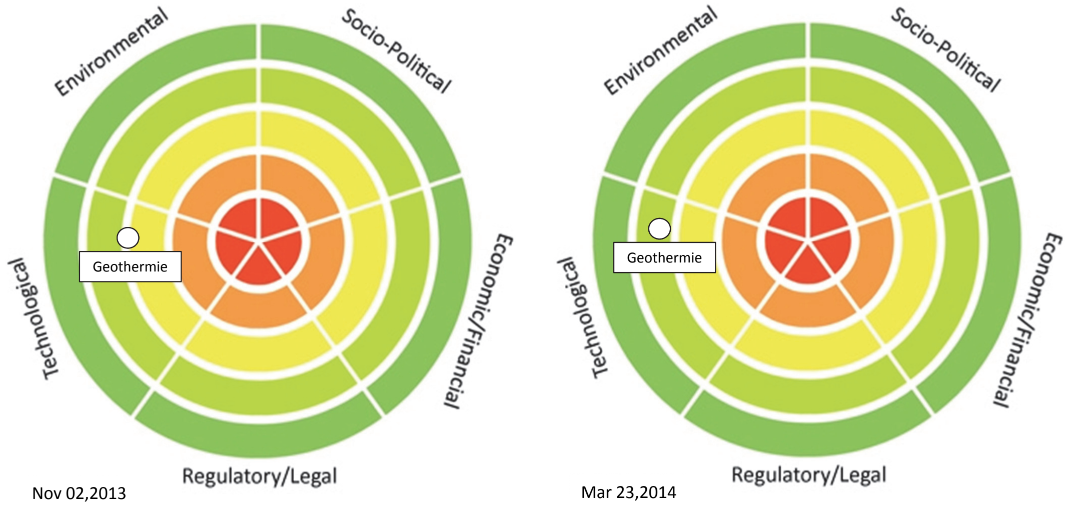
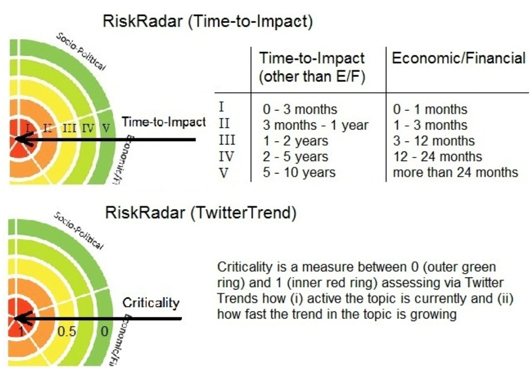


***Figure 146:** RiskRadar (Criticality) in November 2013 (on the left side) and March 2014 (on the right side).*

Legend of the RiskRadar



	Time-to-Impact (other than E/F)	Economic/Financial
I	0 - 3 months	0 - 1 months
II	3 months - 1 year	1 - 3 months
III	1 - 2 years	3 - 12 months
IV	2 - 5 years	12 - 24 months
V	5 - 10 years	more than 24 months

If we look at the feature “Time-to-Impact” in the RiskRadar, i.e. the time span of how long it would take for geothermal energy to become a hot topic in the social media, we can see that the topic was still in the orange area in March 2014 (**Figure 147**, right) meaning that it would take considerable time before it might become a “hot” topic given the normal accumulation patterns of hot issues in the past. If we would expect the issue to explode soon, we would see typical patterns for increasing traffic. This would be indicated by a location in the red cluster.

In summary, geothermal energy is located in the orange cluster, which implies that the issue has the potential to be amplified in the future but, at this time, it is still a sleepy candidate. It would probably take a time period of several months before a full-fledged controversy would arise. Whether geothermal energy will become a critical issue in the social media will depend on whether the local initiatives to get national attention and/or local incidents such as earthquakes receive national or even international press coverage.

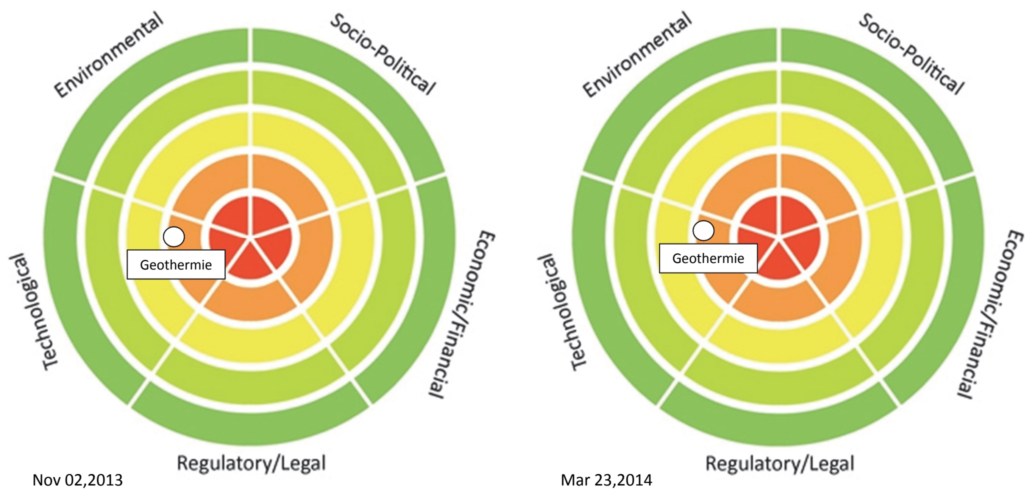


Figure 147: *RiskRadar (Time-to-Impact) in November 2013 (on the left side) and March 2014 (on the right side).*

8.2.7 Conclusions

The social media analysis provides us with insight on how often and with what basic sentiment the Swiss public communicates about geothermal energy in the social media. We are able to evaluate the Twitter tweets in a quantitative way and to interpret its frequency.

Twitter is a very popular social networking media used in Switzerland by around half a million people. The Swiss population accepts Twitter as one of the leading social media, but usage is much lower compared to other European countries such as The Netherlands, UK or Spain.

The topic of geothermal energy is rarely mentioned in the tweets when compared to the content media analysis, which revealed a frequency of up to 30 articles per month in peak time and 10 on the average in Switzerland. In Twitter we counted only up to 4−6 tweets per month. The topic of geothermal energy has produced only low traffic and no trend for an increased activity could be identified. The low traffic indicates that geothermal energy is not a popular topic in the social media at the moment. Furthermore it seems that local concerns are not often aired on Twitter and there is little national or trans-regional discussion on this topic. This is different from the print media that were highly interested in the local situation and local events such as those in Triemli or St. Gallen.

The trend towards low activity is persistent over time and there is no indication that this activity level is going to increase soon. Apparently geothermal energy is not a hot issue at present time in the social media in Switzerland.

The retrieval of text sentiments reveals that the Swiss people in the social media share a predominantly positive or neutral sentiment on geothermal energy with a few outliers. Compared to the newspaper articles, we witnessed more neutral and positive sentiments on the issue in Switzerland.

Summing up, geothermal energy is not perceived as a critical issue in the social media and most of time the entries contain expressions that can be considered as moderately positive or/and neutral sentiments. It will depend on the probability that the fragmented local incidents reach a critical level so that they gain national or international momentum and on the frequency and magnitude of negative incidents associated with geothermal energy.

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9 WP8: Integration

Stefan Hirschberg, Peter Burgherr, Warren Schenler, Matteo Spada, Karin Treyer, Christian Bauer (PSI)

In order to provide perspective on the relative strengths and weaknesses of geothermal energy this chapter contains a comparison of few selected, representative indicators for the performance of electricity generation technologies. This is followed by a limited scope Multi-criteria Decision Analysis (MCDA) covering the major "new" renewables of interest for the electricity supply in Switzerland. The MCDA provides a framework for aggregating multi-disciplinary indicators, i.e. integration of the various quantitative technology performance measures. The overall conclusions and recommendations for policy and future research, which also belong to the integration task, are provided in Chapter 10.

The focus of the integration task is on petrothermal systems.

9.1 Comparison of selected indicators

The indicators of interest cover environmental and economic dimensions, one selected social aspect (accident risk) and security of supply. We limit the comparisons provided here to current technologies. It must be emphasized that in the present analysis we focus on current technologies as primarily implemented in the Swiss electricity supply system and which have been evaluated in recent projects carried out by PSI. These technologies are representative but not necessarily the best available today.

9.1.1 Environmental performance

The aim of the comparison is to provide an overview of electricity producing technologies used today and potentially in the future in Switzerland, deep geothermal power being one of them. Data for other technologies are based on Bauer *et al.* (2008) and Roth *et al.* (2009), which have established detailed inventories for current (year 2005) and future (year 2030) technologies operating in Switzerland or abroad (potential contributors to the Swiss electricity imports). Among them, the following current technologies have been selected for the comparison:

- Natural gas, combined cycle
- Hydro power, run-of-river
- Hydro power, reservoir
- Biogas, CHP
- Synthetic Natural Gas, CHP
- Wind power, onshore, in Switzerland
- Photovoltaic, in Switzerland
- Nuclear mix, in Switzerland
- Swiss electricity mix

It should be considered that geothermal power is a source of base-load power, while the performances of wind and photovoltaic power depend on weather conditions and the time of day. **Figure 148** shows the environmental performance of geothermal electricity production compared to the Swiss electricity supply mix from 2005 and other electricity generation technologies mostly operating in Switzerland or of potential interest for the future.

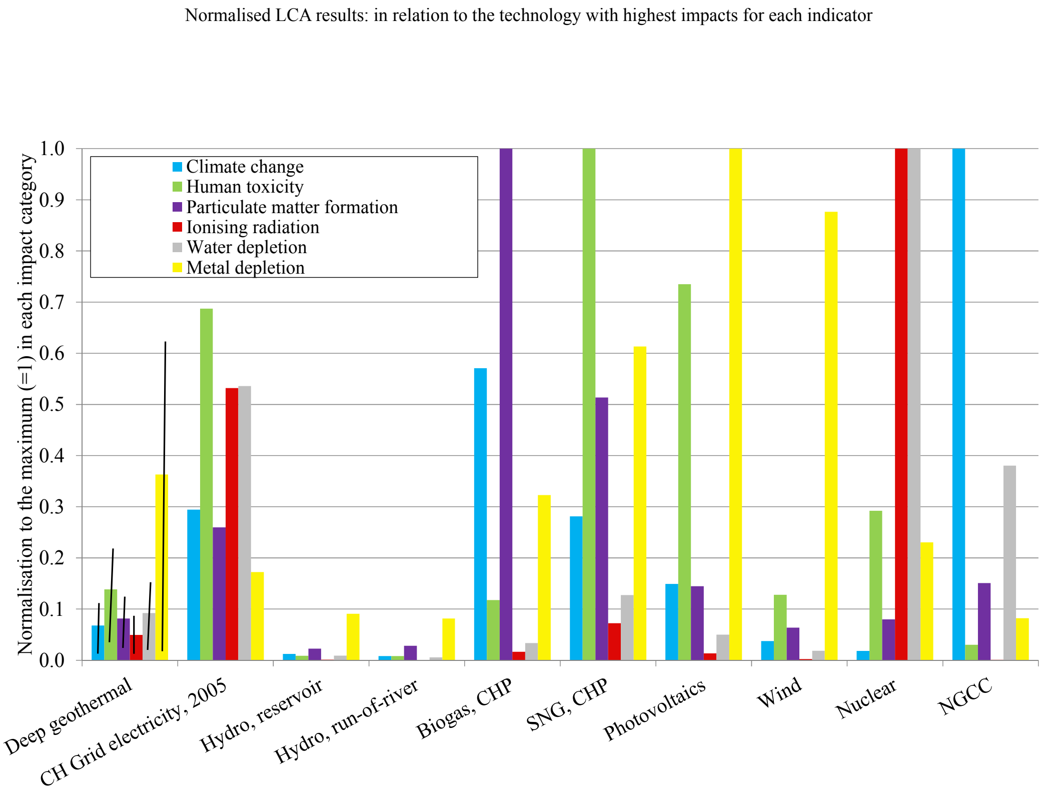

***Figure 148**: Selected LCA indicators[41] for Swiss electricity supply with various technologies in 2005, normalized in relation to the technology with the highest impacts (=1) for each indicator, shown for each technology. NGCC: Natural Gas Combined Cycle; CHP: Combined Heat and Power; SNG: Synthetic Natural Gas. The ranges of values shown for geothermal power indicate the spread of results depending on the plant capacity. Base case: 5.5 MW_e; "best case": 14.6 MW_e; "worst case": 2.9 MW_e net capacity; The medium and low capacity cases have a well life time of 20 years while the high capacity case has a well life time of 30 years.*

"Deep geothermal" represents the base case technology (electricity generation only) as specified in Table 15. Characteristics of the other technologies are based on the ecoinvent database v2.2 ("CH grid electricity, 2005") and appropriate LCA literature (Bauer et al., 2008; ecoinvent, 2013; Roth et al., 2009).

[41] The indicator "water depletion" must be used with care, as the modelling of the water use in the underlying life cycle inventories in ecoinvent v2 is not completely consistent over all technologies and over the whole life cycle chains. As the water use for deep geothermal power is an often discussed topic, the corresponding impact category is nevertheless included in the presentation of the results for this TA-SWISS project. It must be considered that the actual impact on the environment from the water depletion depends greatly on the water scarcity in the region where the water is withdrawn.

Figure 149 shows the relative contributions of the various technological options by burden.

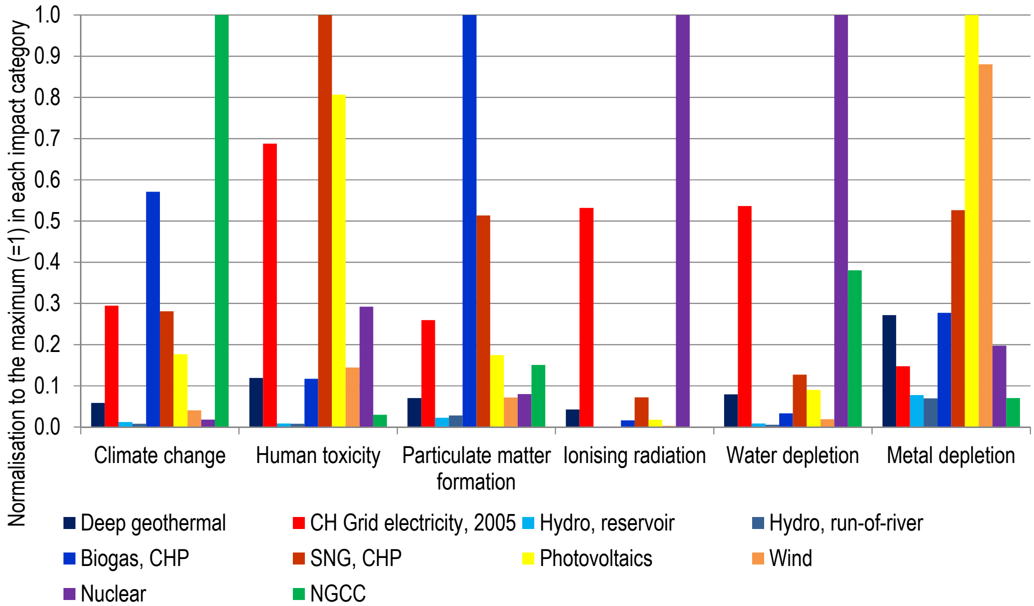

Figure 149: *Relative contributions of various technologies by burden. Selected LCA indicators for Swiss electricity supply with various technologies in 2005, normalized in relation to the technology with the highest impacts (=1) for each indicator, shown per burden. For abbreviations see previous figure. Geothermal electricity is represented by the base case.*

The potential environmental burdens of geothermal electricity (in the base case) are with one exception (metal depletion) clearly below those of the Swiss grid electricity supply mix in 2005 (including imports). The results of the base case shown in Figure 148 are not much worse than for the best case, meaning that increasing the capacity from around 5.5 MW_e will not substantially reduce the environmental burdens, whereas capacity reduction will result in a clearly worse environmental performance. The results for geothermal power are similar to those of the "cleanest" renewables such as hydro and wind power. The overall environmental performance of geothermal appears to be better than the environmental performance of biomass based electricity generation (biogas, SNG from wood), which could also generate base load power.

9.1.2 Economic performance

The most representative indicator of economic performance is the generation cost.

Figure 150 shows the current generation costs. The comparison is limited here to "new" renewables. Two cases are considered for geothermal systems, i.e. a system delivering electricity only and a system delivering electricity and a moderate amount of heat (corresponding to operation of 2500 hours/year). The interest rate is assumed to be 5% in all cases.

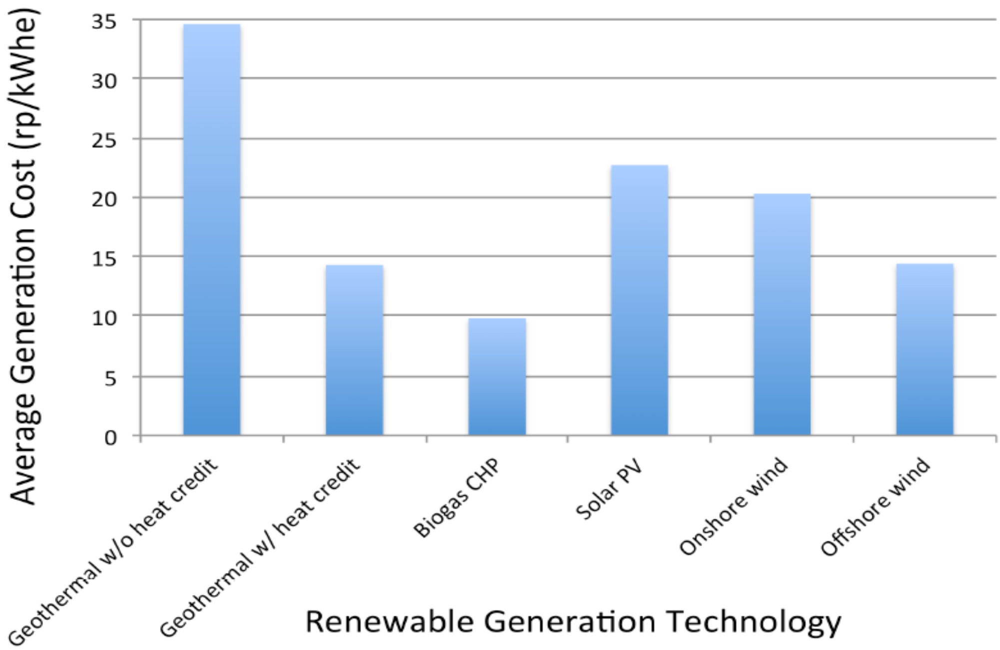

Figure 150: *Electricity generation costs for current "new" renewables.*

Some additional comments are provided below on the assumptions in the calculations. The current estimates represent updates of those published by us in PSI's Energy Mirror No. 20 (2010).

Geothermal

The estimates of 34.6 Swiss cents/kWh without heat credit and 14.3 Swiss cents/kWh with heat credit are for the base case: i.e. 35 ˚C/km, 20 year well life, 20 MCHF/well, 5% interest, and an impedance of 0.2 MPa per l/s. As in all technologies it is expected that research and development, standardization and simplification will lead to significant cost reductions.

Biogas Combined Heat and Power (CHP)

The estimate of 9.8 Swiss cents/kWh originates from PSI's Energy Mirror No. 20 (2010).

Solar PV

The cost estimate is 22.7 Swiss cents/kWh. Current solar prices are reported in the range of 3000–3500 CHF/kW for Switzerland for a 10 kW size. Our reference rooftop system is 20 kW, and module prices have dropped another ~15% since the start of 2013, but modules are 45–50% of total cost. We used a cost of 3000 CHF/kW and a capacity factor of 922 h/a.

Wind, onshore

The cost estimate is 20.3 Swiss cents/kWh, based on a capital cost of 1800 CHF/kW, which is in line with European numbers and a capacity factor of 1250 h/a for Swiss conditions[42], which is much lower than typical values from the north of Germany or Denmark.

Wind, offshore

We include offshore wind in the comparison as a non-domestic resource that will be a likely component of the imported electricity in the future. The estimated generation cost is 14.4 Swiss cents/kWh. The assumed capital cost is 4000 CHF/kW with a capacity factor of 3850 h/a). The German offshore wind power is thus cheaper than the onshore Swiss wind because the Swiss onshore capacity factor is quite poor (reversed from the purely German on/offshore comparison).

For comparison, the current **Swiss hydro** generation cost is 6.4 Swiss cents/kWh. This is a weighted average of storage dam and run-of-river hydro costs, obtained by taking known nuclear generation costs out of overall Swiss-average generation sector numbers. The estimate reflects the fact that capital costs of the existing hydro are partially amortized. The cost of new large hydro in Switzerland would be in the range 12−28 Swiss cents/kWh subject to large case-by-case variations. The generation costs of the current **Swiss nuclear** plants are in the range of 5−7 Swiss cents/kWh with capital costs also partially amortized. The recent estimates of the generation cost of hypothetical new nuclear in Switzerland are on the order of 8 Swiss cents/kWh, although this is subject to quite large uncertainties (Hirschberg, *et al*., 2012).

9.1.3 Risk performance

Risk performance related to severe accidents is chosen here as one (among several) representative indicators of social aspects associated with electricity generation technologies. The most debated risk indicator for geothermal energy is induced seismicity (Section 6.2). Since it is specific for geothermal energy and not relevant for other “new” renewables this type of risk will not be further elaborated here. Rather, we focus on the comparison of other types of risks that could lead to severe accidents within the energy chains associated with “new” renewables. Those applicable to geothermal energy are addressed in Subsection 6.1.

It has been shown in previous studies (e.g. Burgherr and Hirschberg, 2014), that “new” renewable technologies exhibit relatively low levels of severe accident risks, particularly for accidents with very large consequences. There are some open issues with regard to solar PV.

For comparative risk analysis, fatality rate (Fatality/GWeyr) is selected as the risk indicator for all technologies. This choice is made since fatalities generally comprise the most reliable

[42] The load factor for wind energy in Switzerland has been steadily increasing. The current value is higher by about 30% compared to that used in the present study. The main reason for not using a higher value is the need for consistency of LCA results (based on 1250 h/a). The impact of this conservatism on MCDA results is limited and does not affect the conclusions of the present analysis.

indicator with regard to the completeness and accuracy of the data (e.g. Burgherr and Hirschberg, 2008).

In **Figure 151** the severe accident risk indicators for deep geothermal system and for other "new" renewables are compared. The fatality rates for new renewables technologies, except the deep geothermal system, are extracted from Burgherr and Hirschberg (2014). The fatality rate for the deep geothermal system in Switzerland is based only on the onshore blowout risk data (see WP5 Task 1 Section 6.1), since this is the main contributor of accident risk excluding the induced seismicity.

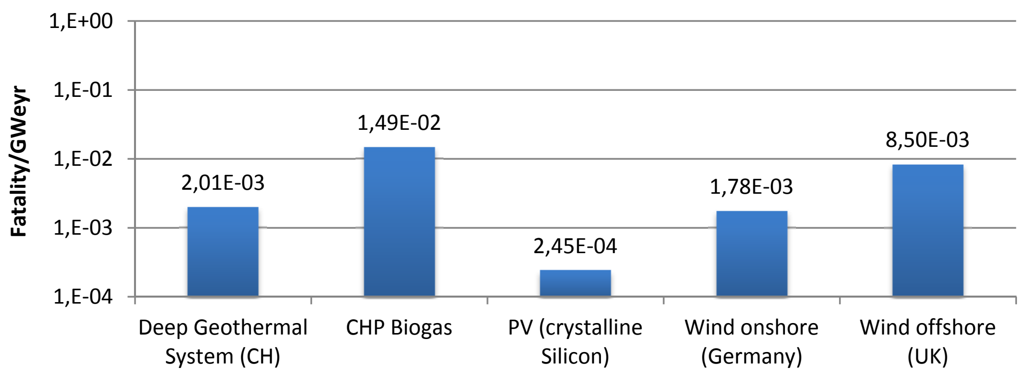

***Figure 151:** Fatality rates due to severe accidents for "new" renewables. Induced seismicity is not considered in the estimate for the geothermal system. (GWeyr: Giga-Watt electric year).*

The result in **Figure 151** shows that for the non-seismic risk the deep geothermal system compares favourably to other "new" renewable technology. In this context, deep geothermal energy compares even more favourably to, for example, natural gas (7.19E-2 fatalities/GWeyr for OECD countries, according to Burgherr and Hirschberg, 2014); in the latter case accidents in the entire energy chain are considered. In the case of deep geothermal energy it must also be stressed that the risk of induced seismicity, probably dominant for this technology, is not reflected in the figure. On the other hand, hypothetical risks related to handling of large amounts of toxic materials in the production of solar cells need to be further investigated.

9.1.4 Security of supply

Security of supply has environmental, economic and social dimensions. For this reason it is treated separately.

Security of supply may be represented by two indicators, i.e. Energy Resource Autonomy of the Supply Chain and Availability expressed by the Equivalent Availability Factor. For baseload plants with low marginal cost (like geothermal), or for non-dispatchable units like wind and solar, the availability factor is the same as the capacity factor (expected annual energy/maximum annual energy). However for peak or intermediate load units that are dispatched, the equivalent availability factor reflects the maximum annual amount of energy that *could* be produced when maintenance and outages are included, and thus is an upper bound to the capacity factor.

Geothermal energy along with biogas, solar and onshore wind is a domestic resource and thus fully autonomous. In the Swiss case this does not apply to offshore wind.

Once established geothermal can supply baseload electricity, which also applies to biogas as opposed to intermittent sources such as solar and wind.

Further details on the relative numerical technology-specific indicators for security of supply will be provided in connection to MCDA.

9.2 Limited-scope Multi-criteria Decision Analysis

9.2.1 Background

The few indicator examples provided above show that none of the "new" renewable technologies is superior compared to the other ones with respect to the various dimensions of performance. Aggregation of indicators is desirable in order to assess the overall performance in comparative perspective.

The application presented in this work is limited to current "new" renewables and thus does not address hydro, nuclear and fossil options. Hydro is widely accepted as both the current and future core of the Swiss electricity supply and its potential for further expansion is subject to severe limitations. Nuclear is supposed to be phased out within the next 20–30 years. Introduction of fossil electricity supply, i.e. natural gas combined cycle plants, is undesirable though it may prove necessary for the secure supply of electricity, at least in the transition period. The focus on "new" renewables is thus understandable, since they are supposed to compensate for the supply gap created by the intended phase out of nuclear energy in Switzerland.

9.2.2 Approaches to aggregation

There are two approaches to aggregation, i.e. estimation of total (internal plus external) costs and Multi-criteria Decision Analysis (MCDA).

Costs are called "external" if they are not born by the party that causes them, but rather by society as a whole. They include the costs of health damages that result from air pollution. Such damages are monetized, i.e. are measured in or converted to monetary units, and also include those resulting from future climate change. Further aspects are the reduced harvests and damages to buildings caused by air pollution.

The total cost is obtained by adding the production (or internal) and external costs of electricity together, and is sometimes also used as a measure of sustainability, although this is controversial since the social dimension is only partially represented. Some aspects of social acceptance such as perceived risks or visual amenity are strongly subjective and may be very difficult to monetize. Non-monetized factors are not considered.

In the present work we abstain from the rather cumbersome quantification of total costs. Given that the technology portfolio to be evaluated is limited to "new" renewables, the quantifiable external costs are rather small (see e.g. Energie-Spiegel, 2010 and Schenler, 2009). Thus, the total costs of "new" renewables considered here are bound to be dominated by generation costs and there is no specific gain from carrying out extensive analyses of external costs.

MCDA, on the other hand, has the capability to explicitly reflect subjective social acceptance issues. The approach builds on the steps shown in **Figure 152**. The technologies to be compared must first be defined. Next, indicators are established that cover all three areas of the 3 pillar model of sustainability supplemented by security of supply, which can be measured for each individual technology. These single indicators can be used individually for technology comparisons. And from them a single, comprehensive index value can be calculated. This index (or rank) reflects how sustainable the individual technologies are compared to each other. When the overall index is calculated the indicators are each weighted, based on the individual user preferences. The results for the sustainability index obtained for each technology may differ, depending on the weighting of the indicators, and there is therefore no “right” or “wrong” outcome.

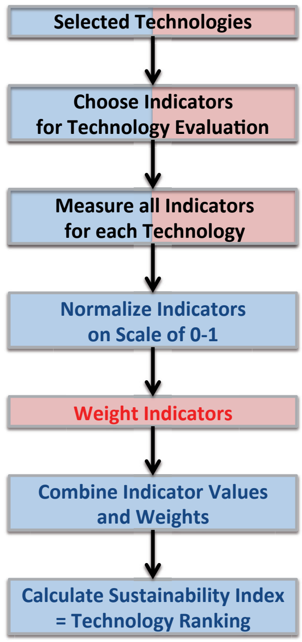

Figure 152: *Multi-criteria analysis process (objective steps in blue, subjective in red; some of the steps are mostly objective but may also have some subjective elements).*

The MCDA approach enables one to account for a wide variety of environmental, economic and social aspects in a transparent manner. It can provide an invaluable support to informed decision-making, and to guiding a public debate and participative processes. However, the MCDA does not provide a definite ranking of technologies but rather illustrates the sensitivity of the ranking to subjective preferences provided by the various individual or group stakeholders.

9.2.3 MCDA implementation and results

Within the TA-SWISS geothermal project a limited-scope MCDA was implemented following the process illustrated in the figure above. The MCDA was implemented using PSI’s web-based MCDA tool “Mighty MCDA”[43], developed in connection with a number of major technology assessment projects.

[43] http://mightymcda.net

Selection of technologies

The technologies selected for the MCDA are:

- Deep geothermal system without heat credit
- Deep geothermal system with heat credit
- Biogas Combined Heat and Power (CHP) with heat credit
- Multi-crystalline solar photovoltaic (PV) roof panels
- Wind onshore
- Wind offshore (in Germany)

Choice of quantitative indicators

The indicators chosen for the evaluation are the ones elaborated in Subsection 9.1, i.e.:

- Environment: Climate change, Human toxicity, Particulate matter formation, Ionising radiation, Water depletion and Metal depletion
- Economy: Average generation cost
- Social: Severe accident risks other than induced seismicity, Induced seismicity
- Security of supply: Energy resource autonomy, Equivalent availability factor

The selected set of indicators is much reduced compared to a full scope application, which would be highly demanding in terms of resources needed for quantification. Thus, the availability of indicators originating from the current work on geothermal and from other relevant projects recently conducted by the Laboratory for Energy Systems Analysis (LEA) of PSI was an essential factor. Nevertheless, the selected indicators are adequately representative for use in a limited-scope MCDA aiming at mapping basic sensitivities in the ranking of technologies. For a state-of-the-art comprehensive set of 36 indicators for use in sustainability assessment of energy technologies we refer to Hirschberg (2008).

Quantification of indicators and normalization

Numerical values for most of the indicators used were provided in **Figure 148** to **Figure 150** in Section 9.1. Here the normalized values for all indicators used in the MCDA are shown in a series of charts. The MINIMAX method was used for the normalization. Thus, for each performance indicator the best option receives the value 1 and the worst the value 0; the values assigned to the other options are then based on linear interpolation.

Environmental Indicators

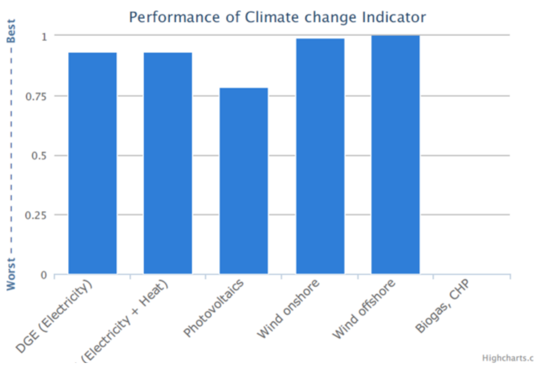

Figure 153: *Normalized climate change indicator.*

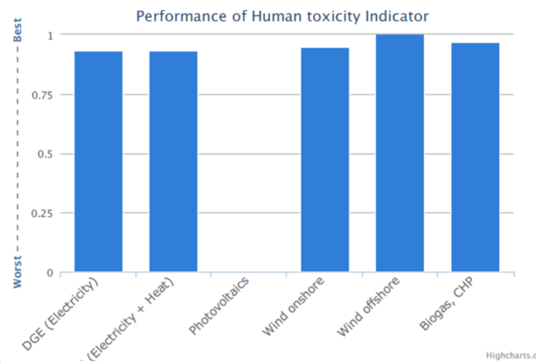

Figure 154: *Normalized human toxicity indicator.*

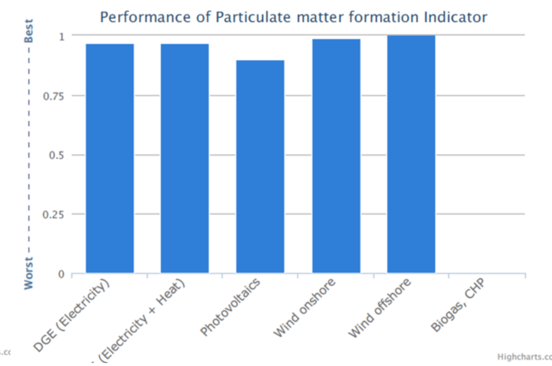

Figure 155: *Normalized particulate matter formation indicator.*

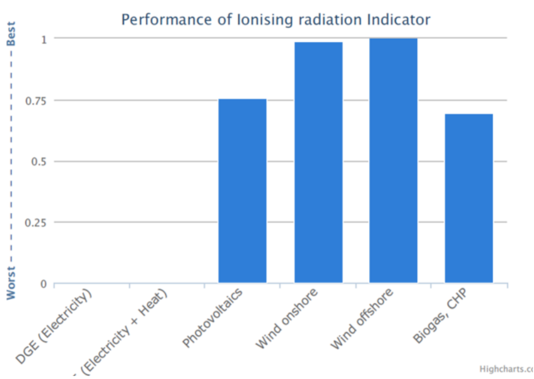

Figure 156: *Normalized ionising radiation.*

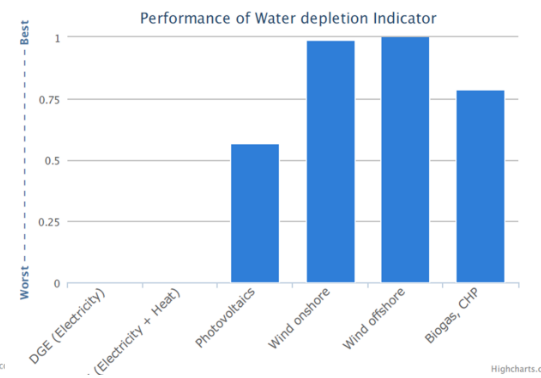

Figure 157: *Normalized water depletion.*

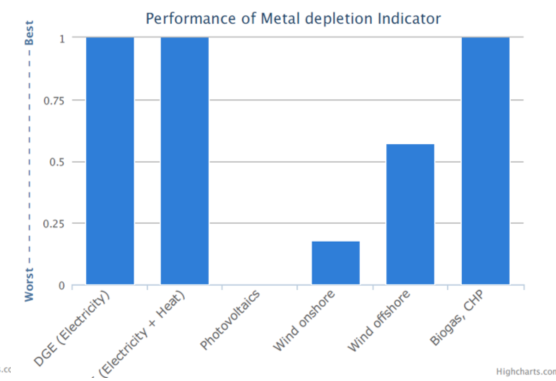

Figure 158: *Normalized metal depletion.*

Economic, Risk and Security of Supply Indicators

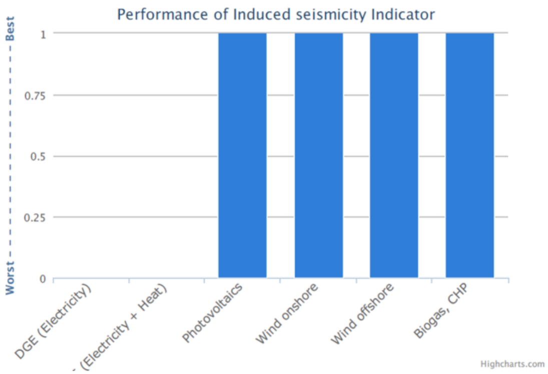

Figure 159: *Normalized induced seismicity indicator.*

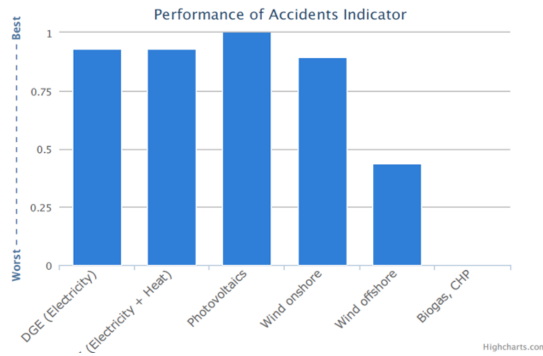

Figure 160: *Normalized severe accident indicator (induced seismicity excluded).*

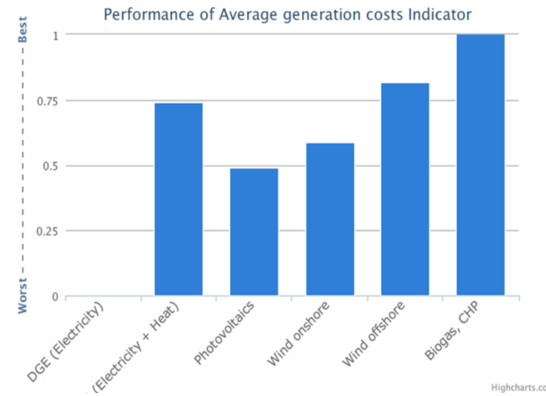

Figure 161: *Normalized average generation costs indicator.*

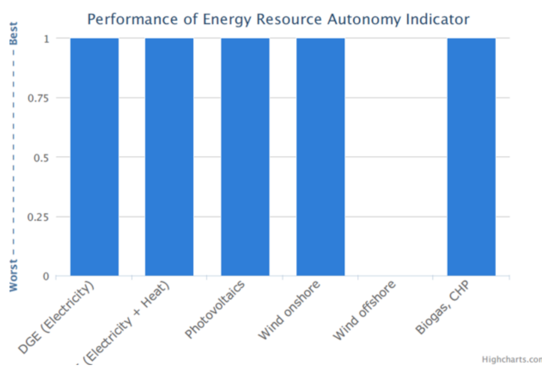

Figure 162: *Normalized energy resource autonomy indicator.*

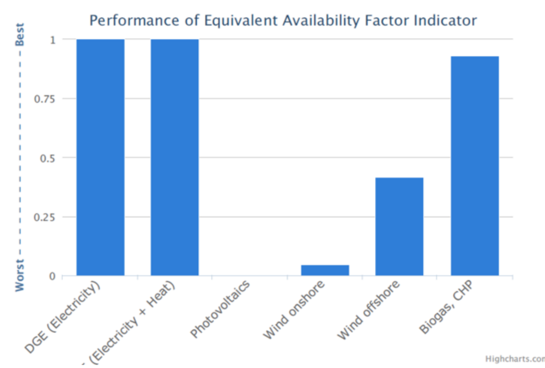

Figure 163: *Normalized equivalent availability factor indicator.*

Sensitivity mapping of sustainability index based on various preference profiles

We apply here the simplest MCDA algorithm, i.e. the weighted sum (WS) approach. Other approaches could be used as elaborated within the NEEDS project by Makowski *et al*. (2009). However, our choice is motivated by the transparency and simplicity of WS.

The hierarchy of criteria and indicators used is shown in **Figure 164**. As the starting point the four top criteria are equally weighted, which corresponds to the spirit of sustainability; also the indicators on the second level of the hierarchy are equally weighted.

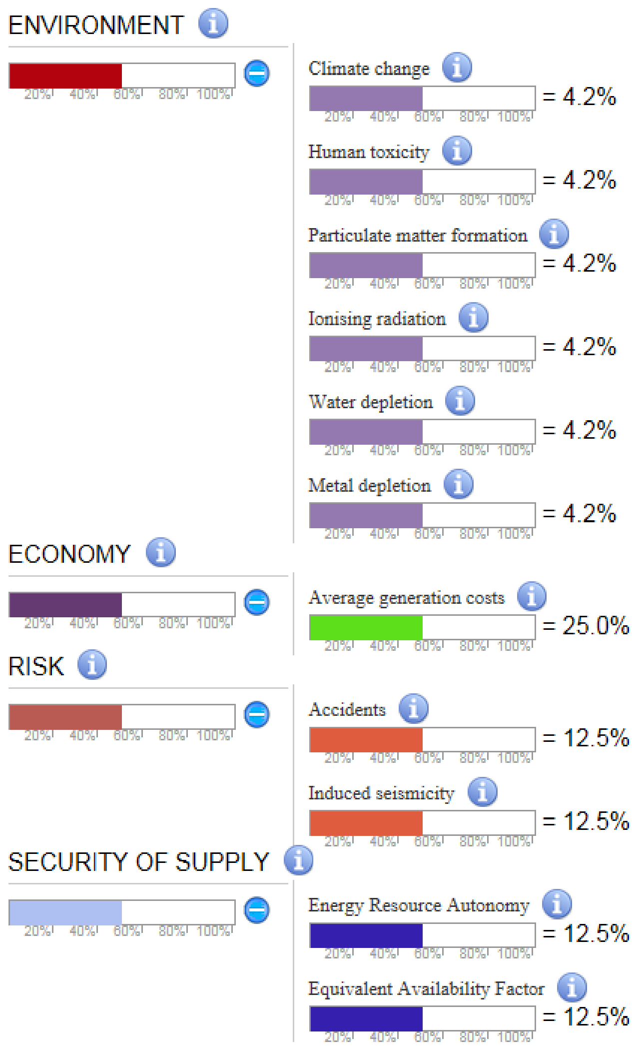

Figure 164: *Hierarchy of criteria and indicators with equal weighting on all levels.*

Figure 165 shows the resulting ranking of the options including the (positive) contributions of specific indicators to the performance index.

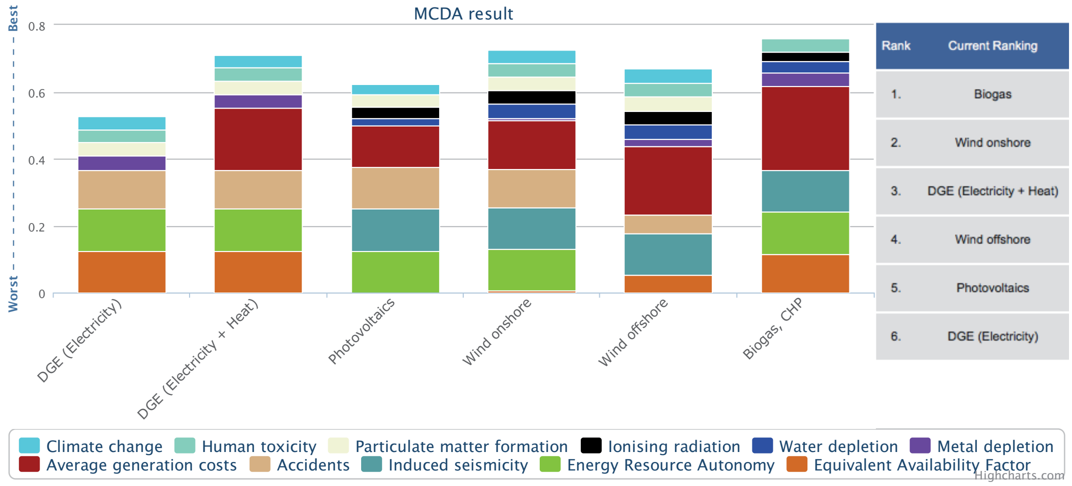

***Figure 165:** Ranking based on equal weighting on all levels in the hierarchy of criteria and indicators.*

Clearly, the use of the heat credit makes geothermal energy much more competitive versus the other renewables not only economically but also in the broader context of sustainability. In addition to treating all criteria equally, we implemented a number of MCDA cases with varying weighting profiles, thus attaching greater significance to some selected criteria. The next four cases show the ranking based on taking each of the top criteria one at a time and giving it a weight of 85%, with the three other top criteria receiving 5%.

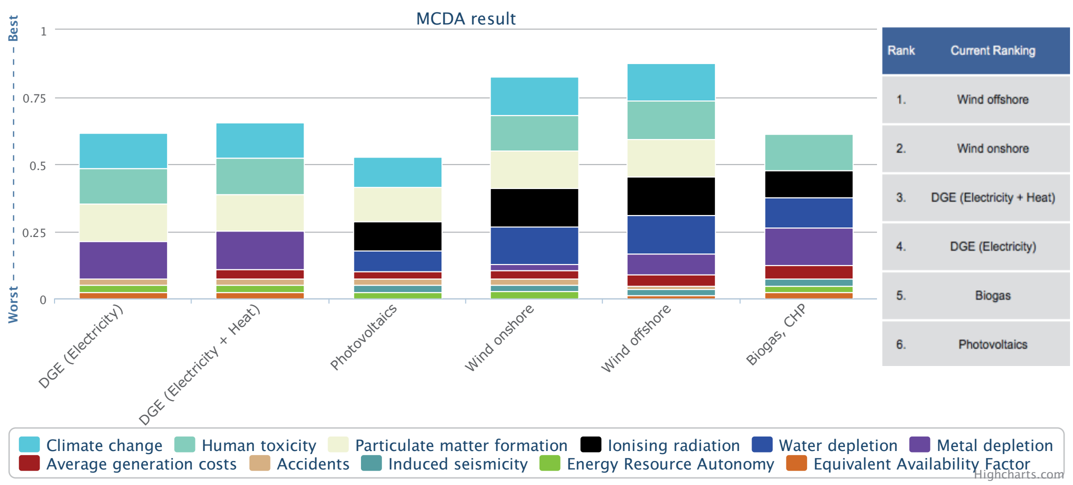

***Figure 166:** Ranking based on environmentally centered weighting (85% on the top level) with equal weights on the lower level in the hierarchy of criteria and indicators.*

The two geothermal options are in the mid-field in the case of the environmentally centered weighting.

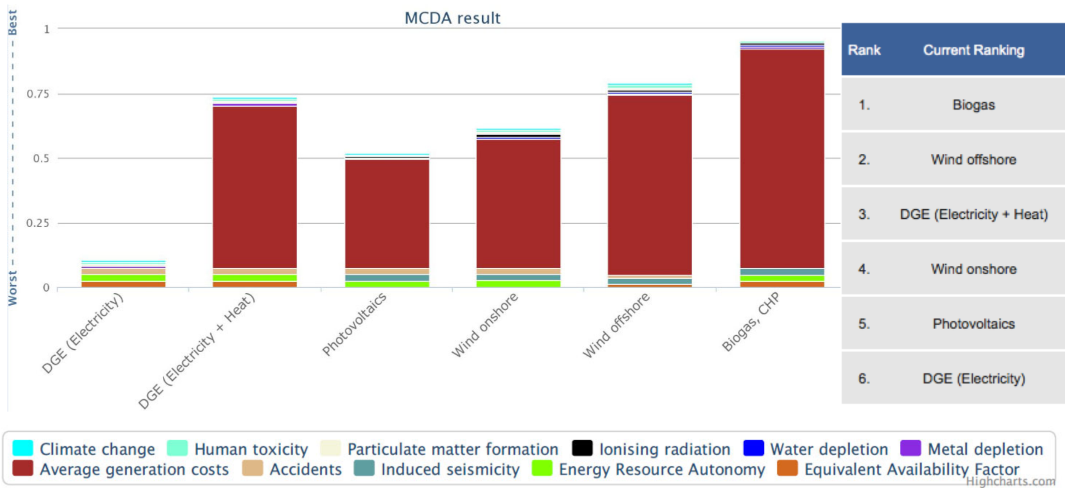

Figure 167: *Ranking based on economically centered weighting (85% on the top level) with equal weights on the lower level in the hierarchy of criteria and indicators.*

Not surprisingly geothermal with the heat credit ranks much better than without it in the economically centered case.

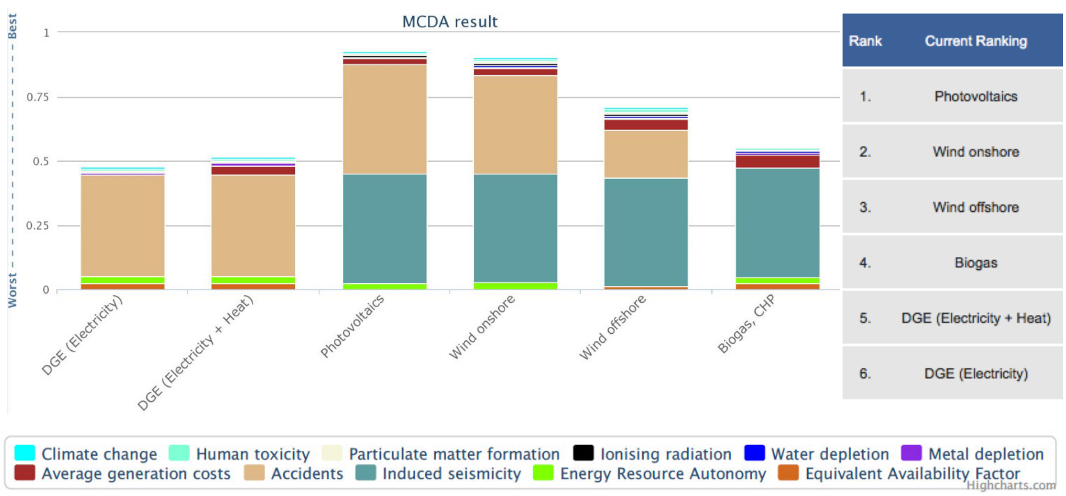

Figure 168: *Ranking based on risk centered weighting (85% on the top level) with equal weights on the lower level in the hierarchy of criteria and indicators.*

In the risk centered case the geothermal systems rank worst due to the impact of induced seismicity.

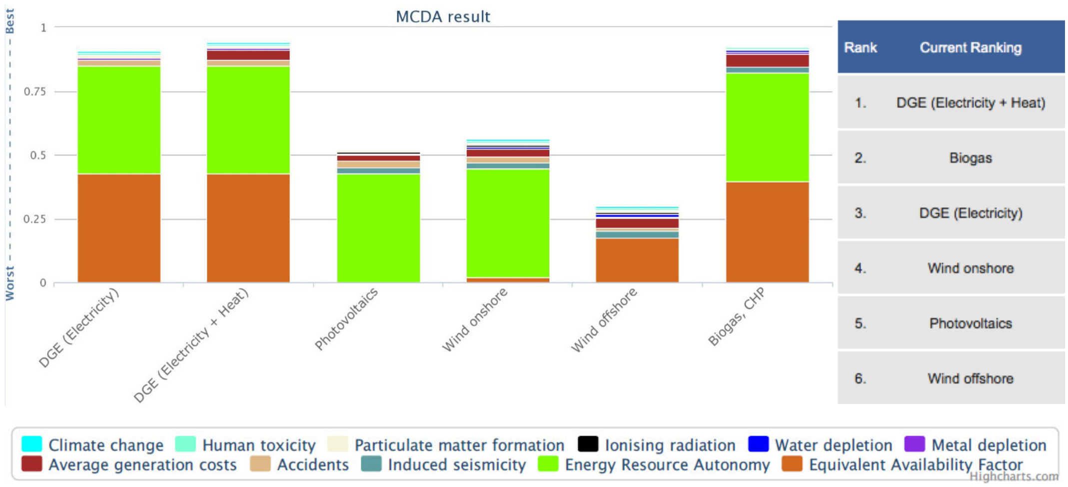

Figure 169: *Ranking based on security of supply centered weighting (85% on the top level) with equal weights on the lower level in the hierarchy of criteria and indicators.*

The security of supply-centered weighting is strongly favourable to geothermal systems.

We now consider a case with equal weights given to the top criteria but with some differentiation of the weight given to indicators on the lower level based on arguments related to the significance of impacts and some priorities reflecting policy concerns. This leads to more emphasis in relative terms being given to climate protection within the environmental criteria and to the equivalent availability factor within the security of supply criteria. It should be noted that such preferences can be supported by arguments but are not without subjective judgments.

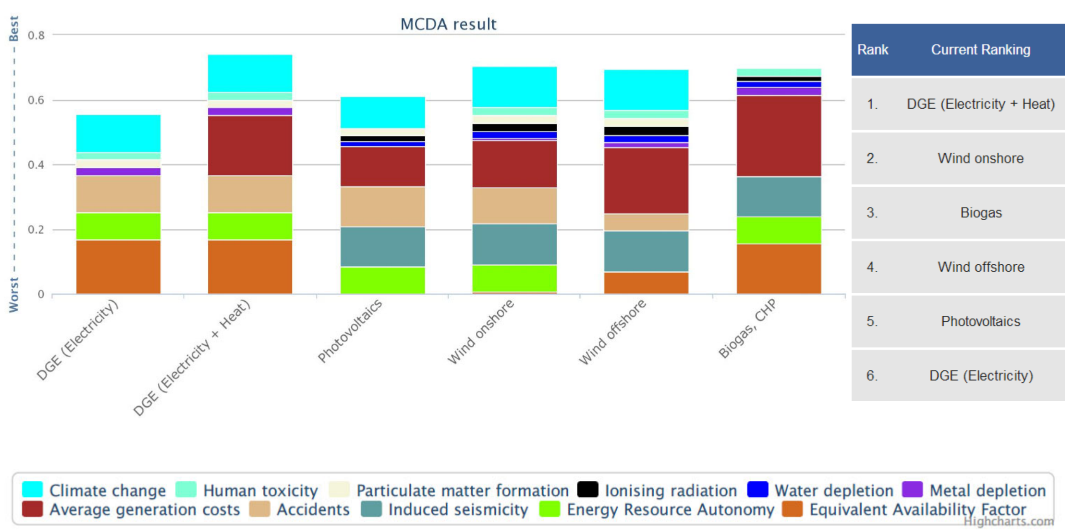

Figure 170: *Ranking based on equal weighting of top criteria but with emphasis on climate protection among environmental indicators and continuity of electricity supply among security of supply criteria.*

The performance of the various options in this case is quite similar with relatively small differentiation, but the geothermal option with heat credit becomes a top technology.

Overall, a preference profile that exhibits balance between the high level sustainability criteria and mostly favors geothermal options is the one that emphasizes climate protection, minimisation of human toxicity, metal depletion, risks other than induced seismicity and continuity of electricity supply.

On the other hand, a preference profile that exhibits balance between the high level sustainability criteria and mostly disfavors geothermal options is one that emphasizes radioactive emissions, water depletion and induced seismic risks.

Generally, geothermal systems combining electricity with heat supply perform clearly better than those supplying electricity only. Compared to other “new” renewables geothermal with a heat credit ranks well for most of the tested preference profiles. One exception is the risk-centered profile due to the geothermal-specific possibility of induced earthquakes.

Current evaluations were carried out for a hypothetical geothermal system with targeted performance parameters. If such targets are not achieved, the ranking of geothermal would be worse. At the same time deep geothermal energy is a non-mature, emerging technology with potential for major improvements.

9.3 References

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10 Conclusions and Recommendations

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This chapter provides the conclusions and recommendations for all the topical areas analyzed in the project. Recommendations are given both in the context of policy issues and as suggestions for the needs of further research.

10.1 Conclusions

10.1.1 Resources

- A **geothermal resource** is the estimated recoverable thermal energy with respect to a predefined base temperature and specific geothermal exploration systems. Based on the current subsurface knowledge, estimates of the geothermal resources in Switzerland can only be made at a very rough level. Current resource calculations include all available heat (> 60°C) and are based on an updated surface heat flow map for Switzerland. High uncertainties remain in key parameters such as temperature, permeability, and volumes. Direct measurements would be necessary to constrain models. In spite of the uncertainties the geothermal resources are considered to be very substantial.
- **Geothermal reserves** are derived from the resources by applying limitation factors (technological, economic, social, legal etc.). The main limitation is seen to be the technology. Estimated potential reserves strongly depend on: 1) The ability to create and operate a reservoir, which is a major challenge with many unknowns; 2) Limits imposed by acceptable seismic risk associated with EGS enhancement and long-term operation. The current knowledge about resources in Switzerland is too vague and the current level of efficiency of deep geothermal heat exchanger is too limited to allow a derivation of reliable reserve estimates.
- The probability of success of finding and developing substantial **hydrothermal systems** is low because favorable geologic conditions (joint probability of appropriate geologic formations and structures, adequate fluid transmissivity and productivity and sufficiently high temperature) are expected to be rare.
- **Petrothermal technology for electric power** production is applicable in a wider range of tectonic environments. Only if EGS technology proves to be a viable option in future pilot and demonstration projects will it be feasible to carry out an informed and reasonably robust assessment of the reserves with proper consideration of major constraints that are not sufficiently known today.
- Considering only the heat supply side, use of geothermal energy for **direct heating** could be a potential option. Sufficiently high temperatures available at about 2 km to 2.5 km of depth would allow direct heating without the use of electrical heat pumps.

For this purpose technical development and major cost reductions of more efficient borehole heat exchangers are needed. Induced seismic risk, even for open-circulation geothermal systems at this depth in the Molasse sediments, seems to be minor compared to Basel and St. Gallen type systems.

10.1.2 Technology

Exploration and reservoir characterization

- It is generally not possible to accurately forecast the permeability at depth, because permeability is determined at the micro-scale. Even extensive and expensive high-resolution 3D seismic surveys, such as the ones conducted in the case of St. Gallen at costs exceeding CHF 5 million are only able to identify potentially promising target regions. The true permeability can only be estimated through drilling into the target.
- While major fault zones, such as the St. Gallen Fault Zones, can be imaged within sedimentary layers with increasing detail, it is currently not possible to image the pre-existing stress distribution on fault zones.
- The capability of imaging fracture zones and faults within the basement from surface measurements is poor, much poorer than in sediments. As a consequence, any petrothermal project will find it difficult to forecast reliably the distribution of fractures in the target region, nor will it be able to rule out with certainty that medium to large-scale fault zones are nearby.
- While some of the limitations listed above may be overcome through additional research and development, it is unlikely that surface-based geophysical methods will improve to the extent that the principal barriers to imaging stresses and local permeability from surface measurements will be overcome. Downhole measurements are necessary in this regard.
- Characterization of the discontinuity distribution (i.e. fractures, fracture zones and faults) within the reservoir is limited by the difficulty in estimating the length of structures seen at the borehole wall. Methods are needed to image larger structures *within* the rock mass from borehole-based methods, such as seismic or radar.
- Stress within the reservoir can be constrained to a useful degree from borehole measurements. However, the variation of stresses within the reservoir is more difficult to estimate from borehole measurements. Stress variability is important for anticipating the seismic response to injections, and could also be an important factor that influences permeability enhancement.
- The process of fracture generation and fluid flow during stimulation is difficult to observe, except at the borehole. Surface-based geophysical techniques such as magnetotelluric or tiltmeter monitoring provide only low-resolution images. Microseismicity provides the most useful tool for monitoring the geometry of the stimulated volume and the activated structures. It also can provide insight into the geomechanical processes on the activated structures.

Reservoir creation

- Significant improvements in reservoir creation are promised by adapting the techniques of multiple stimulation zones in sub-horizontal wells that have proven highly instrumental for exploiting shale gas resources.
- Hydraulic stimulation has been found to be effective in radically and permanently increasing the injectivity of wells in crystalline rock. This implies that substantial enhancement of the permeability of feed zones can be accomplished, in at least the near field of the wells. However, questions remain as to the degree of permeability enhancement that can be accomplished deeper into the reservoir.
- Permeability enhancement appears to occur primarily on existing fracture and fracture zones – thus hydraulic linkage between the wells must be established predominantly by enhancing the permeability of the natural fracture system.
- However, it has so far proved difficult to create a petrothermal reservoir with sufficiently low impedance to allow commercial flow rates, without the benefit of pre-existing, highly permeable fracture zones and faults, such as at Soultz. The inadequate post-stimulation hydraulic linkage of the wells in petrothermal reservoirs probably reflects: a) An insufficient number of stimulated flow paths between the wells; b) Insufficient permeability enhancement in the 'far-field' region between the wells.
- Observations of thermal break-through at relatively early times during circulation of petrothermal systems with well separations of 90−150 m demonstrates that substantially greater well separations will be required for commercial systems. Remedial measures to block-off feed-zones that produce prematurely cool water would probably be taken in a commercial setting.
- Channeling of the flow field within the built reservoir has a large influence on long-term system performance, and needs to be better understood.
- The magnitude of the fluid pressure increase prevailing within the reservoir at distances of more than 100−200 m from the injection well under stimulation conditions remains uncertain. Knowledge of the pressure field is important because it governs the types of permeability creation mechanisms that can be activated (e.g. hydrofracture propagation versus hydroshear).
- There is evidence from at least two sites that some slip that takes place during stimulation occurs aseismically, and is thus not captured by microseismic monitoring networks. The importance of aseismic slip and the factors that promote it need to be better understood.

Drilling

- Deep geothermal drilling is adapted from conventional oil and gas drilling. This process is a mature and well-developed technology with long standing experience. However, currently there is rapid, ongoing development that has produced advances in directional drilling, fracking and blockers. All these have implications for geothermal wells, but must be adapted to new regimes regarding depth, rock types, well diameters and flow rates, etc.

- Overall costs for geothermal power plants are dominated by well costs, which include not only drilling costs, but also well life and the number of wells required. Innovative drilling methods, or combinations of conventional and innovative approaches, have the potential to reduce drilling costs, but only in the long-term. The drilling companies are focusing on short-term developments to continuously improve the state of the art. This will reduce the cost for deep geothermal well drilling.
- One major issue for drilling deep geothermal wells that requires further research and development is the insufficient efficiency of drilling deep, large diameter wells in hard rock, due to low rates of penetration and high wear rates of the downhole equipment (e.g. drill bit). There are two basic ways to reduce conventional drilling costs: increasing the rate of penetration and reducing tripping time. There is a trade-off between these, based on drill bit life, maintenance time, wear on drill strings, drill string vibrations and casing wear.

10.1.3 Economy

- The economic analysis of geothermal generation within the TA-SWISS project has shown that the average cost of generation can vary significantly based on a range of factors, some of which still have major uncertainties, e.g. well costs and reservoir life and impedance. The Swiss reference base case has an estimated average generation cost of 35 Swiss cents/kWh, but the range between the Swiss good and poor reference cases used is from 18 to 61 Swiss cents/kWh, respectively.
- No future cost trends have been modelled which may result from experience, research and development, standardization and simplification. Nevertheless the cost impacts of many anticipated technological improvements can be determined from the sensitivity analysis presented.
- Well-related costs remain the overwhelmingly dominant cost component and cause most of the cost uncertainty. This includes the number of wells necessary for exploration, confirmation and production, the cost to drill and well life before redrilling is required. There is significant room for incremental reduction of conventional drilling costs before reaching the longer-term prospect of revolutionary drilling technologies.
- Fracturing costs are much less than well costs, but an effective heat exchanger is key to well life and this requires demonstration.
- The effect of possible heat sales has been shown to be very important on the average cost – in the base case this reduces the average cost from 35 to 14 Swiss cents/kWh, and in more favorable cases the sale of heat can reduce the effective cost of the electricity generation to zero or even below. Thus, heat sales are key to plant economics. This creates a tension between the necessary proximity to heat markets and the unwanted proximity to a population sensitive to potential induced seismicity. Heat sales will only decrease in importance if the well costs decrease very significantly. We have only considered the wholesale supply side, i.e. selling excess heat to a district-heating grid; we have not considered future trends in heat market demand, future heat costs or additional heat applications for this potentially abundant supply of heat.

- Costs depend upon many more geological factors than just the heat gradient, which are much more difficult (or impossible) to assess without drilling. So the cost supply curve remains very tentative.
- The “Energiewende“ target for geothermal electricity can only be met if the plants can reach their capacity and cost goals. This will depend upon finding, characterizing and developing the geothermal resources, including demonstration of heat exchangers, flow rates and production life. Also, obtaining the appropriate insurance, particularly for seismic risks, could be a factor having a substantial impact on the economics of geothermal energy.

10.1.4 Environment

- Life cycle inventory data have undergone major improvements and have been adapted to the Swiss conditions.
- The models for the Life Cycle Assessment and for the Cost Analysis have been successfully coupled using a physical plant model.
- Environmental impacts of deep geothermal power plants are lower or in the same range as those from other (renewable) technologies considered in Switzerland for a future electricity mix, even when considering the relatively high uncertainties of some parameters determining the performance of future geothermal plants.
- The emissions of greenhouse gases are between 8 and 46 g CO_2 eq/kWh for the low, average and high capacity Swiss case. In the sensitivity analyses, the worst case leads to emissions of 140 g CO_2 eq/kWh, but for a completely non-economic scenario.
- The use of electricity from deep geothermal power supports the goal of climate change reduction. At the same time, it does not lead to a shift of environmental impacts, i.e. the reduction of greenhouse gas emissions does not come along with highly increased impacts in another impact category when compared to other electricity producing technologies.
- The drilling phase causes the major part of environmental impacts in all impact categories with the steel and cement use for the casing and the electricity use for the drilling rig being dominant contributors. In contrast, the stimulation phase only contributes very little to the total environmental impacts, even when assuming a very high energy and water use in this context.

10.1.5 Risks

Non-seismic accident risks

- A comprehensive risk assessment of deep geothermal systems should not only look at induced seismicity, but include other risk aspects as well. The current study addressed the risks of accidental events due to selected hazardous chemicals and blowouts.
- Among the analyzed hazardous chemicals, caustic soda generally exhibits highest risks, except for evacuees where benzene performed worst. Concerning blowout risk,

the fatality rate for onshore blowouts, which is the relevant case for geothermal energy systems, is one order of magnitude lower than for offshore. Overall, normalized blowout risk is one to several orders of magnitudes higher than for hazardous chemicals, depending on the consequence indicator.

- In summary, risk assessment results indicate that blowouts potentially pose a higher risk than the use of hazardous substances for current deep geothermal systems with regard to human health effects. However, environmental impacts due to accidental releases of hazardous substances should not be neglected because it is not only the amount released that determines the consequences, but also toxicity and exposure levels as well as location-specific factors.
- In addition to these quantitative risk assessment results, an in-depth literature review revealed further areas of potential concern. Due to their composition, geofluids are a possible risk to human health and the environment. Various published studies address different impacts associated to geofluids, including potential consequences to the environment due to the leak of hazardous chemicals in the underground, and potential effects on human health and the environment due to the accumulation of the brine containing hazardous substances (e.g. arsenic), or even NORMs (naturally occurring radioactive materials) in the pipes if not correctly treated.

Risk of induced seismicity

- Seismic risk dominates the environmental risk profile. Even though basic risk management strategies exist and have been applied successfully in specific geothermal projects, more comprehensive work is needed to understand the factors that promote the generation of felt events.
- Induced seismicity is at the same time a tool for creating the subsurface conditions that enable the use of geothermal energy. Optimizing induced seismicity, subject to maintaining the hazard and risk within acceptable limits, is the primary challenge that industry and academia need to solve before meaningful reserve estimates can be made.
- It is currently unknown if the inevitable increase of seismicity during reservoir creation and operation is acceptable from an economic, insurance, regulatory and public perception point of view.
- The seismic risk of hydrothermal projects targeting major fault zones is more difficult to estimate and manage than the risks associated with the hydraulic stimulation in petrothermal projects.

Risk perception

- Only scant evidence exists regarding the perception and acceptance of deep geothermal technology, particularly regarding seismic hazards.
- Even if one cannot transfer lessons from nuclear waste, wind power, and CCS directly, the reaction to these technologies still offers insights into potential responses of the public towards geothermal projects.

- Media attention is largely driven by spectacular events with news value: they are focused on important public votes and seismic events surrounding concrete projects in Switzerland, as well as larger events such as the accident in Fukushima.
- The seismic events in Basel and St. Gallen triggered a large increase in media attention; in particular, the negative reactions in Basel led to a general shift towards an overrepresentation of negative arguments.
- Events that may have an impact on planned future projects and their media coverage will certainly play a considerable role for the formation of public opinion.

Risk management

- We have not explicitly addressed industry standards and methodologies used to manage risks.
- We have not addressed the appropriate regulatory regime that need to be deployed by authorities to ensure safe and clean operations.

10.1.6 Regulation

- In principle, the legal situation in the cantons of Switzerland allows an intensified exploitation of deep geothermal repositories. Every application must be examined to determine if the project meets requirements and if a license can therefore be granted to exploit the deep subsoil.
- The legal situation in the cantons of Switzerland is however unsatisfactory for a number of reasons:
  - ✓ First, many cantons lack explicit legislation regulating how and in what way the subsoil may be exploited for geothermal energy. Based on the current legal situation, it is impossible for potential operators of a geothermal power station to anticipate the legal obstacles their project may still have to face.
  - ✓ Second, cantons requiring a permit to conduct exploratory drilling or carry out similar work do not have to guarantee that a license will be granted if requirements are met. Only some cantons provide for such a right.
  - ✓ Third, it has not been sufficiently established whether the cantons should award licenses by public tender, or what the procedure should be if exploration or exploitation permits have already been issued.
  - ✓ Fourth, the need to apply for a variety of permits and – depending on plant size – to conduct an environmental impact assessment, protects various public interests. On the other hand, by federal law the cantons are merely required to apply the so-called “Coordination Model” which requires them to coordinate individual permits to prevent discrepancies in what they cover. However, individual permits can be issued by different authorities, which is inconvenient for power plant operators and not really conducive to expediting the procedure.

- All considered, the current legal situation allows for more intensive exploitation of deep geothermal repositories, while the need to obtain a variety of different permits protects public interests (environmental protection, spatial planning, etc.). On the other hand, the process is extremely complex, less than transparent, and both confusing and time-consuming.

10.1.7 Public opinion

- While the changes associated with the energy transition in Switzerland and the shift to a larger share of renewable energy are generally welcome by the focus groups, the opinions concerning deep geothermal power vary significantly, from “full rejection” to “full acceptance.” No clear opinion pattern among the participants could be established.
- The participants in the focus groups appreciate the potential that energy produced by deep geothermal power plants might contribute to the energy supply, but this is expected to be minor in comparison to the potential supply by hydro, solar and wind.
- A majority of the participants in the focus groups associate positive aspects with deep geothermal power. Some arguments that are often mentioned point to “endless energy from the ground,” “good opportunity for geothermal power to contribute to the renewable energies,” and “low impact on environment.”
- However, the discussion in the focus groups also raised some critical issues, for example financial risks in case the water temperature at depth is too low for sufficient production of heat and power, technical risks that first need to be investigated, and compensation for damages to houses and infrastructure.
- Comparable to the results of the media analysis, the participants were aware of and shared experiences about the incidents at St. Gallen and Basel, and the financial and technical risks including seismic events.

10.1.8 Integrated perspective

Based on a limited-scope comparative analysis of geothermal energy with other “new” renewable sources of electricity and including trade-offs between environmental, economic, risk and security of supply performance criteria the following conclusions can be drawn:

- Generally, geothermal systems combining electricity with heat supply perform clearly better than those supplying electricity only. Compared to other “new” renewables geothermal with a heat credit ranks well for most of the tested preference profiles. One exception is the risk-centered profile due to the geothermal-specific possibility of induced earthquakes.
- Overall, a preference profile that exhibits balance between the high level sustainability criteria and is most favorable for geothermal options is one that emphasizes climate protection, minimization of human toxicity, metal depletion, risks other than induced seismicity and continuity of electricity supply.

- A preference profile that exhibits balance between the high level sustainability criteria and mostly disfavors geothermal options is one that emphasizes water depletion and induced seismic risks.

10.2 Policy Recommendations

10.2.1 Resources

- Promotion of open data policies for underground resources would benefit the assessment of resources and exploitation of reserves in the medium and long-term. Regulatory guidelines in countries such as Australia, which require operators as part of the licensing to make their seismic imaging and well-log data available after some time, could serve as a role model for Switzerland.
- Integrating and harmonizing data on the deep subsurface of Switzerland across cantonal and municipal boundaries would likewise be beneficial for the development of deep geothermal energy.

10.2.2 Technology

- Further promotion of geothermal energy production is necessary to scale up the market. This will motivate the companies to increase their R&D efforts for geothermal well drilling, which in turn will reduce the risks and costs of geothermal power production. Possible promotional measures could include further discovery and characterization of heat resources, technology development and demonstration, in addition to the current risk guarantees and feed-in tariff.
- Research on deep geothermal drilling induces massive costs. Especially field tests and demonstration plants require large budgets. Therefore, a competence center could be established to provide the framework for cooperation between research institutes and drilling companies, and to adapt advances in oil and gas drilling to geothermal purposes.

10.2.3 Economy

- There is still a need for further geological data to improve the geothermal cost supply curve. The geothermal gradient is important, but the reservoir development and flow rates depend on geological conditions that require drilling to determine, and we do not yet know these in a comprehensive way.
- The heat credit used in the present analysis shows that heat sales are very important for geothermal plant economics. The VFS report on future district heating potential gives heat market potential size and location. If all of this potential could be achieved and was supplied by geothermal energy, the amount of geothermal generation that could be achieved with a heat credit would be approximately equal to the BFE's target for the Energiewende.

- It would be a significant advance to link the locations of geological potential, political regulation, population (or sensitivity to seismicity), and heat markets to the economic model within a GIS framework, so that we can map out the resulting costs of geothermal electricity and show where the best potential locations may be, considering all these factors.

10.2.4 Environment

- Electricity from deep geothermal plants demonstrates favorable environmental performance. From the environmental point of view geothermal energy is an attractive potential contributor to the future Swiss electricity mix and deserves to be seriously considered.
- Radioactive deposits may occur in the pipes of the power plants, which may call for appropriate monitoring and treatment of wastes. This topic needs further investigations, and depending on their outcome, it may need to be anchored in the appropriate regulatory framework (e.g. HSE directives like those of HSE UK).

10.2.5 Risks

Non-seismic accident risks

- Based on the analyses and literature review performed in this study, blowout risk, release of hazardous chemicals, and geofluids containing NORMs (naturally occurring radioactive materials) or hazardous chemicals (e.g. arsenic) have been identified as areas of some concern.
- Therefore ongoing and future geothermal projects need to implement and follow adequate risk assessment and management procedures throughout all project phases that are based on state-of-the-art methodologies as well as regulatory regime conditions established by responsible authorities at cantonal and/or federal levels.

Risk of induced seismicity

- Deep geothermal energy is not risk free, and induced seismicity is likely the dominant physical risk of the technology. Even though basic risk management strategies exist and were applied successfully in geothermal projects, a more comprehensive and harmonized approach to induced seismicity risk governance is needed (across both technologies and cantonal boundaries).
- Future projects need to consider induced seismicity in all steps of the operation, embedded into a monitoring and reaction scheme. For Switzerland, industry, permitting and licencing authorities as well as regulators and enforcers need to understand their roles, responsibilities and accountabilities. Induced seismicity risks can be assessed and mitigated, albeit not to zero. There are likely no silver bullet solutions. The success rate and economic viability of deep geothermal energy depends strongly on the level of seismic risk that stakeholders are willing to take (in the extreme case a zero risk acceptance will imply no energy from deep geothermal).

Risk perception

- More attention should be placed by regulators and industry on the non-technical aspects of deep geothermal energy.
- The very process of planning, siting, and implementing geothermal projects must be closely accompanied by a carefully planned, continuously monitored, and scrupulously evaluated process of public and stakeholder engagement.
- Social site characterization could certainly complement the technical site characterization for future (pilot) projects.
- With respect to media coverage, industry members might themselves actively address risks and uncertainties as a major public concern and scientists could also focus on potential and existing risk mitigation strategies.

10.2.6 Regulation

- **Federal Authority:** An autonomous federal authority to regulate the exploitation of the subsoil for geothermal repositories − in a similar manner to the regulation of nuclear energy − would have the advantage that one federal permit (the so-called "planning approval") would make all other permits obsolete, since they would be covered by the planning approval. However from a political perspective, it seems unlikely that such an authority might be created.
- **Cantonal Authority:** In principle, cantons are authorized to issue regulations concerning subsoil use. Such regulations must include the following provisions: responsibility, type of use, expropriation, exploitation permit, procedure, human and material resources, liability, the coordination with other permits, charges, enforcement, and legal protection.
- **Cantonal Structure Plans and Land Use Planning:** The well-established instruments of spatial planning can basically be adapted to include the subsoil. The key instrument used by cantonal administrations is the cantonal structure plan, which is already provided for in Art. 6 et seqq. of the Spatial Planning Act. A cantonal structure plan has to indicate the land area that is suitable for geothermal exploitation (see Art. 6 et seqq. Spatial Planning Act). In addition, the Swiss government may make recommendations concerning subsoil planning which are not legally binding on the cantons.
- **Exemption of Cantonal Land Use and Protected Areas:** In the context of its "2050 Energy Policy", the Federal Council of Switzerland has proposed that the cantons should issue plans to protect their land and allow or prohibit different types of land use, which would have to be ratified by the Federal Council in accordance with the future Art. 13 of the Federal Energy Act (currently under review). Such a plan would create more transparency, enabling future investors to see which land area is actually available for projects to harness renewable resources; among other things, it would also help to expedite permit procedures.
- A **National Structure or Sectoral Plan?** The Bourgois Motion of 15 June 2011 asked for the Swiss government to review whether it would be in accordance with federal

law to issue a national structure plan listing locations suitable for deep geothermic exploitation. At the same time, it must be remembered that in accordance with Art. 75 of the Federal Constitution, spatial planning lies strictly within the competence of the cantons. The Swiss government issues sectoral plans only in areas in which it operates itself, or rather in which it fulfills its governmental role. The construction of geothermal plants is not a responsibility of the Swiss government.

- **Land Use Planning vs. Art. 24 Spatial Planning Act:** The mandate of a conscious allocation of areas to a specific zone based on democratic principles must not be undermined by the fact that geothermal plants, which are usually planned for sites that are not part of an official construction zone, are approved by means of an exemption in accordance with Art. 24 of the Spatial Planning Act.
- **Award of Licenses and Exploration Permits by Public Tender:** According to the Federal Domestic Market Act, a transfer of the exploitation of a cantonal monopoly must be awarded by public tender. With regard to the procedure to be employed in this context, the regulations applying to public tendering procedures might be adapted for this purpose. Since the actual license is usually awarded to the party that has already carried out the necessary preliminary exploration, the permit to conduct preliminary exploration should also be published in the official gazette.
- **Expediting Permit Procedures in General:** Procedures can, for example, be expedited by introducing processing deadlines. However, it must also be remembered that geothermal plants use complex, highly technological processes with a certain risk potential, which is why all interests must be examined carefully and weighed against the need for an expedited award. Furthermore, justifiably rigorous environmental protection and spatial planning requirements must be met. Nevertheless, the Federal Council could pass recommendations to expedite permit procedures in the whole of Switzerland.
- **Expediting Specific Aspects of Permit Procedures:** A geothermal project is usually subject to extensive permit procedures including licensing, planning, and building permits, and it must fulfill different legal requirements and protect the interests of different stakeholders, requiring a complex, intensive process of weighing different interests against each other. Such procedures are necessarily very time-consuming. One way to expedite procedures would be to combine planning permission and licensing procedures and grant the building permit at the same time as the license. Preferably, this should be handled by one authority in line with the Swiss Concentration Model.
- **Federal Act on the Coordination of Permit Procedures for Renewable Energy Projects (Grunder Motion):** In the case of most installations for the exploitation of renewable energy, the Swiss government has no wide-reaching authority, which is why issues concerning procedures and/or competence fall within the regulatory jurisdiction of the cantons. The government does not have the power to impose a single federal authority on the cantons to issue all permits. At most, it could revise Art. 25a of the Spatial Planning Act by providing for the Concentration Model.
- **Introducing the Concentration Model:** Some cantons have adopted a Concentration Model in which an authority coordinates the content of various permits and grants them as a package. According to such a model, the decision to grant a license also

includes all permits and rulings by other authorities. This solution is effective and convenient. After all, in processing a license application many issues regularly need to be addressed that also affect other permits. Such a model would serve to expedite procedures and facilitate communication with those to whom a ruling is addressed.

- **General Land Use License:** An interesting instrument to expedite procedures and ensure investment security is used by the canton of Schwyz: Whenever a cantonal or communal land use plan is to be issued, a decision regarding a general land use license must be made at the same time (§ 34 (1) Ordinance to the Federal Act on Mineral Royalties and Subsoil Use). This general land use license must regulate important aspects at the preliminary stage (§ 35 (1) Ordinance to the Federal Act on Mineral Royalties and Subsoil Use). The general land use license can also contain a permit for preliminary exploration and investigation measures.

10.2.7 Public opinion

- Acceptance of geothermal energy by citizens and stakeholders does not require a very positive attitude, but citizens need to tolerate and integrate the energy concept in their regional living environment. A neutral to quite positive opinion is beneficial. Therefore it is important to have an **understanding of the role of geothermal energy in the future energy mix, an appreciation of the benefits and an emotional possibility to identify with the envisioned project as an element of regional or local familiarity.**
- **Communication and public participation** from an early stage of the project should accompany any public geothermal energy project, but early participation does not guarantee the success and acceptance of the project. Public participation should be implemented in a transparent process with an open outcome; if this is not feasible a good and convincing communication strategy is the better option.
- In some cases, the acceptance will decrease with public participation: people are better informed about risks and benefits, and therefore more aware of the potential consequences for themselves.
- **Clear, easy to understand, and well-balanced information** including the state-of-the-art knowledge on deep geothermal power is essential and needs to be provided to the public. This should especially cover the trends in the energy sector, risks of earthquakes triggered by fluid injection associated with reservoir creation and operation, a clear assessment of financial benefits and risks as well as an estimation of the consequences if a project were about to fail.

10.2.8 Integrated perspective

- It is advisable to turn the attention of decision-makers and stakeholders towards the potentially important role of geothermal energy in an increasingly decentralized electricity supply system with a high share of intermittent renewables. Geothermal energy is one of few “new” renewable options that can supply baseload power and thus substantially contribute to security of supply.

- It is recommended to conduct stakeholder workshops in connection with geothermal projects, illustrating in a balanced manner the relative strengths and weaknesses of geothermal energy in comparison with other electricity supply options.

10.3 Recommendations for further Research

10.3.1 Resources

Additional and updated information is needed for the purpose of generating more reliable estimates of geothermal resources and especially reserves for electricity generation. This includes:

- New and updated surface heat flow map of Switzerland.
- Regional temperature model of Swiss Molasse basin for 70 °C depth environment.
- Regional temperature model of Switzerland for 120 °C to 170 °C depth.
- Reliable map of major fault systems in granitic basement in northern Alpine foreland.
- Seismic risk assessment for petrothermal plants in the granitic basement in relation to regional fault systems and tectonic loading by Alpine orogeny.
- Validated strategies for seismic risk mitigation.
- Improved quantitative modeling of long-term heat extraction and reservoir behavior for resource and reservoir assessment rather than the oversimplified calculations typical for current estimates.

10.3.2 Technology

Reservoir creation

- A major use-inspired, basic research effort, coupled to a program of pilot and demonstration projects, is needed to enable the construction of petrothermal systems that meet commercial performance targets. The program should include the following elements:
  - ✓ Improvement in our understanding of the pressure distribution within reservoirs during hydraulic stimulation.
  - ✓ Improvement in our knowledge of channeling at both the fracture and fracture-network scale, and its effect on impedance, fluid transport and heat transfer.
  - ✓ Improved understanding of the mechanisms of permeability creation/enhancement process (e.g. shear-induced dilation, and pull-apart structures). Improved understanding of the mechanisms of permeability creation/enhancement process (e.g. shear-induced dilation, pull-apart (step-over) structures, and wing cracks).
  - ✓ Answering the question: “How important is hydrofracturing in the stimulation of crystalline reservoirs?” (see Section 3.2.2.2.1)

- ✓ Does aseismic slip or (aseismic tensile fracture opening) contribute significantly to the permeability enhancement, i.e. better understanding of the factors that can lead to slip occurring aseismically (e.g. friction laws).

Drilling

- Further research in drilling, casing-cementing and well completion is needed to significantly reduce drilling related costs and risks in order to enhance the development of geothermal power production. Specifically, R&D is needed for drilling in hard rock, due to current low penetration rates and high drill bit wear rates.
- As the drilling companies are focusing on short-term developments to continuously improve the state of the art, the research institutes should focus on innovative drilling methods that have the potential to reduce drilling related costs in the long-term, including the application of developments in the oil and gas sector. These innovative technologies are connected to major challenges and high risks.

10.3.3 Economy

- An improved understanding of the reservoir creation process and its dependence on geological conditions is crucial for the development of a more robust geothermal cost supply curve. The temperature gradient is important. However, the ability to create a reservoir that delivers the requisite flow of hot water for sufficient time is no less crucial, and this is currently difficult to assess from measurable geological data.

- It would be a significant advance to link the locations of geological potential, political regulation, population (or seismicity sensitivity), and heat markets to the economic model within a GIS framework, so that we can map out the resulting cost of geothermal electricity and show where the best potential locations may be, considering all relevant factors.

10.3.4 Environment

- The Life Cycle Inventory can be improved by:
  - ✓ Further analysis of the number of unsuccessful wells
  - ✓ Implementation of more accurate data on the drilling energy use and composition of the drilling fluid
  - ✓ Implementation of more accurate data for the energy and water use in the stimulation phase
  - ✓ Accounting for possible emissions of natural gas during drilling/stimulation, radioactive emissions or deposits
  - ✓ Modelling different binary cycle plant designs

- The energy use for the downhole pump and for the organic Rankine cycle and the cooling should be separated so that possible different energy sources can be considered.

10.3.5 Risks

Non-seismic accident risks

- A detailed analysis of the risk associated with geofluids in the operational phase is of great importance in order to understand their possible effects, primarily on the workers due to the brine present in the binary cycle. In addition, the risk of underground freshwater contamination due to the geofluid circulation could be a major concern for various stakeholders.
- The risks of chemicals used in hydraulic stimulation in petrothermal systems should be investigated in detail, and also compared to shale gas fracking because this aspect is likely to influence public perception and risk aversion.
- Although the risk related to the use of hazardous chemicals in deep geothermal systems has been roughly assessed, further work is recommended. In order to perform a comparative evaluation of the risk posed by different substances, exposure and toxicity levels must be taken into account.
- Detailed HAZIDs, HAZOPs and HSE will provide a substantial contribution to comprehensive risk assessment for deep geothermal energy projects.

Risk of induced seismicity

- The understanding of induced seismicity, and the ability to forecast it, has advanced greatly over the past eight years, owing largely to the data and experience from the Basel and St. Gallen projects, and supported through a range of projects funded by the academic community and industry. These efforts need to be continued over the next few years.
- Validation of the emerging induced seismicity modeling tools and mitigation strategies is now the most important need of the community. Future pilot and demonstration projects are key to these validation efforts.
- Studying induced seismicity at the scale of a deep underground laboratory offers an opportunity to significantly enhance the understanding and forecasting ability of induced seismicity related to reservoir creation in a repeatable, controllable and safe environment. Most of the processes relevant for induced seismicity are scale invariant – so they can be studied in-situ, for example using a setup at the scale of 1:10. The observed micro-earthquakes would then pose no risk.
- Research in deep geothermal energy needs to be increasingly cross-disciplinary because solving the coupled problem of efficient reservoir creation while limiting seismic risk requires experts from geophysics, geology, mineralogy/petrology, physics, engineering and computational sciences to work closely together as team.

Risk perception

- A content analysis of newspapers from the French-speaking part of Switzerland similar to the one done here in the German-speaking part could point to existing differences in the media discourse on deep geothermal energy. Further, an analysis of local newspapers could provide a more detailed view of regional political discussions.
- It would be interesting to measure directly how the public reacts to the different arguments and frames used by different actors. Psychological experiments could offer more insights into these processes. Such experiments would potentially be relevant for public communication of deep geothermal energy in Switzerland.

10.3.6 Public opinion

Research into public opinion and public acceptance should address the following questions:

- Which are the main factors affecting the acceptance of a given geothermal energy project in more detail?
- What factors and processes can be identified that influence individual and group decision-making about tolerating or accepting a geothermal project?
- How could the government combine the political and strategic planning process with public participation in Switzerland's different cantons and communities?
- In detail, how could the different communications strategies be made more transparent and clear?
- Which legal requirements are necessary to assure that communication and participation are implemented in each planning process?

10.3.7 Integrated perspective

- Scope extensions of the current analysis are needed with respect to comparative assessment. This includes carrying out analyses for a much wider spectrum of technologies including future ones that reflect technological advances. Furthermore, the set of evaluation criteria should be extended.
- The future potential role of geothermal energy in Switzerland needs to be addressed in the context of the overall energy supply system. This can be accomplished using state-of-the-art technology-rich energy-economic models with detailed representation of geothermal energy and other supply options.

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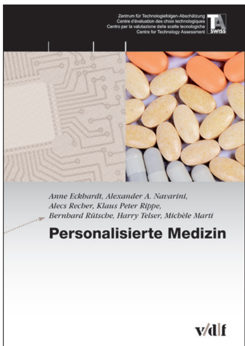

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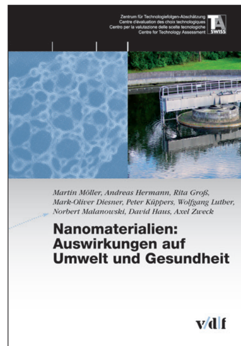

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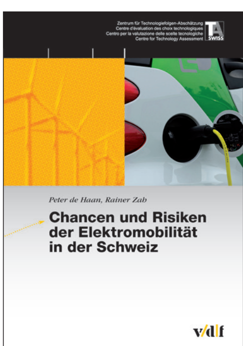

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Tel. +41 (0)44 632 42 42, Fax +41 (0)44 632 12 32, verlag@vdf.ethz.ch, www.vdf.ethz.ch

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Switzerland's Energy Strategy 2050 requires energy efficiency to be substantially improved, the proportion of fossil fuels in the energy supply to be considerably reduced, and nuclear power to be phased out, while meeting highly ambitious climate protection targets. One of the core implications is the need for a massive increase of the use of renewable sources for electricity generation.

In this context, the Swiss Federal Office of Energy (SFOE) estimates that by 2050 deep geothermal energy could contribute 4–5 TWh per year to electricity generation in Switzerland, which would be a substantial contribution to a projected annual power need of 60 TWh. Geothermal energy is attractive because of the very large scale of the resource, its expected relatively low CO_2 *emissions, and its reliable, all-day domestic availability. However, the future contribution of deep geothermal energy is subject to major uncertainties: How much of this resource can be exploited and at what economic cost? What are the environmental and risk-related externalities that the public must be willing to bear? How does its overall performance compare to competing energy resources? And will the regulatory framework and public acceptance be sufficient to allow geothermal energy to provide a significant contribution?*

By way of this major interdisciplinary study, already considered a work of reference, TA-SWISS provides answers to these questions in a comprehensive and balanced way, thereby supplying a sound basis for stakeholder decision-making.

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TA-SWISS 62/2015

ISBN 978-3-7281-3654-1 (Print)
Download open access:
ISBN 978-3-7281-3655-8
DOI 10.3218/3655-8