

Charting the Path to Net-Zero: A Case Study of Integrated Energy Systems in a Swiss Valley

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Abstract

Closely aligning with Switzerland's long-term climate policy, the canton of Graubünden is committed to achieving net-zero emissions by 2050 through the Aktionsplan Green Deal. In support of these ambitions, this study investigates cost-optimal future energy system configurations for an urban-industrial cluster in the Rheintal valley of canton Graubünden. Due to the presence of waste incineration and cement industry, per capita CO₂ emissions in the valley are approximately 10.5t per annum (2024), nearly three times the Swiss average. A sector-coupled energy system model based on mixed-integer linear programming is employed to evaluate the most cost-effective solution while complying with the emission targets of reaching Net-Zero by 2050. By explicitly incorporating the carbon cycle into the energy system model, the framework enables a comprehensive evaluation of both energy infrastructure and carbon capture and storage solutions.

A reference model for 2024 was first built and validated in close collaboration with local industries, energy providers, and governmental authorities. Building on this calibrated and validated reference, two contrasting scenarios for 2050 were developed. The results consistently show that reaching net-zero emissions by mid-century in the Rheintal relies on implementing two key solutions: 1) utilization of waste heat from industry using district heating networks; and 2) deployment of carbon capture technologies to capture residual emissions. Besides these, extensive electrification of buildings and mobility will also play a crucial role in achieving this goal. Despite substantial upfront investments, results from the sensitivity analysis indicate that total annualized system costs in 2050 could decrease by approximately 20-40% relative to current levels, assuming significant learning effects across the carbon capture, transport, and storage chain. This reduction is driven primarily by efficiency gains, increased use of local resources, and reduced reliance on fossil fuel imports. The analysis highlights the inherent synergy between industries and households in shaping a resilient future energy landscape and promotes coordinated decision-making among regional stakeholders to achieve climate targets.

Glossary

MILP: Mixed Integer Linear Programming
CCS: Carbon Capture and Storage
DHN: District Heating Network
AGD: Aktionsplan Green Deal
ANU: Office for Nature and Environment of Graubünden
Excess heat: Usable heat from industrial processes at different temperature levels
Waste heat: Excess heat which is not used currently
CAPEX: Capital expenditure
FOM: Fixed operation and maintenance cost
VOM: Variable operation and maintenance cost
PV: Photovoltaic
EV: Electric Vehicle
MSW: Municipal Solid Waste
CSW: Cement Solid Waste
CHP: Combined Heat and Power
ThLt: Thermal energy at low-temperature (20-60 °C)
ThHt: Thermal energy at high-temperature (60-120 °C)
ThPhl: Thermal energy for process heat (120-200 °C)
ThPhll: Thermal energy for high-temperature process heat (>200 °C)

1. Introduction

1.1. Background

Switzerland has set an ambitious goal of achieving net-zero Greenhouse Gas (GHG) emissions by 2050 as part of its long-term climate strategy. While significant progress has been made, with a 24% reduction in emissions since 1990, residual emissions remain a major challenge. In 2022, Switzerland's total GHG emissions stood at 41.6 Mt CO₂eq* ¹ ([link](#)), and despite ongoing decarbonization efforts in some sectors, approximately 12 Mt CO₂eq could persist in 2050 ^{2,3} ([link](#), [link](#)). These emissions originate primarily from hard-to-abate sectors such as industry, aviation, and agriculture, where carbon-intensive processes are difficult to replace. Notably, waste incineration and cement industry alone contribute nearly 5 Mt CO₂eq, underscoring the need for mitigation strategies.

A key issue in this context is the close proximity of many industrial sites to residential, commercial, and office areas, which can increase local exposure to emissions and associated environmental impacts. While industrial activities emit direct CO₂ emissions, they also generate substantial amounts of excess heat. A major portion of this excess heat, referred to here as waste heat, is commonly released unused into the environment ^{4,5} ([link](#),

* excluding international aviation and shipping and land use changes/forestry

[link](#)), with one study estimating a total annual waste heat potential of 37 TWh in Switzerland ⁶ ([link](#)). Integrating synergies of industrial and residential energy systems offers a valuable opportunity to improve energy efficiency, reduce emissions, and strengthen overall system resilience. A holistic and integrated approach that embraces and leverages these synergies and interconnections is essential for designing effective and resource-efficient transformation pathways toward Switzerland's net-zero future.

1.2. Literature review

The integrated analysis of energy systems is an essential strategy for advancing the energy transition. The European Commission defines it as the coordinated planning and operation of the energy system as a whole, spanning across various energy carriers, infrastructures, and consumption sectors ⁷ ([link](#)). Sector coupling has emerged as a concept of enabling technologies for integrating traditionally siloed sectors such as electricity, heat, transport, and industry and energy systems ^{8–10} ([link](#), [link](#), [link](#)). Previous studies highlight sector coupling technologies like power-to-gas, power-to-heat, and other power-to-X solutions ^{11–14} ([link](#), [link](#), [link](#), [link](#)). These technologies convert surplus renewable electricity into hydrogen, thermal energy, and synthetic fuels, thereby enhancing system flexibility and reducing fossil fuel dependency. A handful of modeling studies further demonstrate that a holistic, sector-coupled approach can unlock significant cost efficiencies, improve resource utilization, and facilitate a more robust transition toward net-zero emissions by exploiting cross-sector synergies ^{15–19} ([link](#), [link](#), [link](#), [link](#), [link](#)).

Sector coupling goes beyond utilizing renewable electricity, harnessing other energy carriers such as excess heat through District Heating Networks (DHN) ^{20–22} ([link](#), [link](#), [link](#)). DHN, powered by renewable or excess heat sources, can offer an effective alternative to fossil-based heating systems by distributing heat from centralized sources to residential, commercial and office areas. In Denmark, for instance, the integration of DHNs with renewable energy sources demonstrated a significant reduction in carbon emissions while enhancing energy security ²³ ([link](#)). Several studies further explore cross-sector synergies, demonstrating additional efficiency gains via the integration of industrial residual heat into residential DHNs ^{24–26} ([link](#), [link](#), [link](#)).

Industrial processes involving combustion and calcination processes generate flue gases with high CO₂ concentrations (approximately 10-30 V%) ²⁷ ([link](#)), contributing to a quarter of global emissions in 2019 ²⁸ ([link](#)). Point source CO₂ capture is a key approach to curb emissions from cement, waste incineration, chemicals, and steel industries among others enabling a net-zero transition without requiring major redesigns ^{29–32} ([link](#), [link](#), [link](#), [link](#)). Large-scale carbon capture and storage (CCS) projects demonstrate its feasibility, such as Norway's Longship project ^{33,34} ([link](#), [link](#)), which aims to capture industrial emissions from cement and waste-to-energy plants using an amine-based technology and transport them offshore via the Northern Lights project ³⁵ ([web](#)). Similarly, DemoUpCARMA highlights CCS integration into existing energy systems ³⁶ ([web](#)). Moreover, establishing CCS hubs ³⁷ ([link](#)), like Net Zero Teesside Power ³⁸ ([link](#)), can optimize transport by aggregating CO₂ from multiple industries and utilizing shared infrastructure for cost-effective storage.

While CCS offers potential merits, its energy-intensive capture process incurs a 25–40% energy penalty ³⁹ ([link](#)), adding significant electricity and heating demand on the overall energy system and limiting the feasibility of standalone applications. Industrial processes offer opportunities for CCS implementation due to both the

high CO₂ content in flue gases and the potential for heat integration ^{40,41} ([link](#), [link](#)). By upgrading and utilizing industrial excess heat to power CO₂ capture infrastructures, there is an opportunity to not only maximize energy efficiency but also to drive decarbonization ^{42,43} ([link](#), [link](#)).

Moreover, a holistic energy system design requires integrating the carbon cycle into energy models to capture system-wide emissions and feedback. Traditional energy models optimize energy flows and technology deployment but often overlook dynamic carbon interactions across carbon sources, sinks, and reservoirs. Li et al. emphasize that incorporating carbon flows in multisectoral complex energy system models is crucial for accurately assessing decarbonization strategies ⁴⁴ ([link](#)). Without this integrated assessment, emissions reductions in one sector may be offset by increases elsewhere. Integrating carbon cycle dynamics can provide system designers and policymakers with the required insights for sustainable urban planning and policy, supporting carbon neutrality goals set by international climate agreements ⁴⁵ ([web](#)).

When looking at integrated energy systems, clusters with urban areas and industries present a unique opportunity to exploit synergies through shared energy infrastructure. For example, excess heat can either be redistributed to residential, commercial, and office areas with DHNs, power CCS units at the industries or both. A comprehensive review by Butturi et al. look into the urban-industrial energy symbiosis and reinforces the importance of systems that jointly benefit both heavy industries and adjacent residential sectors ⁴⁶ ([link](#)). Such integration is critical to achieving net-zero emissions as it enables synergistic use of resources.

However, expanding energy models beyond electricity poses several difficulties, since detailed representation of industry processes and high-resolution data on demand, excess heat, and other key factors are often unavailable to academic energy system modelers ^{47,48} ([link](#), [link](#)). Complexity also increases with the involvement of multiple stakeholders, including industrial partners, energy providers, local authorities, and citizens, requiring a collective approach ⁴⁹ ([link](#)). Many studies overlook the socio-economic dynamics and stakeholder coordination needed for effective implementation. A recent study by Jiang et al. reveals that while firms set emission reduction targets, many fall short due to lack of accountability and inadequate incentives ⁵⁰ ([link](#)). Lombardi et al. highlight the disconnect between the energy system models and stakeholder needs as a reason for the slow progress in energy transition ⁵¹ ([link](#)). Involving stakeholders in decision making, modeling the system close to reality, and leveraging cross-sectoral synergies can help achieve the prescribed targets.

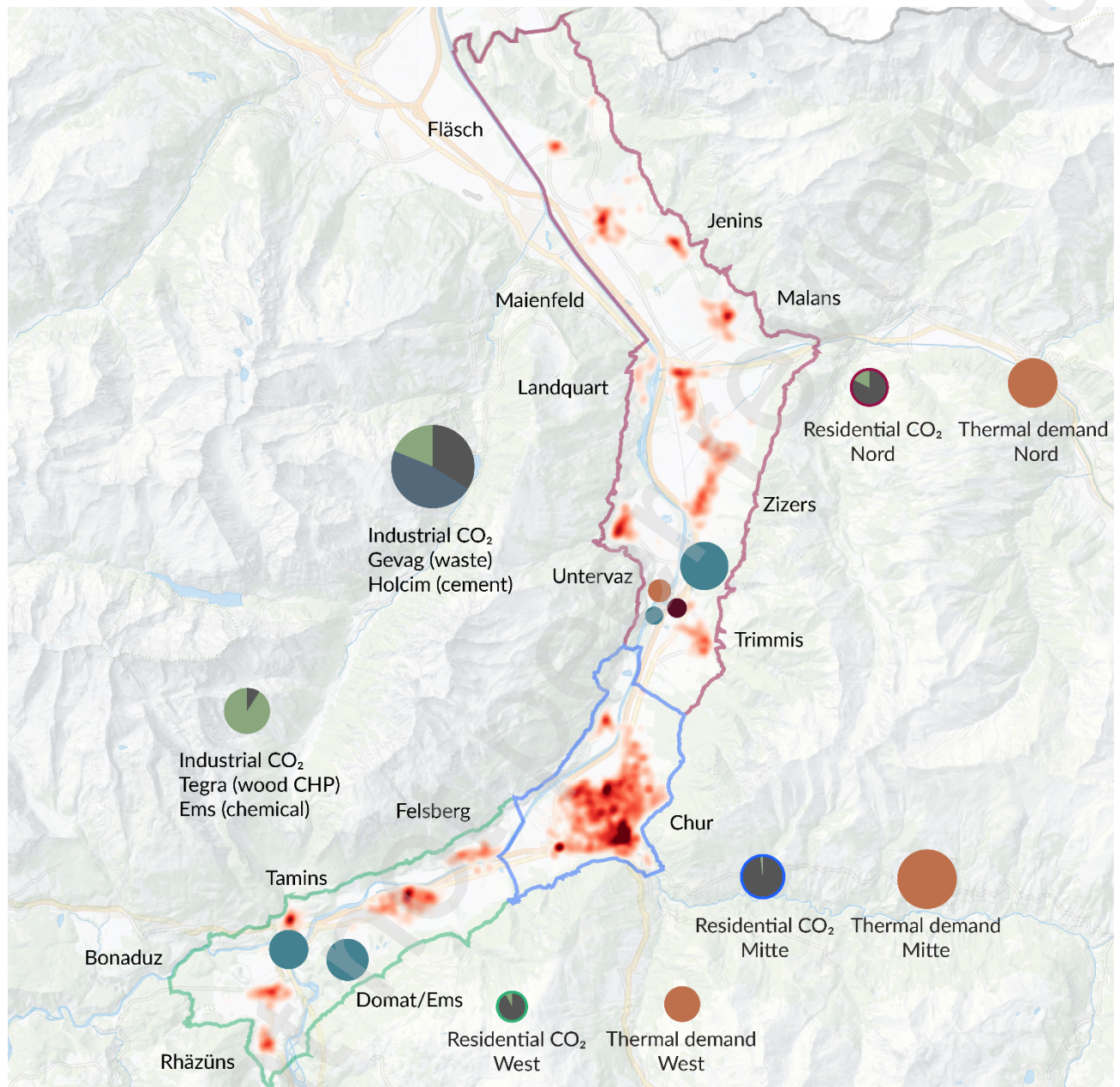
Past research underlines the importance of integrating energy systems, DHN, CCS, and the carbon cycle for designing sustainable and robust decarbonization pathways. While industry-residential clusters present opportunities for system integration, they remain underexplored in modeling studies. Enhanced modeling frameworks that consider regional dynamics and stakeholder coordination are essential to support timely and actionable progress toward achieving net-zero goals. However, gaps persist in the ability of models to reflect regional complexities, particularly in scenarios requiring high-resolution analyses of energy demands, carbon flows, and stakeholder interactions.

1.3. Contributions of this paper

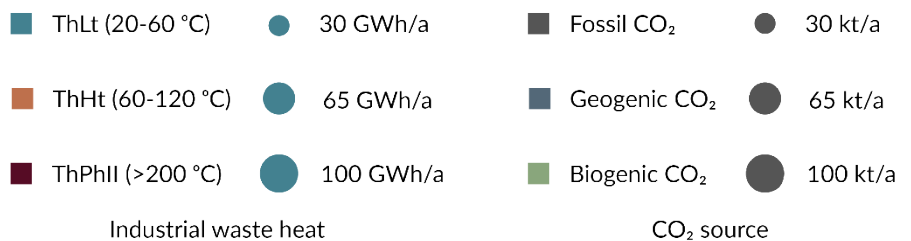
To address these gaps, this paper explores the cost-optimal transition pathways for the urban-industrial cluster in Rheintal, a regional valley in Switzerland's canton of Graubünden. Under the Aktionsplan Green Deal (AGD),

the canton, in collaboration with local stakeholders and the public aims to achieve net-zero emissions by 2050⁵² ([link](#)). Rheintal's per capita CO₂ emissions are nearly three times the Swiss average predominantly due to emissions from the cement and waste incineration plant. However, conducting detailed regional energy system analysis requires real-world data from key stakeholders. To facilitate collaboration and knowledge sharing among decision-makers, the Office for Nature and Environment of Graubünden (ANU) established the *Energy System Rheintal 2050 round table*. The aim was to jointly develop an independent regional energy system analysis with the stakeholders and Empa as scientific partner.

A reference energy system model for 2024, reflecting the current energy landscape, was developed and validated in close collaboration with local industries, energy providers, and governmental authorities. A detailed analysis of CO₂ emissions and excess heat flows identified key inefficiencies within the system. Building on this calibrated and validated reference, two contrasting baseline scenarios were defined for 2050, with separate models constructed to explore potential transition pathways. The results of these models were analyzed, followed by a sensitivity analysis to assess the robustness of the findings and their implications for long-term system planning. This study aims to answer two research questions: 1) How can we utilize synergies and interdependencies between different sectors within a regional energy landscape to achieve net-zero targets? and 2) What are the roles and impacts of CCS and DHN in achieving net-zero targets for an urban-industrial cluster?



Thermal demand



Industrial waste heat

CO₂ source

Graphical abstract

2. Methodology

Energy system models provide critical support for energy policy development, decision-making and the assessment of various energy transition pathways ⁵³ ([link](#)). Through mathematical representation of energy systems, these models help system planners to determine the most cost-optimal ways to generate, store, transport, and use energy while taking into account spatial and temporal scales, and across multiple possible future scenarios ⁴⁷ ([link](#)). Here, the sector-coupled ehubX optimization framework is deployed to build, calibrate and validate an urban-industrial cluster model representing the “current state” of the system, based on comparisons with historical data. Using this validated model as a baseline, we further optimize the future system and explore the solution space to achieve net-zero emissions by 2050.

2.1. Formulation of the energy system model

The ehubX optimization framework is based on a mixed integer linear programming (MILP) formulation. Model formulation in ehubX follows the energy hub principle ⁵⁴ ([link](#)). The mix of technologies, imports and exports is chosen based on the objective function to minimize system cost and the set boundary conditions, including net-zero emissions by 2050 ⁵⁵ ([VSE](#)). Costs, efficiencies and CO₂ emissions factors for all technologies and energy carriers can be found in **Supplementary Information**. The input data, decision variables and constraints to the Rheintal model implemented in ehubX are summarized in **Table 1**.

Table 1: Overview of the input data, decision variables and constraints to the ehubX optimization framework

Category	Key aspects
Input data	Energy demands (electricity, space heating and cooling, domestic hot water, industrial process heating), renewable capacity factors, available area for solar technologies, cost parameters (CAPEX, VOM, FOM), direct CO ₂ emissions of primary energy (imports and exports), technical performance (efficiencies, lifetime, availability), geographic distances for heating networks.
Decision variables	Installed capacities, area footprint for renewables, primary energy consumption, energy generation, CO ₂ emissions.
Constraints	Energy balance (demand-supply matching at every timestep), technology behavior (minimum or maximum capacities, time availability, operation), system-wide CO ₂ emission limits.

Objective function

The objective function is to minimize the total annualized system cost

$$\min C_{\text{total}}$$

where C_{total} includes investment, operation and maintenance, import costs and export revenues as

$$C_{\text{total}} = \sum_{c \in \text{Tech}} C_{\text{inv}}^c + \sum_{c \in \text{Tech}} \sum_{t \in \text{TTS}} \sum_{e \in \text{EC}} (C_{\text{fom}}^{c,t,e} + C_{\text{vom}}^{c,t,e}) + \sum_{t \in \text{TTS}} \sum_{e \in \text{EC}} (C_{\text{imp}}^{t,e} - R_{\text{exp}}^{t,e})$$

Here,

C_{inv}^c refers to the annualized overnight investment capital for installation and commissioning of all technologies

$C_{fom}^{t,c}$ refers to the annualized fixed operation and maintenance costs for all technologies

$C_{vom}^{t,c}$ refers to the variable operation and maintenance costs specifically for all technologies at each timestep

$C_{imp}^{t,e}$ refers to the cost for importing an energy carrier into the system boundary at each timestep

$R_{exp}^{t,e}$ refers to the revenue generated from exporting an energy carrier out of the system boundary at each timestep

2.2. Abstraction of the energy system

General modelling approach

The Rheintal valley stretches along the Rhine River and comprises of three major towns along with several smaller municipalities in the surroundings. In this study, the system boundary of the urban-industrial cluster extends from Fläsch to Rhäzüns. The requirements of urban areas and CO₂-intensive industries were evaluated in an integral energy system model with ehubX and a cost-optimal pathway for the valley to reach 2050 net-zero goals was charted.

The current energy system in Rheintal, equipped with state-of-the-art conversion, storage, and network technologies, served as the reference energy system (REF). This system model was developed closely with the stakeholders, calibrated to reflect the existing primary energy demands and consumptions, and validated against the status-quo energy system. This detailed approach ensured that the REF system was grounded in the real-world constraints and capabilities of the Rheintal valley, providing a robust foundation for subsequent analyses.

Energy balancing zones: Hubs

We clustered the valley into seven energy balance zones, hereafter referred to as hubs. Of these, three are classified as urban hubs, named after their geographic location in the Rheintal: West, Mitte, and Nord, representing the major towns of Domat/Ems, Chur, and Landquart, respectively. These hubs also include their neighboring municipalities and small to medium-sized industries. The remaining four hubs consist of four large industrial sites, including a municipal solid waste (MSW) incineration plant "Gevag", a cement plant "Holcim", a wood-fired combined heat and power (CHP) plant "Tegra", and a chemical plant "Ems". The energy system model with seven hubs required an abstraction of the Rheintal valley to represent its complexity at the necessary level of detail as presented in the **Supplementary Information**.

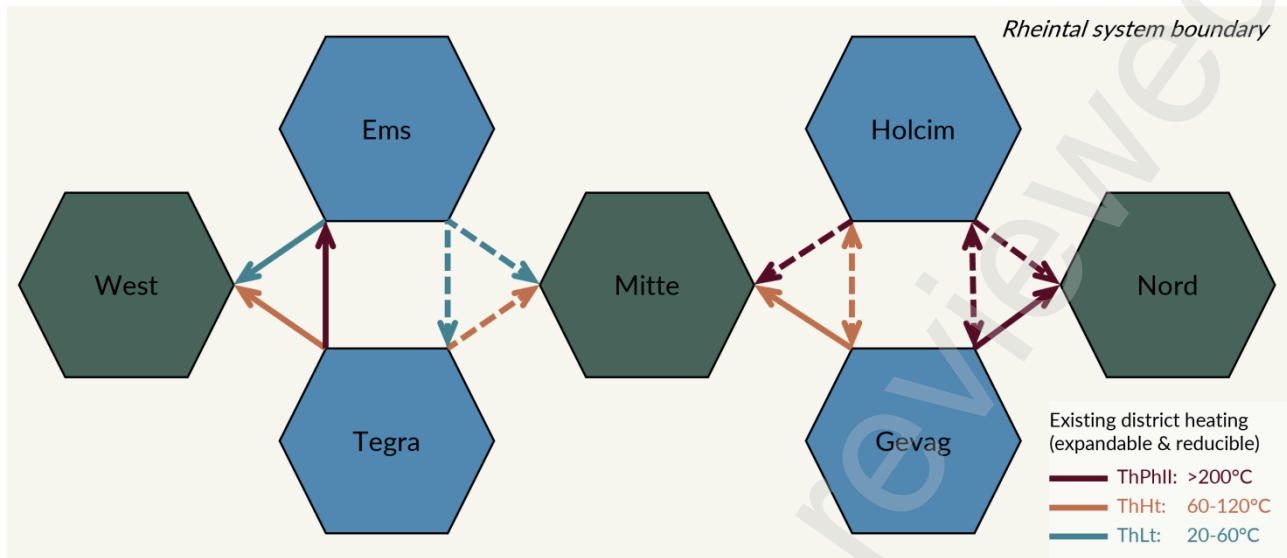


Figure 1: Overview of the individual energy balancing zones of the Rheintal, also referred to as hubs. The energy system Rheintal is built up of three urban (green), and four industry hubs (blue). District heating network at different temperature levels connect the hubs in the Rheintal valley. Solid lines stand for existing connections which can be extended or reduced in 2050. Dashed lines stand for future network connections.

Networks

The connection between hubs focused on heat integration via district heating networks (See **Figure 1**). District heating networks in the model were divided into three temperature levels as shown in **Table 2** along with the existing district heating networks in Rheintal. The temperature levels were estimated using indicative ranges from a previous report ⁵⁶ ([link](#)).

Table 2: Classification of existing district heating connections in Rheintal by different temperature levels, categorized according to their respective temperature ranges. The annual energy flows from the networks, in brackets, already account for efficiency losses in individual network lines. In addition, certain medium-sized industries had process heat requirements (ThPhI: 120 °C – 200 °C) that remained outside the scope of the district heating supply.

Temperature level	Range	Existing District Heating Connections
Low-temperature heat (ThLt)	20 °C – 60 °C	Ems -> West [2.1 GWh/a]
High-temperature heat (ThHt)	60 °C – 120 °C	Gevag -> Mitte [44 GWh/a] Tegra -> West [3 GWh/a]
High-temperature process heat (ThPhI)	>200°C	Gevag -> Nord [69 GWh/a] Tegra -> Ems [100 GWh/a]

Electricity and gas grids were also considered in the model, but not explicitly modeled as networks between hubs. Instead, each hub in the model was connected separately to the high-voltage electricity transmission grid. Grid fees were considered on a per-hub basis. Large power plants, such as run-of-river or hydro

reservoirs, connected to the higher voltage grids were outside the system boundary of Rheintal and hence were not explicitly modeled. A similar approach was chosen to integrate natural gas, biogas, synthetic methane, and hydrogen imports and distribution to each hub.

Gevag primarily supplies 69 GWh/a high-temperature process heat (steam) to Landquart, serving medium-sized industries such as a paper manufacturing facility. Additionally, it supplies 44 GWh/a high-temperature district heating to Chur besides also generating electricity for the high-voltage grid. The CHP plant supplies 100 GWh/a high-temperature process heat demand for the neighboring chemical plant in Domat/Ems. Since 2024, it also supplies a small amount of high-temperature district heating to Domat/Ems. Lastly, discharge water from the chemical plant is upgraded using a heat pump in Domat/Ems to supply a small quantity of low-temperature heat.

Urban energy demands

The energy requirements of the urban hubs were determined with a bottom-up approach using the Urban Building Energy Modeling (UBEM) tool CESAR-P⁵⁷ ([link](#)). A set of building characteristics (type, age, and 2.5D geometry) were first compiled based on the methodology from Eggimann et al., 2022⁵⁸. Building type and age were used to apply typical constructions and use patterns based on Swiss building archetypes developed in ([link](#))⁵⁹. The useful energy demands for space heating and cooling, domestic hot water, and electricity of each building were then simulated using CESAR-P, which is based on EnergyPlus⁶⁰ ([link](#)). Additionally, we accounted for past retrofits when simulating the energy demands for the REF system^{61,62} ([link](#), [link](#)) whereas an annual retrofit rate of 2.7% was assumed until 2050*. These demands were then aggregated by hubs and integrated into the energy system model with an hourly resolution. **Figure 2** shows the annual energy demands and CO₂ emissions for the urban hubs in 2020 and in 2050. The types of buildings, age categories and retrofits considered in this study are mentioned in **Supplementary Information**.

* The retrofit rate is based on data from an article currently under preparation for publication.

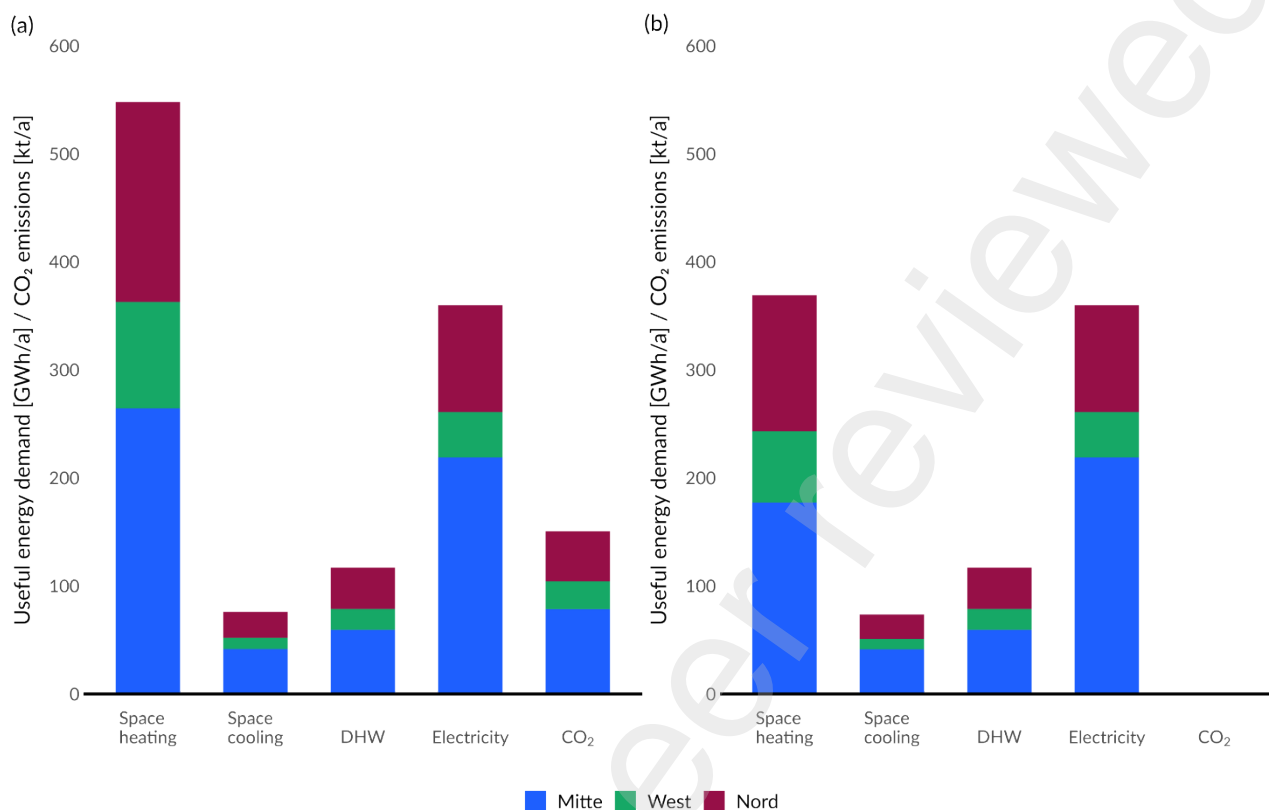


Figure 2: Overview of useful energy demands and CO₂ emissions (Scope 1 and 2) for the three urban hubs in (a) 2020 and (b) 2050. The electricity demand shown excludes electricity for electric vehicles.

Urban heating systems

Currently, fossil-based sources supply more than two-thirds of the heating demand of buildings in the valley. In the REF system, the distribution of heating technologies in the urban areas was based on data from the cantonal firing register. In addition, the supply of gas and district heating in the towns of Chur and Landquart, the boreholes approved for heat supply using geothermal heat pumps, and the air-to-water heat pumps subsidized since 2017 were also included. The distribution of heating system output was as follows: 37% gas boilers, 32% oil boilers, 14% heat pumps, 8% wood boilers, 7% district heating, and 2% electric resistance heaters. Renewable heating systems such as air-source heat pumps (ASHPs), energy grid heat pumps (AGHPs), ground-source heat pumps (GSHPs) along with an expansion of the district heating networks were candidates to replace fossil-based heating systems in the future.

Mobility

In the mobility sector, three types of vehicles were considered in the mobility sector: gasoline-powered vehicles, diesel-powered vehicles, and electric vehicles (EVs). The energy consumption of a gasoline or diesel vehicle was assumed to be 9,085 kWh per year, while an EV was estimated to consume 2,862 kWh per year on average. Fossil-fueled vehicles were modeled with a constant average demand time series, whereas EV demand was based on an archetypical charging profile^{63,64} ([link](#), [link](#)). Additionally, due to urbanization and population migration to larger cities, the total vehicle fleet in Rheintal was assumed to decrease by 5% by 2050, with 80% of the remaining fleet transitioning to EVs⁶⁵. **Figure S5 in Supplementary Information** shows

the evolution of the vehicle fleet in Rheintal from 2020 to 2050. The energy demands from the mobility sector were modeled as part of the urban hubs in this study.

Industry representation

The energy demand analysis of the four industry hubs was carried out in close cooperation with the respective partners. Two models were developed for each industry hub: one depicting the current state of the plants in the REF energy system, representing the energy infrastructure between 2020 and 2024, and one representing the plants in 2050 including all technology candidates for expansion and conversion options. The energy demands of low-temperature, high-temperature and process heat for the industries were based on the actual -and expected usage in the future. A detailed overview of the MSW incinerator plant Gevag in both the REF system and in 2050 is shown in the **Supplementary Information**.

CO₂ capture techs

Certain processes in industries such as cement production and waste incineration result in inherently hard-to-abate emissions, meaning that fuel switching alone cannot fully eliminate them. For example, in cement production, the decomposition of limestone (CaCO₃) accounts for 60% of total emissions due to its chemistry⁶⁶ ([link](#)). To address these unavoidable process emissions, integrating post-combustion CO₂ capture technologies into the energy system is crucial. Based on previous studies^{67, 68}, amine scrubbing and Hot-Potassium Carbonate (HPC) processes were identified and parameterized as capture technology candidates for three industrial hubs in 2050. The parameters and the expected energy demand for powering these capture technologies are detailed in the **Supplementary Information**.

CO₂ transport and storage

Once captured, CO₂ is compressed and transported to geological storage sites. It can be transported via trucks, rail, pipelines, or ships for offshore storage. Given their suitability for industrial clusters, our study assumes CO₂ transport via pipelines, with the additional option to export CO₂ across Swiss borders. The assumed costs for the transportation and storage of CO₂ are provided in the **Supplementary Information**.

2.3. Scenario definitions for 2050

To comprehensively explore potential future energy pathways, two main scenarios for 2050 were defined based on the REF energy system: A progressive (2050-pro) and restrictive (2050-res) scenario. These scenarios were designed to capture contrasting potential trajectories of technological development, policy interventions, and infrastructure investments and therewith explore opposing points in the solution space.

Progressive scenario

The progressive scenario (2050-pro) represented an optimistic and rapid transformation of the Swiss energy system, characterized by significant infrastructural and policy advancements. It assumed full integration of the European Hydrogen Backbone through Switzerland, facilitating cost-effective cross-border trade of hydrogen. This scenario anticipated a substantial expansion of the electricity grid at distributional level from the REF system, without any constraints on import-export capacities.

Restrictive scenario

In contrast, the restrictive scenario (2050-res) represented a more constrained future, where technological and infrastructural progress was slower and more challenging. It assumed that the European Hydrogen Backbone bypasses Switzerland, leading to higher costs for importing hydrogen and synthetic methane via trucks and railways. Moreover, this scenario projected only modest expansion of electricity grid capacities and imposed stricter limitations on annual electricity imports into the valley. Additionally, the amount of MSW decreased to 305 GWh/a (from 436 GWh/a in the progressive scenario) due to reduced waste generation and increased recycling rates.

By developing these divergent yet plausible scenarios by the Rheintal stakeholders, we aimed to provide decision-makers with a comprehensive understanding of potential transformations for regional-level energy systems, highlighting both opportunities and challenges in achieving net-zero emissions. To assess the robustness of our scenarios, we conducted sensitivity analyses to evaluate how variations in key assumptions, such as price developments and availability of energy sources, influence the results. Both 2050 scenarios included a base case, named identically to the scenario itself, along four sensitivities each, allowing for a comprehensive analysis of different developments and their effects on the energy system. Hence, in total 10 cases for 2050 were considered in this study as summarized in **Table 3** along with their individual features. The general model assumptions and boundary conditions for the different cases are documented in the **Supplementary Information**.

Table 3: Overview of the cases analyzed in this study: The reference (REF) system and two future scenarios for 2050 (2050-pro and 2050-res). Each 2050 scenario further includes four sensitivity cases. There are no emission targets imposed in the REF system while the 2050 scenarios are designed to achieve net-zero CO₂ emissions, except for the S4 sensitivities.

Scenario	H ₂ import price (CHF/kg)		Syn. CH ₄ import price (CHF/kWh)		Specific features
REF	-		-		Reflects the status-quo Rheintal energy system in 2020
2050-pro	2.5		0.1		No capacity expansion limits for the electricity grid.
2050-res	6		0.2		Electrical grid capacity expansion is limited to 20% above current levels (REF) and electricity import into the valley are capped at 800 GWh annually. Also, increased recycling quota of waste results in 30% less MSW imports than REF.
Sensitivity	2050-pro	2050-res	2050-pro	2050-res	
S1	2.5	6	0.1	0.2	H ₂ import is limited to 400 GWh annually.

S2	2.5	6	0.1	0.2	H ₂ & syn. CH ₄ imports are not allowed. Open-field PV is available in the 2050-res scenario.
S3	2.5	6	0.1	0.2	Grid electricity imports price same as in REF scenario. Higher distribution costs for H ₂ , i.e. same as that of the electricity network.
S4	2.5	6	0.1	0.2	The net-zero CO ₂ target does not have to be achieved.

3. Results and discussion

The energy system in Rheintal reveals two major challenges today: 1) high carbon emissions per capita and 2) a significant amount of industrial waste heat. The analysis begins with an assessment of the reference energy system (REF), identifying key opportunities for decarbonization and improved energy efficiency. Next, the technologies required to address these challenges are evaluated, followed by a comparison of energy imports and exports across all cases to assess regional energy dependencies. Finally, a comparative analysis of system costs is presented, providing insights into the economic feasibility of the proposed transition pathways.

3.1. Waste heat potential and emissions in the Rheintal today

Waste heat

Industrial processes in Rheintal generated substantial excess heat at various temperature levels, a significant portion of which remained unutilized today. This heat resulted from high-temperature processes, cooling systems, and other industrial discharges. A part of the excess heat is already utilized and distributed to urban areas via district heating networks. For instance, high- and low-temperature heat is supplied to the West hub. Whereas the remaining portion of excess heat, i.e. waste heat, was currently released into the environment, thereby warming the surroundings.

Figure 3 qualitatively illustrates the thermal demands in the urban hubs alongside the waste heat from the four large industrial players: GEVAG, Holcim, Axpo Tegra and Ems-Chemie. In total, approximately 548 GWh/a of low-temperature heat, 49 GWh/a of high-temperature heat and 35 GWh/a of high-temperature process heat are available for potential utilization in the Rheintal valley. In comparison, the thermal demand of the urban hubs, consisting of space heating and domestic hot water, is 665 GWh/a in the REF system. The scale of available waste heat presents a compelling case for improved energy integration within the valley. Therefore, waste heat from industries could play a major role in meeting thermal energy needs.

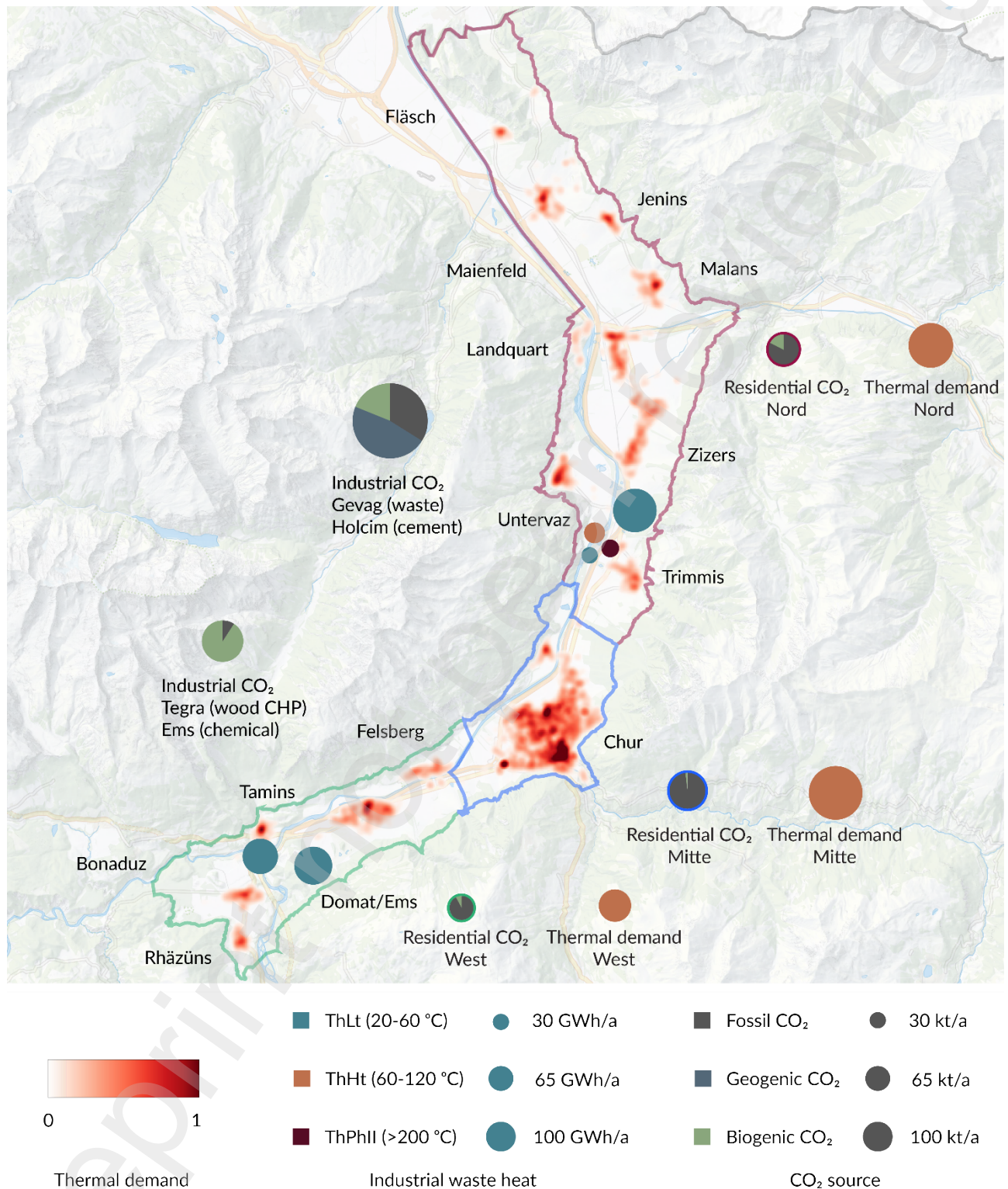


Figure 3: Spatial distribution (qualitative) of thermal energy demand in the Rheintal valley. The three urban hubs and their constituent municipalities are outlined in red (Nord), blue (Mitte), and green (West) borders. Waste heat sources from the industries are georeferenced and shown as circles of varying sizes and colors, indicating different temperature classes (low: ThLt, high: ThHt, and process: ThPhII). Thermal demands and CO₂ emissions are positioned near the corresponding hubs for visual clarity. Thermal demands of urban hubs

are shown on the right side of the map. Pie charts on the right illustrate CO₂ emissions within urban hubs, while those on the left depict emissions from industrial hubs.

Carbon emissions

The current energy system and its industrial processes in Rheintal emitted approximately 840 kt CO₂ per year from fossil and geogenic* sources. With a population of around 80,000, this corresponded to a per capita emission of 10.5 t CO₂, more than double the Swiss national average of 4 t CO₂ per capita annually in 2024 (REF). A large share of the emissions in the Rheintal originated from industrial activities, particularly the cement plant in Untervaz, which alone contributed nearly half of the region's combined fossil and geogenic emissions. Overall, industrial hubs accounted for 63% of total CO₂ emissions, while the urban and mobility sectors contributed the remaining 37%. In addition to fossil and geogenic emissions, 324 kt CO₂ of biogenic** origin was released, primarily from the Axpo-Tegra wood-fired CHP and the GEVAG MSW incinerator. These biogenic emissions do not count as climate-impacting emissions but are considered climate-neutral in the carbon cycle. Even with the complete phase-out of fossil fuels and their replacement with renewable energy sources, hard-to-abate emissions from the cement plant and MSW incinerator will persist in the future. **Figure 3** also shows the distribution of CO₂ emissions in the urban and industrial hubs of Rheintal.

The comparably high CO₂ emissions in the Rheintal highlight the urgency of implementing additional carbon reduction measures, beyond the partial benefits of electrification and fuel switching. To effectively reduce emissions, both waste heat utilization through district heating networks (DHN) and carbon capture and storage (CCS) are required as complementary strategies. In addition to district heating, waste heat from the industries can be utilized to power CO₂ capture systems co-located at industrial sites, allowing for large-scale point-source carbon mitigation.

3.2. Technological solutions in the future system

3.2.1. District heating

Figure 4 illustrates the energy flows in the District Heating Networks (DHNs) of the Rheintal valley across different cases. The comparative analysis revealed distinct patterns of waste heat utilization under different infrastructure conditions and scenario definitions. In the REF system, which represents the status-quo infrastructure without new pipelines, the district heating system operated within existing constraints. However, in the 2050 scenarios, DHN utilization was influenced by H₂ price and availability, as well as electricity costs and supply.

The 2050-pro scenario showed limited expansion of the district heating networks when there was cheap availability of renewable gases like hydrogen and synthetic methane (2050-pro and S1). This occurred because, when hydrogen was inexpensive, it was imported and reconverted into electricity using fuel cells,

* Geogenic CO₂ emissions are mainly caused by the calcination of limestone in cement plants which is a necessary process step for clinker production.

** Biogenic CO₂ is mainly produced in waste incineration and wood-fired cogeneration plants by the combustion of organic materials. A small amount is also produced from wood heating in the urban hubs.

which also generated heat as a byproduct. Additionally, affordable synthetic methane was used locally in boilers. Together, these heat sources reduced the incentive to expand DHNs. Similarly, in the 2050-pro S2 case, when renewable fuel imports were fully restricted, each hub operated independently with a more self-sufficient approach, resulting in minimal energy exchanges between hubs. Notably, Tegra stopped supplying high-temperature process heat to Ems, significantly reducing DHN flows in this sensitivity. However, when grid electricity prices dropped to REF system levels in 2050-pro S3, hydrogen and synthetic methane became unattractive as heating sources. As a result, high-temperature heat from industries flowed through DHNs, particularly for urban heating in the Mitte hub. While some low-temperature waste heat was upgraded and utilized in 2050-pro scenario, a substantial portion remained unexploited due to reduced economic incentives.

The 2050-res scenario demonstrated the most comprehensive utilization of waste heat in the valley. This expansion was particularly evident in the increased exchange of both high- and low-temperature heat. With constrained electricity imports and higher renewable fuel prices across all sensitivity cases, the existing DHN underwent significant expansion, effectively capturing available industrial waste heat streams. This scenario achieved near-complete utilization of available high-temperature waste heat and substantial recovery of low-temperature waste heat, optimizing resource use within the system. The expanded district heating infrastructure served a threefold purpose: it contributed to the region's local heat supply, relieved the pressure on the electricity grid, and provided high-temperature heat requirements for the CO₂ capture (see **Section 3.2.2**).

The potential for a winter energy shortage in Switzerland has become a growing concern since 2022, particularly in light of geopolitical uncertainties, changing climate patterns, and the ongoing transition to intermittent renewable energy sources. DHNs can help mitigate the impacts of such shortages by providing an efficient, low-emission alternative for urban and industrial heating. By integrating renewable and locally sourced heat, district heating can make the energy system more flexible and less reliant on imports, helping to ensure greater energy security during winter shortages.

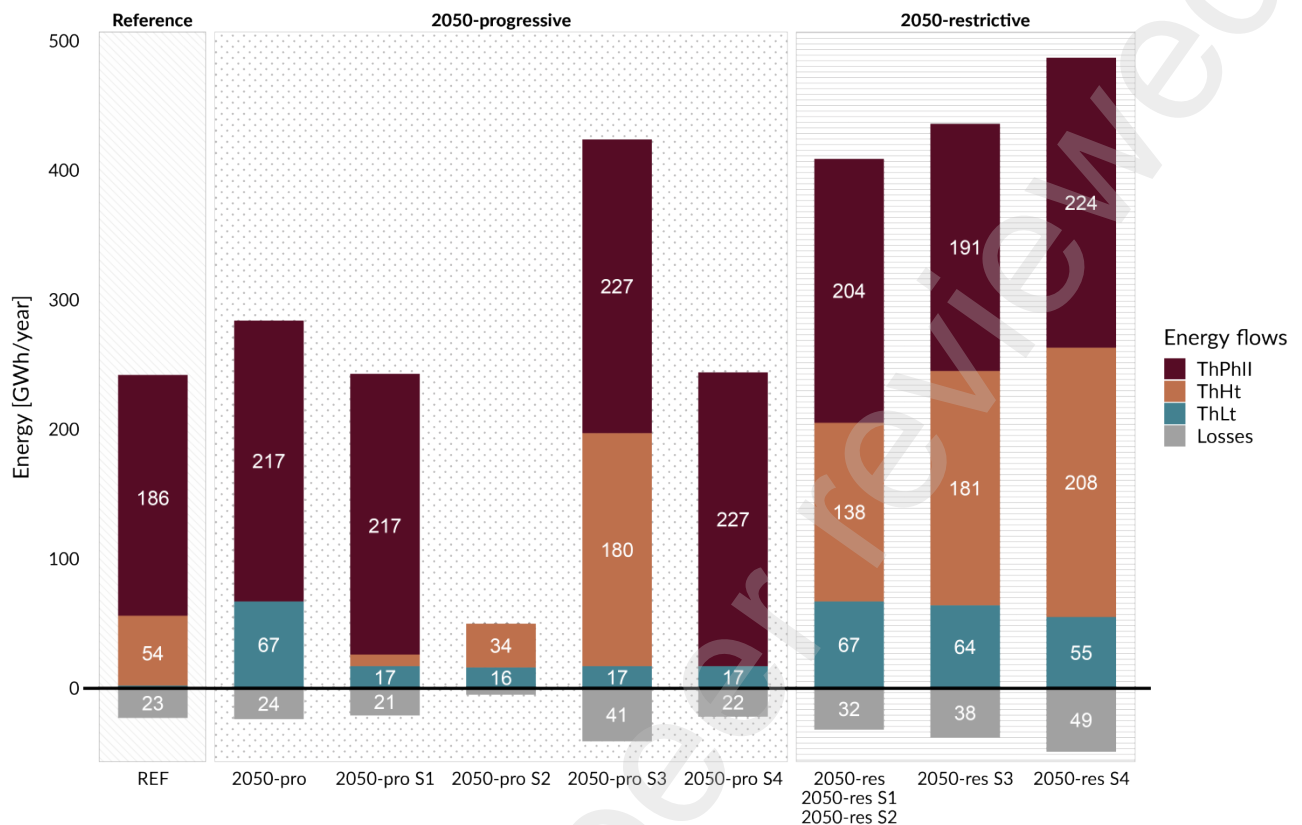


Figure 4: Comparative analysis of energy flows across different temperature levels and cases in Rheintal valley's district heating networks. The energy flows of low-temperature (ThLt), high-temperature (ThHt), and high-temperature process heat (ThPhII) are shown in the graph. Negative values in the graph represent the total heat losses in the pipelines for every case.

3.2.2. CO₂ capture

Our analysis demonstrated that all 2050 cases achieved net-zero CO₂ emissions, except for S4 sensitivities, where emission reduction constraints were not applied (**Figure 5**). Electrification and mandatory infrastructure investments, such as retrofitting the building stock, played a major role in reducing CO₂ emissions from urban and mobility sectors. However, point-source post-combustion carbon capture was necessary to eliminate fossil and geogenic emissions, particularly in cement production and waste incineration facilities.

The choice of carbon capture technology differed between the two scenarios. In the 2050-pro scenario, where electricity imports were unrestricted, Hot Potassium Carbonate (HPC) technology predominantly emerged as the preferred option. In contrast, under electricity import restrictions in the valley in 2050-res scenario, amine scrubbing dominated due to its lower electricity requirements. This shift in technology choice increased the use of high-temperature heat to replace electricity for CO₂ capture across all 2050-res cases.

Both technologies captured not only fossil and geogenic but also biogenic CO₂ from multiple sources, including waste incineration, cement production, and wood CHP plants, in varying quantities. These captured biogenic emissions also offset the remaining fossil emissions from urban and mobility sectors. While the 2050-res scenario exactly met the net-zero emissions target, the 2050-pro scenario proved to be climate positive,

capturing additional biogenic emissions beyond the net-zero threshold. This excess capture provided an economic advantage due to additional CO₂ capture revenues, resulting in a negative carbon balance for the overall system. The surplus biogenic CO₂, beyond what was required to achieve net-zero emissions, presents opportunities for utilization in the synthesis of renewable fuels and chemicals in the valley.

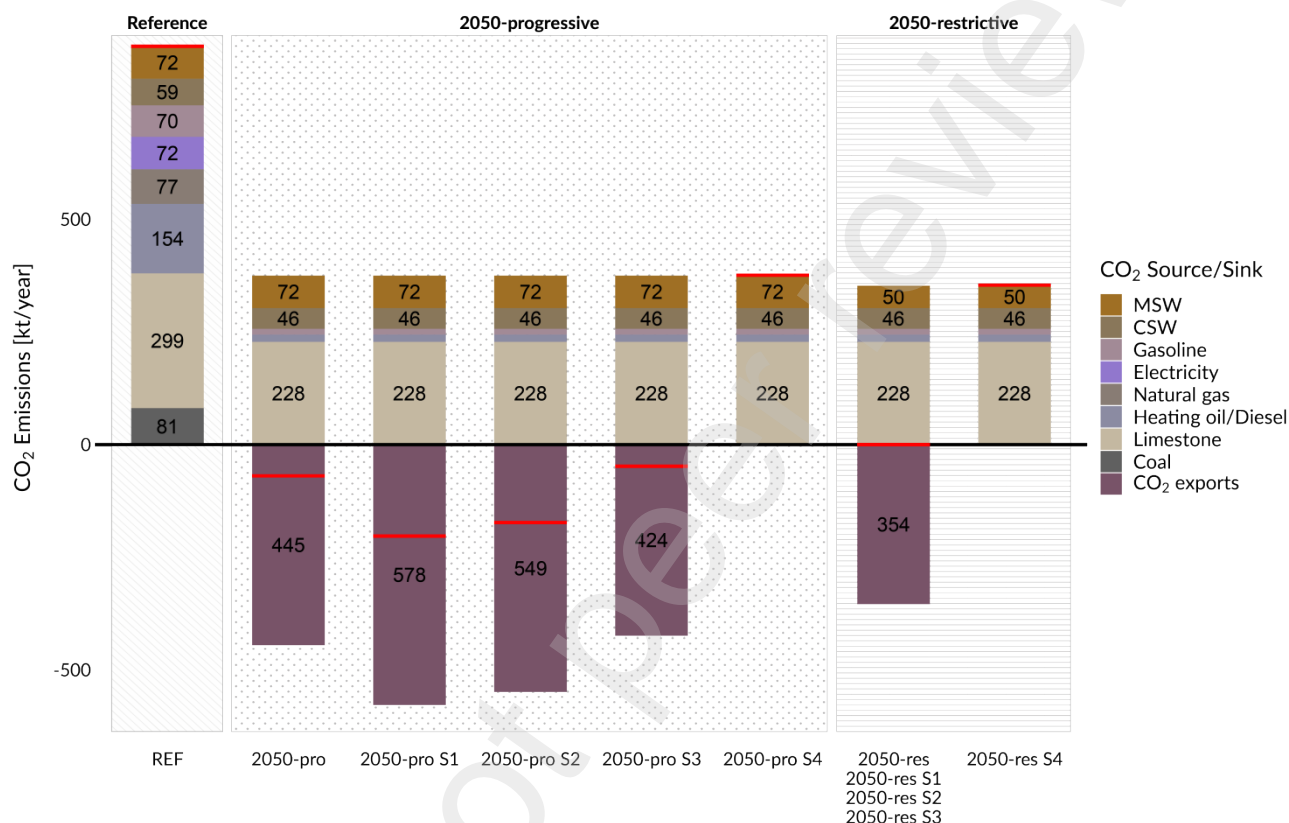


Figure 5: Fossil and geogenic CO₂ sources and sinks across the different scenarios in Rheintal. The negative values illustrate the total CO₂ emissions (fossil, geogenic and biogenic) captured and exported out of the system boundary. The red line shows the net CO₂ emissions for the respective scenarios.

3.3. Imports/Exports / Shifts in regional energy dependence

The REF energy system was predominantly dependent on fossil fuels, constituting the bulk of the total primary energy supply. Price signals and availability of the different energy sources determined the imports and exports of the system. As seen in **Figure 6**, the valley's dependence on energy imports decreased in 2050, while there is an increase in exports in most cases. Cleaner renewable fuels, such as hydrogen, synthetic or bio-methane, and biological waste, completely replaced the fossil-based sources like coal, natural gas, and heating oil in the future. Since the European Hydrogen Backbone passed through Switzerland in the 2050-pro scenario, low carbon hydrogen could be imported at a lower cost. The combined energy and network distribution costs for hydrogen amounted to 0.1 CHF/kWh, whereas for electricity it averaged 0.28 CHF/kWh. Consequently, inexpensive hydrogen largely substituted grid electricity for end-use applications with fuel cells. However, when hydrogen imports were increasingly restricted in the sensitivity cases S1 and S2, synthetic and bio-methane, along with electricity, filled the gap left by hydrogen.

In 2050-pro S3 sensitivity, although hydrogen and synthetic methane imports were occasionally cheaper than grid electricity, the model did not find them cost-effective from a system-wide perspective. This outcome resulted from a combination of factors: the versatility of electricity, the higher efficiency of electric technologies like heat pumps, and a technology lock-in effect. The system may have already committed to electric-based solutions, making a switch to hydrogen or synthetic methane impractical, as it would require additional investments in fuel cells, boilers, and distribution upgrades.

However, in the 2050-res scenario, the energy costs of hydrogen were assumed to be more than twice as high as in the 2050-pro scenario, rendering hydrogen imports ineffective for the valley. In the absence of hydrogen, the system switched back to a higher reliance on electricity and consistently reached the grid import limit of 800 GWh for the valley. The portfolio of energy imports remained more robust and consistent in the restrictive scenario across the different sensitivity cases.

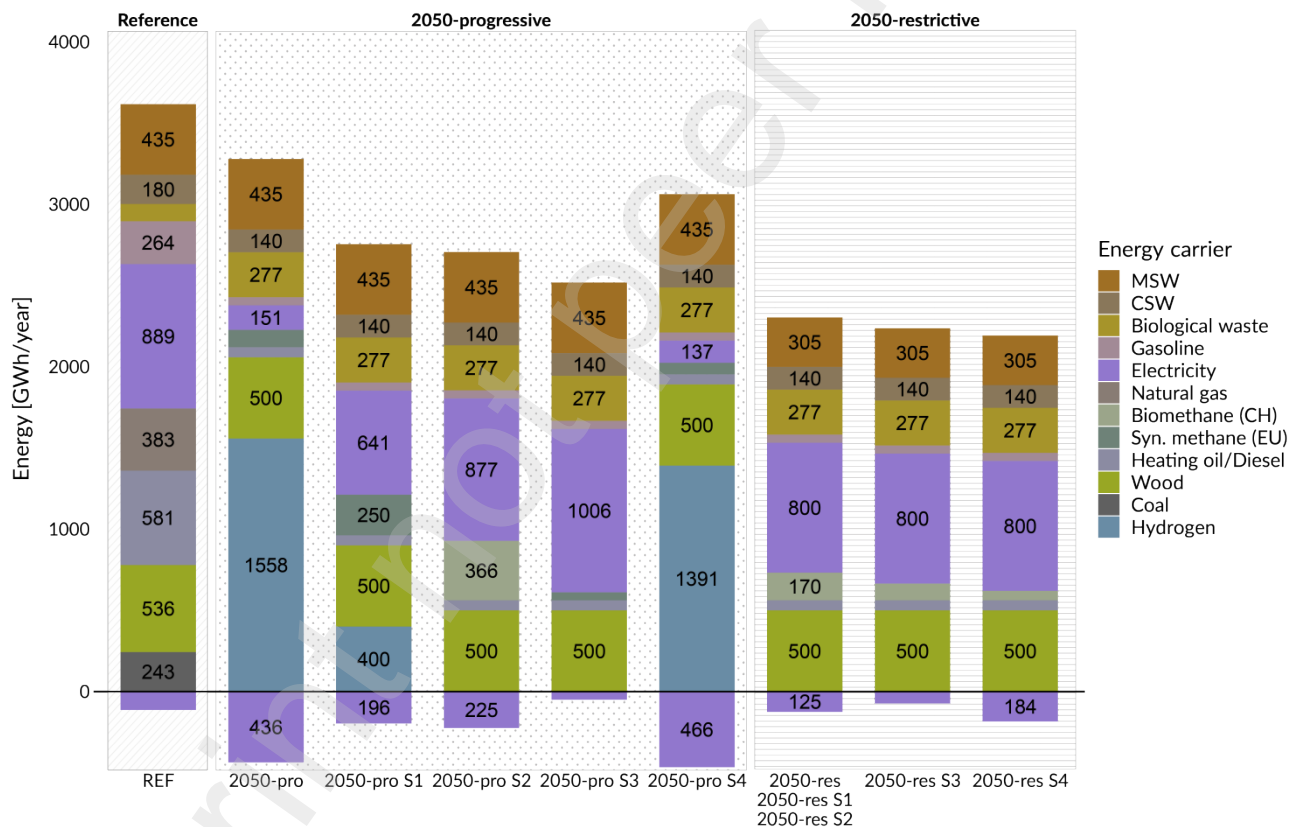


Figure 6: Imports and exports of different energy sources across the Rheintal system boundary for all cases.

3.4. System costs / Economic feasibility of the Net-Zero transition

Despite additional investment in clean technologies and increased electricity prices in most cases, the 2050 scenarios could have 20-40% lower annualized system costs than the reference energy system (**Figure 7**). The primary driver of this cost reduction was a 30% decrease in urban space heating demands due to building renovations and retrofitting, along with lower industrial energy requirements or increased energy efficiency of industrial processes. An increase in the usage of local energy resources with PV rooftop systems, heat pumps upgrading ambient heat for thermal needs, and the utilization of valuable waste heat in the valley further

reduced the costs. Additionally, the electrification of building heat and mobility, combined with a shift to cleaner fuels, decreased the imports of expensive fossil fuels in the system.

On average, all cases under the 2050-res scenario were more expensive than their respective progressive counterparts. However, 2050-pro S2 stood out with significantly higher system costs than its restrictive equivalent due to two key factors: 1) limited waste heat utilization by DHNs, which reduced efficiency gains, and 2) greater reliance on costly biomethane and grid electricity as renewable fuel imports were restricted. Interestingly, completely restricting hydrogen and synthetic methane imports in this case led to a greater increase in system costs than limiting electricity imports in the 2050-res scenario. As S4 sensitivities allowed for a system without net-zero constraint, its annual system costs were 5-20% lower than the other 2050 cases. However, the S3 sensitivity remained the cheapest across all cases, highlighting that lower electricity costs had a greater impact on system costs than net-zero targets.

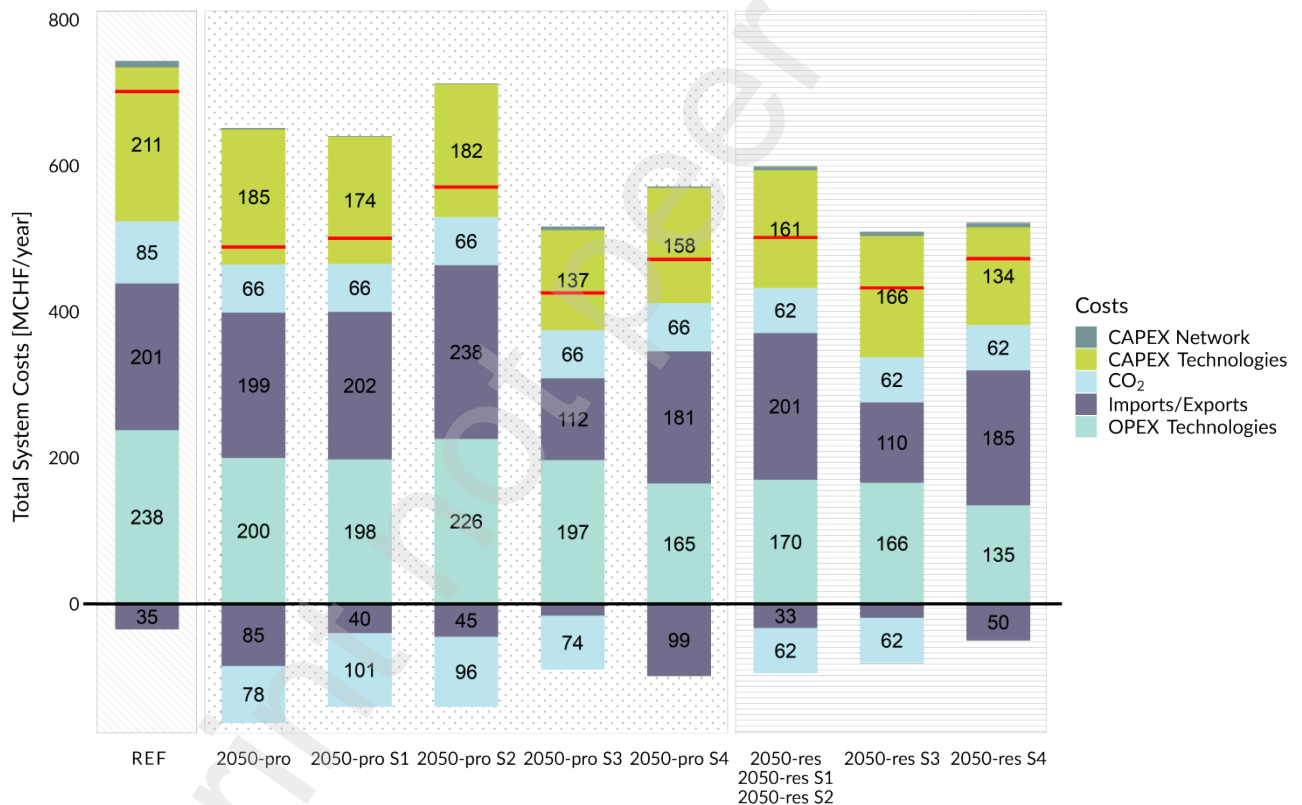


Figure 7: Annualized total system costs of the energy system in Rheintal across all cases. The red lines in the bars show the net annualized system costs.

4. Conclusions and outlook

This study explores the cost-optimal net-zero 2050 energy system for industry and urban clusters of the "Rheintal valley" in Switzerland. The sector-coupled MILP model integrates the carbon cycle with the energy system to assess both energy infrastructure and CCS solutions. A bottom-up demand analysis was conducted for the urban sector, while a detailed modeling in collaboration with industry partners was performed for the industrial sites. A reference model, describing the current state of the energy system in 2024, was developed

and validated with the regional stakeholders, forming the foundation for the 2050 scenarios. Additionally, a sensitivity analysis was conducted to assess the robustness of findings.

Our analysis of the Rheintal energy system addressed two major challenges today: 1) high per capita carbon emissions and 2) significant industrial waste heat. Due to the presence of hard-to-abate emissions in industries, the valley can only achieve the net-zero target with the deployment of CCS technologies. The study also finds that expanding the district heating infrastructure can play a vital role in supporting the local heat supply, relieving the pressure on the electricity grid, and providing thermal energy for CO₂ capture. Furthermore, enhanced integration of waste heat into the regional energy system could reduce reliance on fossil-based heating and lower overall emissions, making it a key strategy for the valley's sustainable energy transition. Our findings also emphasize that energy efficiency measures, such as building retrofitting and electrification of heat and mobility significantly reduce overall energy demand.

By 2050, the valley's dependence on energy imports is expected to decrease. Cleaner renewable fuels, such as hydrogen and synthetic or bio-methane, could play a crucial role in the future energy mix, particularly in ensuring a diversified and stable energy supply during winter months. However, the price of hydrogen coupled to the connection of Switzerland to the European Hydrogen backbone remains a critical barrier to adoption, as it competes with grid electricity imports. Despite substantial up-front investments, the total annual system costs could decrease compared to current levels, primarily due to efficiency gains, increased use of local resources, and reduced reliance on fossil fuel imports.

The analysis of the Rheintal valley highlights the inherent synergy between industries and urban areas (residential, office and commercial buildings) in shaping a resilient future energy landscape and promotes coordinated decision-making among regional stakeholders to achieve climate targets. These insights provide a robust foundation for guiding policymakers and stakeholders in making informed decisions to drive the Rheintal valley toward a sustainable and cost-effective net-zero future.

Ultimately, system integration leads to more resilient solutions and more attractive economic outcomes. While technologies like CCS might not appear economically attractive on their own, when integrated into a larger system, the overall system performs better economically, demonstrating the value of a holistic and integrated approach.

5. Limitations and outlook

Despite the comprehensive nature of the study, certain limitations must be acknowledged. First, the model assumes perfect foresight, meaning that future energy demand and prices are known with certainty. Although a sensitivity analysis was performed, it only partially addresses the uncertainties related to price fluctuations, technological advancements, and the availability of energy resources. A more thorough uncertainty analysis could enhance the robustness of the findings.

Second, while the modeling of CCS technologies incorporates updated public data available at the time of the study, it does not fully capture the variability and uncertainty in their future costs and potential revenue streams such as those from negative emissions credits or carbon markets. As more CCS projects are realized and operational experience grows, cost estimates and economic assumptions are likely to change. Future studies could incorporate these updated insights to better capture the feasibility and deployment potential of CCS technologies.

Third, although sensitivity analysis was conducted to explore the solution space, alternative system configurations with comparable costs but different technological pathways were not explored in depth. This may limit the range of viable solutions considered within the current modeling framework.

Future work could integrate dedicated supply security assessments, as emphasized by a recent study⁶⁹ ([link](#)). Finally, while this study demonstrates that reaching net-zero emissions is technologically and economically feasible, the success of the transition will depend on more than these dimensions alone. Ensuring social acceptance, environmental sustainability, and effective navigation of land-use constraints⁷⁰ ([link](#)), alongside the development of an enabling regulatory framework, will be critical for implementation.

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Authors contribution

Conceptualization: R.M., M.S., B.K.; Methodology and Visualization: A.U., R.M., E.J., N.V., D.B., B.K., M.S.; Software: A.U., R.M., D.B., B.K., N.V.; Formal analysis: A.U., R.M.; Data curation: A.U., R.M., B.K., M.O., B.C.; Writing – original draft: A.U., R.M.; Writing – review and editing: all; Funding acquisition: M.S., R.M., B.K.

Data availability

The data needed to reproduce all figures and results have been added to the supporting information and will be publicly available as of the date of publication.

Declaration of interests

The authors declare no competing interests.

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