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Energy Trading in the Smart Stability Network

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Abstract

The current implementation of the electrical grid has not changed since the last 50 years and due to the increase of energy demand the stability of the electrical grid is strongly affected which can result in power cuts respectively blackouts, brownouts or poor quality. One of the main reasons of these issues is the current design of the electrical grid, which is designed for centralized power production in big power plants from where the customers are served with electrical energy. In the case that one of these power plans has an outage, the impact is huge because it could affect several major cities or worse, e.g. the Northeast blackout of 2003.

This paper proposes an approach to improve the stability of the electrical grid through decentralized networks and energy trading. The idea is to decrease the deviation from the schedule of the power plant operators and to create an economic incentive for homeowners. This is achieved by tradable goods, which are traded in such a network. This paper presents a model of a decentralized network, which consists of several smart houses with data taken from real consumers. The model or rather trading process is implemented with the multi-agent framework JADE that allows implementing a distributed network with different type of participants. The trading process works in a way that a leader is elected in the beginning of the process. Once the leader is elected, all other participants inform the leader in short time intervals about their energy demands and their offers. An offer corresponding here to a tradable good such as receiving energy from a photovoltaic system, storing energy in a battery or switching on a boiler. In each interval, respectively cycle, the leader calculates the deviation from the schedule according to the schedule and the energy demands of the participants. When the deviation from the schedule is greater than zero, the leader looks for the best offers to decrease the deviation. Hereby, a participant gets paid when the leader accepts its offer.

According to the findings and results in this thesis, it is feasible to improve the stability of the electrical grid and to create an economic incentive for homeowners. While smart houses with a battery help to reduce the deviation from the schedule immensely, introduce smart houses with a photovoltaic system fluctuation and therefore increase the deviation. On the other side, smart houses with a photovoltaic system get more profit than houses with a battery because the produced energy of photovoltaic system has to be used at any price.

Although, this thesis shows that energy trading can improve the stability of the electrical grid and create an economic incentive for homeowners at the same time. A concrete business model is missing, which describes how such a decentralized network can be introduced and sold to homeowners. Furthermore the simplifications of the energy demand forecast function and the leader election in this thesis are to be considered.

Statement of Authenticity

I confirm that this master thesis research was performed autonomously by myself using only the sources, aids and assistance stated in the report, and that quotes are readily identifiable as such.

Date: Signature:

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1 Introduction and background

1.1 Introduction

The current implementation of the electrical grid has not changed since the last 50 years (Kok, Scheepers, & Kamphuis, 2010) and due to the increase of energy demand (Netherlands Organisation for Applied Scientific Research, 2014) the stability of the electrical grid is strongly affected which can result in power cuts respectively blackouts, brownouts or poor quality (Fairley, 2004): Power cuts means that an area has lost electric power for a certain amount of time. A brownout on the other side is a drop in voltage in an electrical power supply system and can be compared with the dimming experience by lighting when the voltage sags.

One of the main reasons of these issues is the current design of the electrical grid, which is designed for centralized power production in big power plants from where the customers are served with electrical energy. In the case that one of these power plans has an outage, the impact is huge because it could affect several major cities or worse, e.g. the Northeast blackout of 2003 (Fairley, 2004).

Moreover, since the events of the last decade such as the Fukushima nuclear disaster, the demand of abolition of nuclear power plants are enormous in favor of renewable energies like solar and wind energy (Bundesamt für Energie BFE, 2012; Presse- und Informationsamt der Bundesregierung, 2014; Tabuchi, 2011). But in the current design, there is no space for fluctuating power production because it would affect the whole electrical grid and every customer that obtains energy from it (Kok et al., 2010). The reason for this is that the produced energy must be consumed and energy demand must be fulfilled otherwise the stability of the electrical grid is at risk (Kok et al., 2010). Unfortunately, the production of solar and wind energy are variable by nature and therefore means fluctuating power.

One approach to face this issue is the introduction of the Smart Grid (U.S. Department of Energy, 2010). The idea behind the Smart Grid is the extension of the current electrical grid with information, telecommunication and power technologies (Vijayapriya, 2011) to modernize the electricity industry (U.S. Department of Energy, 2010). With these technologies in place, the power operators can measure, monitor and manage the electrical grid and respond to sudden energy demand peaks or outages in a smart way. The Smart Grid approach seems to be promising but still relies on the same design where fluctuating power production is a high risk for the whole grid (Digital Grid Consortium, 2014c). Hence, smart micro grids can be an approach to reduce the impact on the electrical grid. In this scenario, the current electrical grid is divided into tiny smaller electrical grids or rather micro grids. Each micro grid consists of electrical power generation, energy storage and load, and is usually connected to the superior grid. Thus, a micro grid can either consume or provide its produced energy to the superior grid. Because the micro grid has its own electrical power generation and energy storage, it could optimize the scalability for its own grid without affecting the superior grid. In other words, the micro grid would be responsible for the scalability of the power network for itself and not the superior grid. Especially in terms of renewable energy, the micro grid could use such energy resources as solar and wind energy to improve its own scalability and energy demand, but still obtain power of the superior grid if required.

As a conclusion, the electrical grid operators and governments are facing a big challenge in the future energy market: saturation of the energy demand and ensure a high stability and quality of the electrical grid at the same time.

2 Problem statement

As mentioned in the introduction, the design of the current electrical grid is not longer sufficient due to the infrastructural and political influences (Abe, Taoka, Member, & Mcquilkin, 2011; ACT, 2008; Fairley, 2004; U.S. Department of Energy, 2010; Vijayapriya, 2011). The operation of the infrastructure generates additional effort to balance the production and demand of electricity that comes from e.g. renewable energy sources. The political influence is the increasing call for phasing out nuclear power stations and moving to renewable and sustainable energy production scenarios (Bundesamt für Energie BFE, 2012; Presse- und Informationsamt der Bundesregierung, 2014; Tabuchi, 2011).

Renewable energy production cannot just replace the current nuclear power and coal-fired plants. There are several challenges to ensure the stability of the electrical grid during peaks. These peaks may have different reasons as for example hundred of people want to have warm water from their electric hot-water tank at the same time in the morning for having a shower. Such a peak is an issue because the energy demand cannot be served by renewable energy production due to environmental dependencies, e.g. doldrums, or other inclement weather conditions.

In order to respond to these challenges, the idea of Smart Grids has been extended by the idea of building an interactive grid with many micro grids that tries to balance consumption, production and storage of energy by arranging, planning and coordination before requesting energy supply from the superior grid. This requires communication among the micro grids in decentralized manner. Such a decentralized communication makes a central coordination superfluous and as a result the micro grids can act independent among the others without their influence.

As already mentioned, the stability of the electrical grid is affected by the increasing energy demand and the introduction of renewable energy resources. New approaches as the Smart Grid or Digital Grid are invented to handle this kind of problems but they mainly concerns about the stability of the electrical grid in a technical manner (Abe et al., 2011; Vijayapriya, 2011). But with the possibilities today of renewable energy and storage facilities, an economic incentive can be created for citizens. For example, a citizen with a photovoltaic system cannot just use her own produced energy; instead she is able to sell it. Witch such an economic incentive or rather business model in place, having a photovoltaic system is not just about participating the idea of green energy or reduce the energy cost, it is about earning money too. Until now there have been many approaches have tried to implement it, but it was never accepted by the population. Therefore one question is how energy trading can be attractive for the population to participate it? Which goods should be traded between the participants and how is the trading of goods negotiated?

Regarding the technical benefit from this approach, a citizen would be able to buy and receive energy from another citizen in the neighborhood instead of demanding the energy from the main electrical grid. This means that the electrical grid would not be liable for the energy demand and therefore it is relieved.

Summarized, the introduction of a new grid design should not only attractive for grid operators but for the end consumers as well because it should not only deal with the technical part of the current design issue; it must create a new business too.

2.1 Research Statement

The following thesis statement is derived from the problem description to give a concise solution to the issue being addressed in this paper:

"The use of distributed communication for trading energy between smart houses in a decentralized network can improve the stabilization of the electrical grid."

The following list qualifies the research more in detail:

Phrase	Description
Distributed communication in a decentralized network	The smart houses are participants in a decentralized network where everybody communicates with each other. Such a decentralized network can be connected with other networks but are still independent from the others. This rule also applies to the participants inside the network.
Trading energy	Instead to obtain the energy only from the current electrical grid, the participants should able to buy and sell energy from other participants in their network as well. But not only energy, even storage capacity could be a trading item among the participants.
Smart houses	A smart house in this paper refers to a house with energy production and storage facility attached and communicates with other smart houses in a decentralized network.
Improve stabilization of the electrical grid	Stabilization means discharge of unforeseen energy demand by the consumers or energy shortages.

Table 1: Master thesis statement glossary

2.2 Research Questions

Based on the context and purpose of the research study, the primary research question is:

PRQ: How can the trading of energy between smart houses improve the stability of the electrical grid?

The sub-research questions defined for this study are the following:

SRQ1: What does stability of the electrical grid mean?

SRQ2: What will be traded between the smart houses and at what price? What kind of goods will be traded, e.g. energy and the capacity for storing energy?

SRQ3: How does the trading of goods between smart houses works?

SRQ4: How is the communication done between the smart houses?

As a result of this thesis, the answer of the primary research question should give the evidence if the trading of energy can improve the stability or not. But in order to answer this question, it must be understood what is meant with the stability of the electrical grid (SRQ1). Moreover, the trading of energy is a general concept and so it is important to define this term for this thesis by the answer of SRQ2. Once the tradable goods are identified, the question appears how these goods can be traded between the smart houses as indicated by SRQ3 and SRQ4.

3 Literature Review

The weaknesses of the current electrical grid are been known and therefore a lot of research was done in this field. For researchers such as (ACT, 2008; U.S. Department of Energy, 2010), the smart grid seems to be the answer for the current and upcoming challenges in the electrical grid. Nevertheless, others proposed a distributed electrical grid solution such as self-organized Micro Grids (Villiger, 2014) or the Digital Grid (Abe et al., 2011).

In terms of energy trading, there exist several proposals which are described in chapter 3.3.

3.1 Requirements

The requirements shown in Table 2 are derived from the thesis statement and refer to the research questions described in chapter 2.2.

Criteria	Description
Micro grid	Focus on a micro grid level where a micro grid consists of several smart houses with energy production and storage facility attached.
Distributed Communication	Each participant in the grid should communicate with the other participants excluding a centralized control unit to react flexible to a changing environment.
Decentralized Network	The micro grids are operating independently from the other grids in a decentralized manner and therefore another cannot influence a micro grid.
Trading Goods	Each participant is able to buy or sell goods from and to other participants in the same grid, e.g. energy or storage capacity for energy.
Improve grid stabilization by trading energy	Trading of energy between the participants in a micro grid improves the stability of the superior electrical grid, especially during peaks.

Table 2: Smart Stability Requirements

As mentioned in the problem statement in chapter 2, the research in this paper focus on improving the stability of the electrical grid by introducing a few changes to the current grid design. Technically speaking, new micro grids should be created which represents a set of smart houses. These micro grids are self-organized in regard to energy consumption; either the participants demand energy from other participants or from the superior grid. Because the current grid is struggling with its centralized synchronization, the micro grids should be part of a decentralized network so that they cannot have an impact on each other and an issue in a micro grid only affects itself instead of the whole superior grid. Although that the size of a micro grid is not yet determined, a synchronized central control-unit will be avoided and a distributed communication among the participants should be used instead. This communication is suggested to prevent the blackout of a whole micro grid when the centralized synchronization component has an issue and to improve the reliability of the grid. But it is alone not enough with the breakdown of the grid in smaller micro grids; the ability of the smart houses to trade goods with each other should improve the stability of the electrical grid as well. The participants should still be able to communicate with the remaining functioning smart houses during a failure to sell or buy goods from those or from the superior grid.

Due to the fact that a smart house should have attached an energy production and storage facility, enabling these smart houses to trade different kinds of goods should create an economical incentive too. Although it is not yet determined what kind of goods are traded, obtaining energy from another smart house and storage capacity for preserving energy could be one of them.

Summarized, these requirements are necessary to answer the research questions and to verify the thesis statement. Moreover, they are required for comparing the material found during the literature review to determine on which material this research can be built up.

3.2 The Grids

The design of current electrical grid or conventional grid is based on a strictly connected network (U.S. Department of Energy, 2010). Every participant in this network has a single point connection to the next participant and stays under a synchronized control. If such a single point connection has an outage, every participant below this connection is affected too and the synchronization of the grid is at risk.

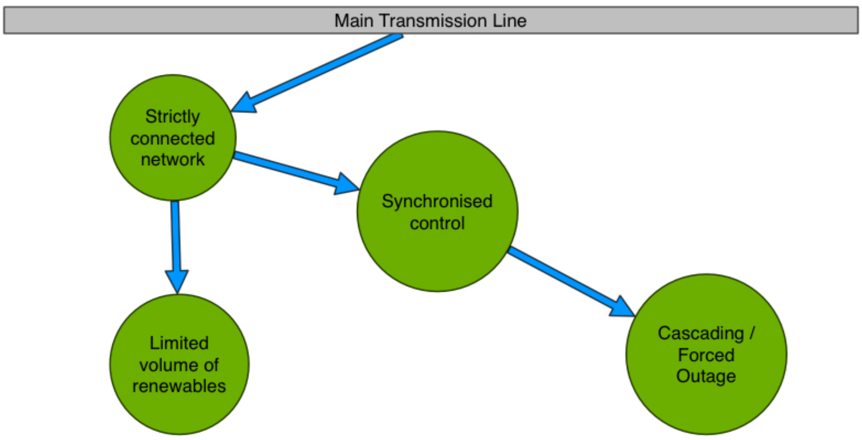

Figure 1: Conventional grid design based on (JCC, 2013)

Another design issue is the fact that a grid operator is not able to determine if an outage has happened because the connection flow goes into one-direction: from the power plant to the energy consumer. To solve these issues, the Smart Meter was invented which is an electronic device that records energy consumption and communicates that data back to the grid operator for monitoring purposes (Zheng, Gao, & Lin, 2013).

The Smart Meter was the precursor of the Smart Grid, which is by definition a modernized electrical grid that uses information and communication technologies (ICT) to gather data about the behavior of energy producers and consumers (Communication, 2010; Vijayapriya, 2011). The Smart Grid adds a full-duplex communication technology to devices associated with the grid to gather data and report it to the utility's network operations center. One of its key features is automation technology that allows the utility to adjust and control all devices from a central location (U.S. Department of Energy, 2010). With this approach, the grid benefits from the gathered data to improve the efficiency and reliability of the production and distribution of energy. For instance, when a blackout happens in a city because a connection has an outage, the Smart Grid determines the blackout by using ICT and estimates a new path to create a new connection to the grid for the city. Nevertheless, in the Smart Grid approach the electrical grid is still a strictly connected network. Thus, a small grid failure can easily start cascading outages that can result in a large-scale blackout and therefore this approach does met the requirements defined in previous chapter.

The Digital Grid Consortium was founded to promoting and developing the concept of the Digital Grid (Abe et al., 2011). This approach divides large synchronous grids into smaller segmented grids so-called cells, which are connected asynchronously through information and communication technologies. Each cell consists of its own energy production and energy storage facilities to cover the energy demand of the consumers.

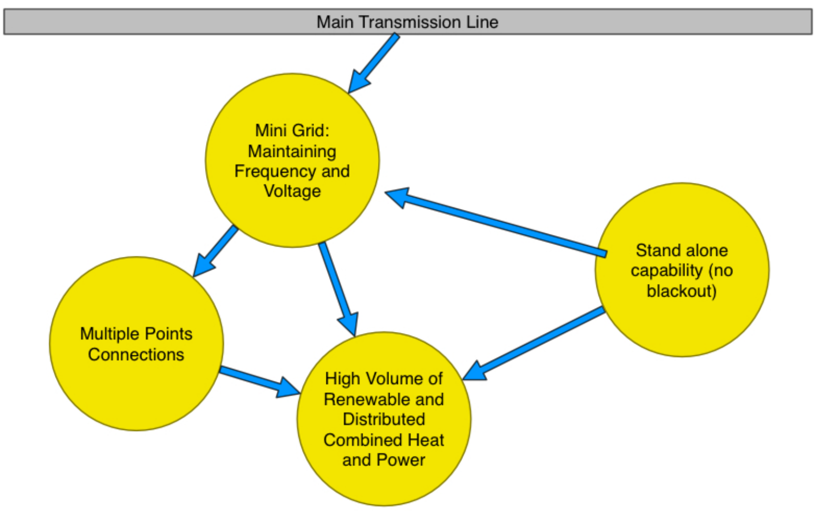

Figure 2: Digital Grid design based on (JCC, 2013)

Because such a cell is also connected to the superior grid or respectively to other cells, it can either purchase energy from these cells or sell energy to them. Thanks to this distributed design, an outage of a cell affects only that cell and has no influence to the other cells. Another benefit of this design is the fact that in such a situation the affected cell can determine new connections to receive energy from the other cells as it is suggested in the Smart Grid design.

Because each cell has its own energy storage facilities, the usual restriction that energy must be produced and consumed at the same time is relaxed (Abe et al., 2011). It enables flexible commercial trading so that energy can be reserved for future use and the energy consumer can select the time of delivery.

Regarding the criteria of the previous chapter, the Digital Grid satisfies the design requirements of a decentralized network that is divided into several smaller segments. According to (Digital Grid Consortium, 2014b) the Digital Grid is a new architecture for the electrical grid and not a single point solution. Furthermore, the Digital Grid enables the segments or cells to exchange energy with each other even between cells that are not even directly connected, which is a fundamental requirement for energy trading (Digital Grid Consortium, 2014a, 2014b).

Nevertheless, the exchange or rather energy trading is so far limited between the cells of the Digital Grid and not applied inside the cell itself. Which means that the stability of the grid could be improved by trading energy among the cells but it is not primarily intended. Basically, the approach of this thesis is to apply the idea behind the Digital Grid on a micro grid level or respectively inside such a cell. This means that each smart house can be represented as a cell in the Digital Grid, which communicates with others to trade and exchange energy. Although the Digital Grid looks promising and the design could be applied on a smart house level, there is no approach to divide the Digital Grid in several smaller Digital Grids that are decentralized connected with each other.

3.3 Energy Trading

Regarding the research for improving the current electrical grid, the Smart Grid approach seems to be the solution that is most discussed at this time. Although the Smart Grid design considers the act of energy trading, it mostly just concerns about the economic aspect in relation to profit that can be made (ACT, 2008; Chen, Shroff, & Sinha, 2013; Rahimi & Ipakchi, 2010).

Nevertheless, the Neighborhood Oriented Brokerage Electricity and Monitoring System (NOBEL) has a different design for delivering energy to the consumers compared to the Smart Grid. According to (NOBEL, 2011) the distrusted generation of energy from vendors and private homes is a big challenge for tomorrow's power management system which cannot be done under a central control. Therefore, the NOBEL project will build an energy brokerage system where each individual consumer can communicate her energy needs directly. The goal of NOBEL is to reduce the currently energy usage of the consumers by providing an efficient distributed monitoring and control system for system operators and prosumer through information and communication technology (Marqués & Serrano, 2011). In particular, it aims to facilitate and manage energy trading inside a segmented grid using market driven demand response.

NOBEL's market model enables the actors in the grid to trade their energy based on their forecast, level of production and consumption needs (Ilic & Silva, 2012). In contract to a traditional stock exchange, the model promotes trading periods, which are discrete fixed-size time slots throughout the day. Such a time slot has a defined start and end time where the end time is used as the start time for the next trading window to perform energy purchases and sell-transactions. Every actor is able to place a market order, which is stored in its personal order book. As long as the trading window is open, an actor can modify its placed market order in the personal order book. In order to interact with the market, a producer or consumer should be able to predict its specific energy supply and demand according to NOBEL.

Even though NOBEL's design takes the technical and economical incentive into account, it does not fulfill all defined criteria. It is maybe possible to apply this approach on a micro grid level but it would lack of having distributed communication inside the micro grids. Moreover, its trading capabilities are limited to energy and the trading of other goods has not yet provided.

Differentially to the NOBEL's design, the PowerMatcher design is a distributed energy systems architecture and communication protocol that facilities implementation of standardized and scalable Smart Grids and it can include both conventional and renewable energy sources (Kok et al., 2010). According to (Kok et al., 2010), this technology can creating a significant degree of added-value in electricity markets through intelligent clustering of numerous small electricity producing and consuming devices.

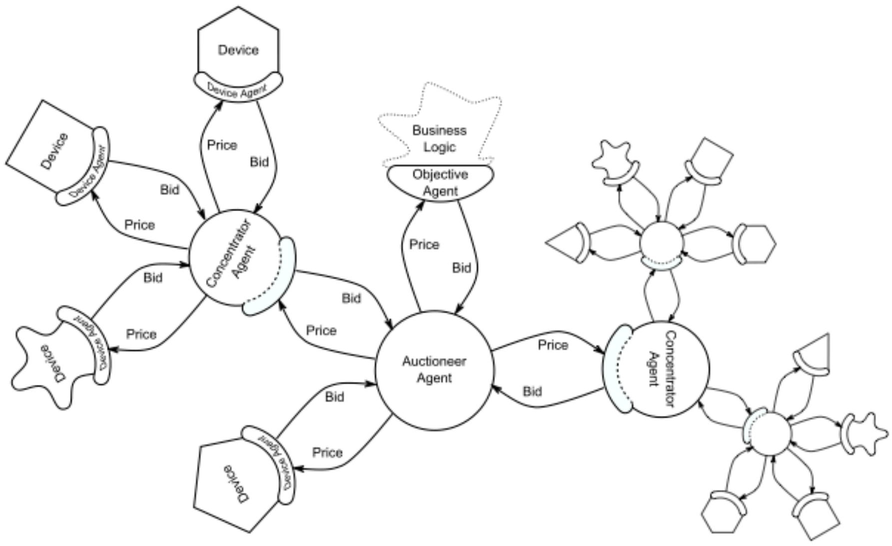

Figure 3: PowerMatcher Agent Cluster (Kok et al., 2010)

These devices are optimized to adjust their operation in order to increase the overall match between energy production and demand. Here takes the so-called auctioneer agent the responsibility for the energy market within the PowerMatcher cluster by establishing the energy price by search for the equilibrium price. Thus, this device collects any bid from the devices in the cluster, creates the equilibrium price based on these bids and sent this price back to the connected devices when a significant price change happens.

Just like NOBEL, PowerMatcher enabling the participants in the grid to trade energy but does not propose the trading of other goods such as providing energy storage capacity. Although the design of PowerMatcher relies on decentralized and distributed communication, it does not allow the participants to communicate with each other directly inside the micro grid or cluster in terms of PowerMatcher. Because a cluster is organized as a logical tree where the Auctioneer Agent is the root of the tree, it leads in particular to the issue of a centralized control unit inside the micro grid. In other words, if the Auctioneer Agent has a failure then it would not be possible for the smart houses to trade energy anymore. Therefore, the PowerMatcher does not met the all requirements of chapter 3.1 as well.

3.4 Conclusion

Table 3 gives an overview over the different approaches discussed in this chapter and shows how they fit to the requirements specified in the beginning of this chapter:

Approach	Micro Grid	Distributed Communication	Decentralized Network	Trading Goods	Improve stabilization by trading energy
Smart Meter	-	-	-	-	-
Smart Grid	-	-	-	(✓)	-
Digital Grid	(✓)	-	✓	(✓)	-
NOBEL	-	-	(✓)	(✓)	(✓)
PowerMatcher	(✓)	-	✓	(✓)	(✓)

Table 3: Compare approaches

The Smart Meter and its successor the Smart Grid are applied ***only on the superior grid level*** regarding renewable energy production and energy storage facilities. Furthermore, it is not the intention to change the current design of the electrical grid but rather try to extend it. Such as the Smart Grid, the Digital Grid ***is applied only on the superior grid level*** except it is based on a distributed electrical grid design.

Although NOBEL and PowerMatcher look promising, some of the requirements cannot be satisfied. In the case of NOBEL**, it is not intended to apply it on a micro grid level and using distributed communication**. Nevertheless**, the trading mechanism of NOBEL is an interesting approach**, which must be pursued in this paper. Even if the PowerMatcher concept **is designed for creating energy markets,** it concentrates more on how energy can be traded in the different energy markets **instead of improving the stabilization of the electrical grid**. Also both concepts **only concentrate on trading energy and no other goods.**

Regardless of the design of the electrical grid, **the question remains** how the trading of energy can be efficient and beneficial for the producer and consumer and how the network stability can be improved at the same time. Designs such as the Smart Grid, Digital Grid, NOBEL or PowerMatcher aims to reduce the energy production and consumption in the grids. **The stability of the electrical grid can be improved with these approaches but their main objective is to reduce the energy demand instead of challenge it in a new way**.

4 Research Methodology

The goal of this thesis is to create a concept for energy trading in a distributed network and to develop a simulation system based on an existing multi-agent framework. For this reason, research methodologies such as survey studies (Krosnick, 1999), experiments (Hinkelmann & Kempthorne, 2007) and case studies (Yin, 2009) are not sufficient in order to create such an artifact. The goals of those are either to find patters in data, test hypotheses or to study the characteristics of a real-life instance. Therefore, the Design Science Research approach is used to create the artifact, or respectively the concept for energy trading in a distributed network (Hevner, March, Park, & Ram, 2004). Because this concept should be implemented in a simulation system based on an existing multi-agent framework, a tailored version of the iterative software development process Rational Unified Process (RUP) is used as well (Teams, 2004). Due to the fact that the Design Science Research framework and RUP consists of very similar phases, these two approaches are combined together to verify the thesis statement and to answer the research questions. The reason for this combination is that the Design Science Research Framework follows the waterfall-approach, which is nowadays abandoned in software development and replaced through the agile development approach (Cockburn & Highsmith, 2001; Fowler & Highsmith, 2001; Highsmith & Cockburn, 2001). The key features or rather ideas of agile software development is adaptive planning, early delivery, continuous improvement, rapid and flexible response for changing requirements (Highsmith & Cockburn, 2001). Thus, the combination of Design Science Research Framework and RUP is a great approach in order to answer the research questions and to develop a simulation system according the academic and agile software development principles.

4.1 Design Science Research and RUP

The Design Science Research Framework consists of five while the RUP approach consists of four phases:

#	Design Science Framework	Rational Unified Process
1	Awareness of the problem	Inception phase
2	Suggestion	Elaboration phase
3	Development	Construction Phase
4	Evaluation	Transition phase
5	Conclusion	

Table 4: Design Science Framework vs. Rational Unified Process

In the Design Science Research Framework the first step is to get aware of the problem that should be solved. The suggestion step determines what kind of artifact might solve the problem. The goal of the development phase is to design and create the artifact. In the evaluation step, the artifact is verified whether it solves the problem and analyzing its strengths and weaknesses. In the final phase, the compilation of results and future aspects for further development are presented.

Compared to the Design Science Research Framework, the Rational Unified Process consists only of four partly overlapping phases instead:

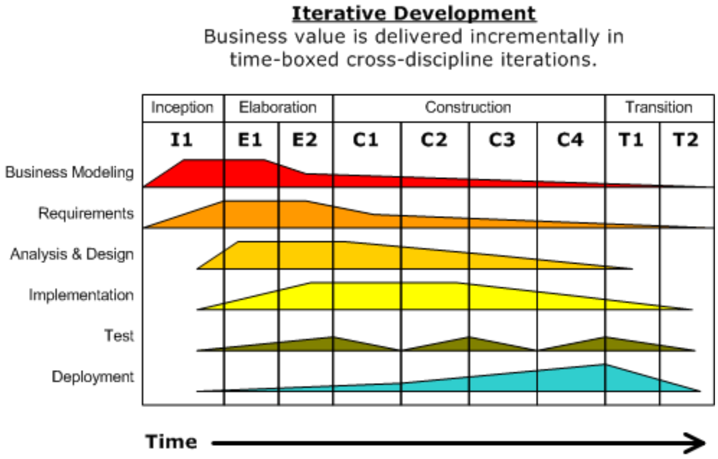

Figure 4: RUP phases and disciplines (Dutchguilder, 2007)

In the Inception Phase the scope of the software product is be defined regarding the validation of initial costing and budgets. The primary objective of the elaboration phase is to minimize the project risks through a problem domain analysis to identify the most important use cases of the software product. Based on this analysis, the software architecture is proposed maybe including a prototype implementation in order to create a development plan. The construction phase consists of several iterations in which the use cases are be implemented according to the development plan. At the end of each phase the project team comes together and review the current project's progress and to prioritize the next features that should be developed. The goal of the final phase is the transition from the development to the production environment. Some of these phases are partly overlapped in favor of agility during the software development project. For instance, due to constant feedback of the stakeholders and change tolerance, RUP allows or rather enabling the adjustment of requirements during the project to satisfies the stakeholders' needs (Teams, 2004). Thus, RUP respects and enforces the idea of agile software development: adaptive planning, early delivery, continuous improvement, rapid and flexible response for changing requirements (Highsmith & Cockburn, 2001).

As mentioned in the introduction of this chapter, the phases of the Design Science Research Framework and RUP can be combined because of their similarity. This new approach based on this combination is essential to verify the thesis statement in a scientific approach and to implement the suggested artifact in an existing multi-agent framework regarding the advantage of agile software development. By the combination of the two approaches the following steps are extracted in order to find and develop the required artifact, which solves the problem:

1. Awareness of the problem
2. Suggestion / Inception
3. Elaboration
4. Development / Construction

5. Transition
6. Evaluation
7. Conclusion

During the creation of the artifact, the result of each phase is discussed with the Smart Stability team to take course corrections and to optimize the further developments.

4.1.1 Awareness of the problem

Due to the fact that this thesis is part of a strategy initiative between three Universities of Applied Science and Arts of the Northwestern Switzerland, several workshops are performed to define the bigger picture of the Smart Stability project. Although interviews can be performed to gather the bigger picture as well, the created concept in this thesis has an essential impact on the design of the Smart Stability approach and therefore a close collaboration is necessary to fulfill or adjust the requirements during the time of this paper. Because the concept has a fundamental influence on the result of the Smart Stability project in terms of energy trading, it is necessary to have a common understanding of the problem to determine how energy is traded in a distributed environment to improve the stability of the electrical grid.

In order to gain a better perspective of the current situation about the electrical grid and possible solutions, a literature review is conducted to find out how other research was accomplished in this field. It is important to find existing approaches where this thesis can benefit from it and to find gaps in the literature where it could be embedded in.

4.1.2 Suggestion / Inception

The suggestion is created through various workshops in the Smart Stability project with the people who are interested in the energy trading approach of this thesis. As mentioned in the previous chapter, a common understanding of the problem is required but also of the suggested artifact in respect to the criteria of Smart Stability and the derived requirements in chapter 3.1.

In addition, literature is conduced that proposes possible approaches towards the goal to reduce the amount of energy demanded from the superior grid and therefore the stability of the superior grid. Based on literature and conducted workshops, the suggested artifact becomes mature and takes shape in order to start with the development phase. Moreover, the scope of the simulation system based on the suggested artifact and the existing multi-agent framework is defined in this phase. Therefore the core requirements, key features and constraints and risks are determined as well.

4.1.3 Elaboration

A problem domain analysis is performed to identify the most important use cases for the implementation of the suggested artifact. Based on this analysis, the software architecture is proposed including a prototype implementation in order to create a development plan for the next phase and to minimize the project risk. Therefore, another literature research is conducted to get the knowledge about the multi-agent framework. The development plan defines how the suggested artifact is implemented in the existing simulation system.

4.1.4 Development / Construction

The goal of the development phase is to design and create the artifact. This means that the suggested design in chapter 4.1.2 and 4.1.3 gains substance in a concrete artifact. Hereby, the artifact is refined over several iterations until it is developed according to the development plan.

The application of the suggest energy trading concept in a real-life situation is currently not possible within the scope of this thesis because of time, money and technical constraints. Instead, a simple model of a micro grid is used with prosumers, which are consumers and producers at the same time. These prosumers, respectively smart houses, consist of a renewable power production such as a photovoltaic system, a storage facility in the form of a battery, a heat-pump and a hot-water tank that consumes energy. The behavior of such a smart house is based on an energy consumption data collection, which was recorded over a year. This data collection is provided by the Smart Stability project to simulate a real consumer behavior of a house in Switzerland from January to December. The model is then implemented in the simulation system to verify the economic impact of different energy trading approaches between the participants in the micro grid and the technical impact regarding the stability of the superior grid. At the end of an iteration the project team comes together and review the current project's progress and to prioritize the next features that should be developed.

4.1.5 Transition

The goal of the final phase is the transition from the development to the production environment. This means that the simulation environment is ready to use by the members of the Smart Stability project to evaluate the created artifact or rather concept with the implemented model. The transition is an important phase that proves that the implemented simulation system works as intended in the production environment.

4.1.6 Evaluation

In this phase, the artifact is verified whether it solves the problem and analyzing its strengths and weaknesses. In particular, the artifact is validated against the defined criteria of chapter 3.1 and the created user cases of the Elaboration Phase in order to determine if the created artifact meets the requirements. The simulation of the micro grid and its participants show if the implemented concept of energy trading is improving the stabilization of the electrical grid. For this simulation, the energy consumption data collection for a standard house is used to investigate the energy consumption of the smart houses. The collected data from the simulation shows if the electrical grid is relieved from energy peaks and how the energy demand from the superior grid is affected. If this attempt fails then the reasons for and why this happened is explained in this thesis.

In any case, the result of this phase is to gain new information and can be used for further development.

4.1.7 Conclusion

In the final phase, the compilation of results and future aspects for further development are presented. In particular, the conclusion suggests how the results of this thesis could be applied in practical real-life applications and what research is still required to do so.

5 Trading in the Smart Stability Network

As mentioned in chapter 2.1 and 2.2, the goal of this thesis is to improve the stability of the electrical grid by trading different goods.

According to (Swissgrid, 2014), the balance between production and consumption is the requirement for a stable electrical grid. This means that production and consumption need to be coordinated to achieve this requirement. Thereby, the production of energy can be predicted apart from new renewable energy sources. On the other hand, consumption can be estimated but never accurately predicated. For example, an unexpected cold snap can increase the energy consumption contrary to the estimated plan.

To achieve the balance and thus the stability of the electrical grid, the power plants need to fulfill a specified schedule. This schedule is determined with the Dispatch & Redispatch approach (Next Kraftwerke, 2014). The purpose of the Dispatch is to enable the power plant operators to implement a lucrative business viable method for using their power plants. Hereby, the power plant operator makes the use of all available power plants, taking into account the variable cost of the operation (for coal power plants including the cost of fuel) and taking into account the expected prices on the relevant energy market, because a power plant will only be used if its variable costs are lower than the achievable selling prices. The result of the Dispatch is the allocation of available power plan capacity of the next day that is held in a so-called schedule. Each power plant operator sends its schedule to the transmission system operator. When the Transmission System Operator received all the schedules, then he calculates the load of the network for the upcoming day to see which parts of the electrical grid would be highly stressed regarding the reported Dispatch. In order to keep the number of short-term intervention in the operation of power plants as low as possible, the result of the network load calculation is used one day before to instruct the power plant operators to postpone their planned energy production. This instruction to move the current production is denoted by the term Redispatch and allows to avoid proactive bottlenecks in the electrical grid. After the Dispatch & Redispatch is done for the upcoming day, all power plant operators are committed to comply with its schedule.

Based on this requirement, the trading of goods inside the Smart Stability Network should be used to meet the schedule of the community and thus to keep the balance of energy production and consumption to improve the stability of the electrical grid.

5.1 Actors

The Smart Stability Network consists of the following actors:

Smart Stability House: The Smart Stability House represents a house in the network that consists at least of a boiler and a heat pump. It demands energy from the community or rather Micro Grid to power these devices. In addition, a house could be equipped with a photovoltaic system and/or energy facility storage such as a battery. Therefore, the Smart Stability Network consists of several houses in which each house can have different energy production and consumption devices in addition to the boiler and the heat pump.

Market Place Coordinator: This actor is responsible to coordinate the trading between the different houses in the network.

5.2 Tradable goods

As described in the introduction of this chapter before, the goods that can be traded by a Smart Stability House must be suitable to reduce the deviation from the defined schedule of the Smart Stability Network. There are two possibilities for the deviation from the schedule, either the actors in the network demand more energy as granted to them by the schedule or the actors demand less energy as predicted. There is thus either an energy surplus or an inadequate energy demand. In both cases there is a need for action to keep the balance respectively to keep the electrical grid stable. Based on this fact, there must be goods available to consume and produce energy in the Smart Stability Network.

Due to the fact, that a Smart Stability House is equipped with a boiler, a heat pump and in addition can be equipped with a photovoltaic system and a battery, the following goods can be determined to consume and produce energy:

Device	Tradable Good	Produce Energy	Consume energy
Photovoltaic system	Consume solar energy	✓	-
Battery	Consume stored energy	✓	-
	Store energy	-	✓
Boiler	Switch boiler off	✓	-
	Switch boiler on	-	✓
Heat pump	Switch heat pump off	✓	-
	Switch heat pump on	-	✓

Table 5: Tradable goods

As shown in Table 5, there is a distinction between consumption and production of energy which both can be fulfilled by some of the devices, e.g. boiler, heat pump and battery.

5.3 Price formation

Regardless that each good adds value to the community, there are goods that have a higher priority as the others. For example, when the energy demand of the Smart Stability Network is higher than the schedule then the produced energy of photovoltaic systems should more preferred than switch off the boiler. The reason for this approach is that the photovoltaic systems produces energy anyway and produced energy must be used somehow according to the law of energy consumption and production. On the other side, a house has more value when the heat pump is switched on when a Smart Stability Network has produced too much energy instead of storing that energy into the battery because the homeowners are more likely interested in a warm home that a full battery level. Furthermore, it is not enough to prioritize the processing of the offers because there are some risks that must be taken into the account. For instance, when a house decides to switch off its boiler then it could be possible that this house is not able to produce warm water at the end of the cycle. This is a high risk because the homeowners expect to always have warm water. For this reason, the price formation takes the priority and risks into account, which means that such a good as produced energy by a photovoltaic system is cheaper than switching a boiler off for the next cycle. In order to define the sequence of offers to be processed to decrease the deviation from the schedule, the Market Place Coordinator sorts the offers by price.

5.3.1 General Price Formation

Each good has its own base price value, which is lower or higher than the other goods to define a natural ordering or respectively prioritization. For example, the base price value for produced energy by a photovoltaic system is lower than the base price value to switch a boiler off.

The following base price values are used for the goods in the simulation system:

Device	Tradable Good	Price value
Photovoltaic system	Consume solar energy	5
Battery	Consume stored energy	7
	Store energy	20
Boiler	Switch boiler off	10
	Switch boiler on	10
Heat pump	Switch heat pump off	15
	Switch heat pump on	15

Table 6: Used base price values in the simulation system

5.3.2 Specific Price Formation

Each good has an additional specific price formation to take the risks into the account, e.g. a boiler can be switched off but it must be switched on at a certain time regardless what it costs. The following table lists the different risks for the tradable goods:

Device	Tradable Good	Risk
Boiler	Switch boiler on	The boiler is running at the limit and must be switched on soon; otherwise there will be a warm water bottleneck.
	Switch boiler off	The boiler has almost reached the maximum amount of warm water and must be switched off soon.
Heat pump	Switch heat pump on	The heat pump is running at the limit and must be switched on soon so that the temperature in the house can be hold.
	Switch heat pump off	The heat in the house has almost reached the maximum temperature and must be switched off soon.

Table 7: Risks of tradable goods

As can be derived from the table above, the risk of each listed tradable good depends upon a time factor. Either the time span until a device must be switched on or until a device must be switched off. This time factor can be used to determine the specific price for a tradable good now. Thus, the specific price for a tradable good can be calculated by the base price value and the time factor.

A possible solution would be a linear price formation where the price is linearly increased depended on the base price value and the time factor:

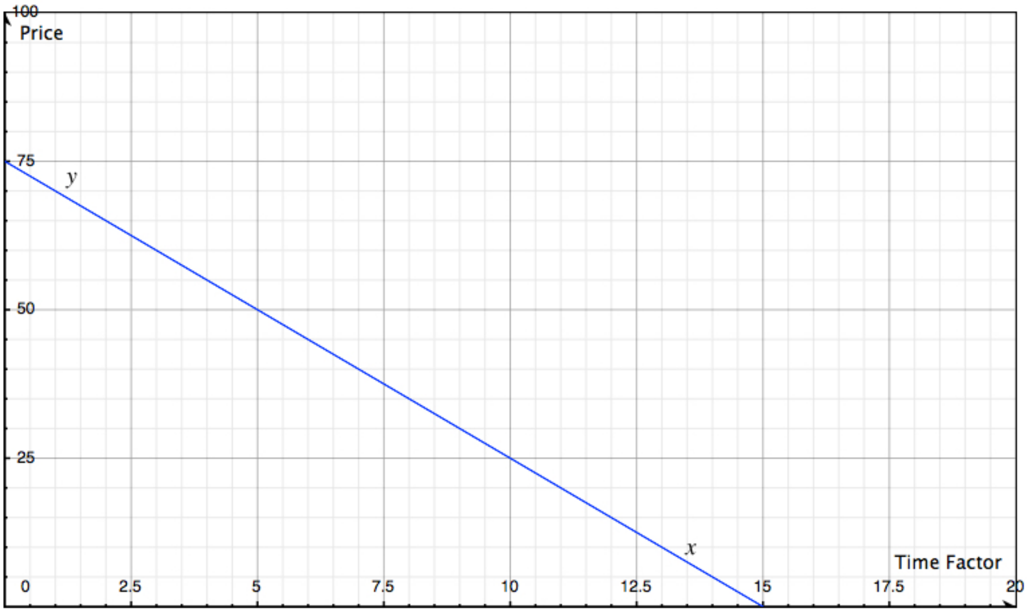

Figure 5: Liner price formation example

The figure above shows the example of the linear price formation for a tradable good, which has a base price value of 5 and a time factor from 0 to 15. As mentioned before, when the time factor tends to zero then some action must happened, e.g. switch on the boiler. This means that the price is highest when the time factor tends to zero. This approach uses the following function to determine the price:

$$y = b * (-x + tc)$$

Equation 1: Linear price calculation

Where y corresponds to the calculated price, b to the base price value, x to the time factor and tc to the time span of the next cycle.

Although it is a simple solution, the real risk for a house in this example is much higher than it can be applied by a linear function. This means that in such a situation the price must be that high that when the Smart Stability Network take that risk all the other possibilities must have been exhausted. Furthermore, the homeowners must be rewarded so that it is worthwhile for them to take the risk, for instance to not have warm water for a small time period. So instead of a direct proportionality, the concept of inverse proportionality is used to calculate the specific price:

$$y = b * \frac{tc}{x}$$

Equation 2: Price calculation through inverse proportionality

With this approach, a high risk leads to a higher price and therefore to a higher reward for the homeowners as shown in Figure 6.

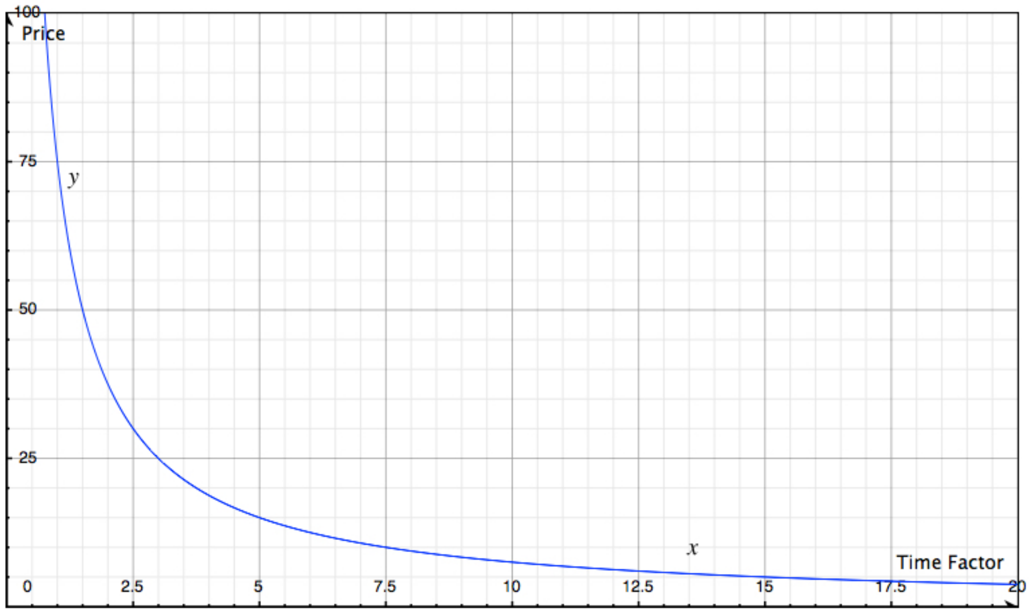

Figure 6: Inverse proportionality price formation example

Thanks to this approach, an economic incentive can be created for homeowners who are willing to take higher risks into account than others. This means, there could be a mechanism which enables a homeowner to define how much risk he is willing to take into account to receive a higher reward. In the example of the boiler, a homeowner could set its own limits when a boiler has to be switched on or off. This means that a homeowner being willing to take higher risks allows the time factor to reach almost zero to get a high reward for his risk.

5.3.3 Penalty fee

When the schedule for a cycle could not be applied in a Smart Stability Network then the participants have to pay a penalty fee. In other words, the higher the deviation from the schedule is, the higher is the penalty fee. A solution could be a linear penalty fee formation, which is calculated from a base value and the deviation.

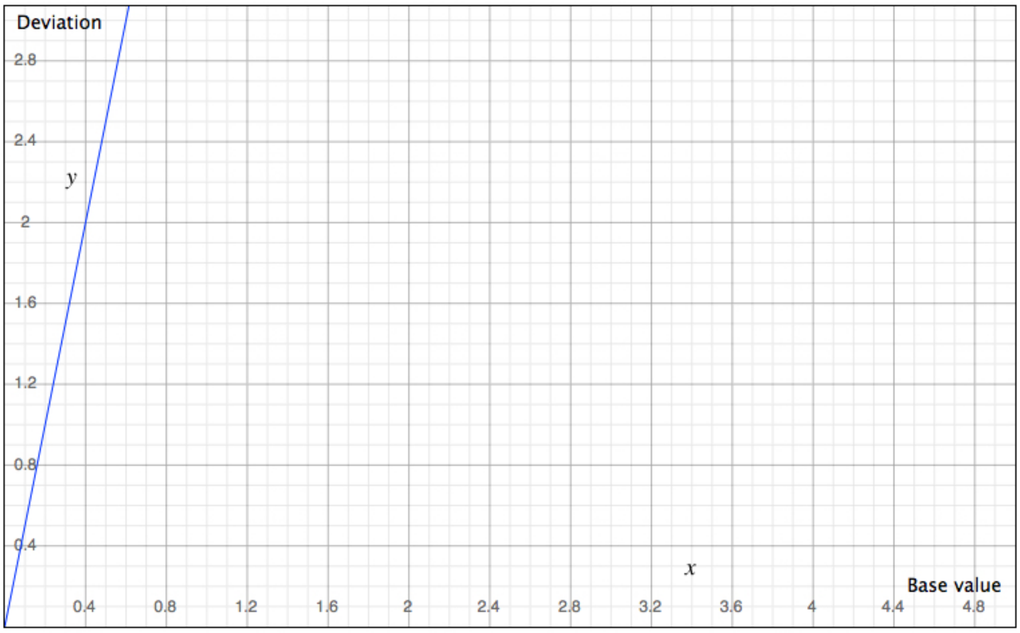

Figure 7: Linear penalty fee formation

Figure 7 shows this approach to calculate the penalty fee with the following linear function:

$$p = b * d$$

Equation 3: Penalty fee

Where p corresponds to the calculated penalty fee, b to the base value and d to the deviation from the schedule.

Although this is a simple approach, it carries out the purpose to let the participants in the Smart Stability Network to pay a higher fee when a large deviation from the schedule is present.

5.4 Communication

Each community is represented as a Smart Stability Network, which is a decentralized network connected to the superior grid as shown in Figure 8.

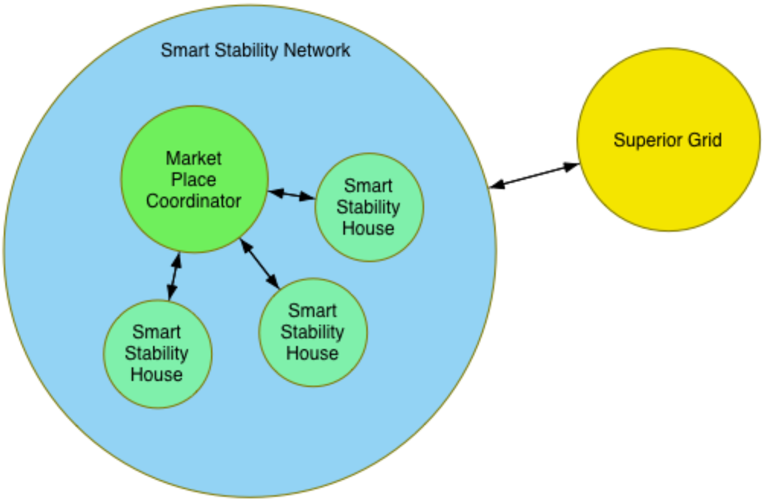

Figure 8: Smart Stability Network

A Smart Stability Network can operate even when the connection to the superior grid is missing by using its own resources capabilities such as photovoltaic systems or energy storage facilities. Although these capabilities maybe not enough in order to produce enough energy for their selves for a long it time, it could still allow a community to survive a short- or mid-term interruption from the superior grid.

As can be derived from Figure 8, a Smart Stability Network consists of many Smart Stability Houses but only one Market Place Coordinator. Due to the fact that this actor is responsible to handle the trading process for all the members of the network, it could be seen as a centralized control unit but it is actually just a Smart Stability House that took this role when the network was initialized. In the case that the Market Place Coordinator were disconnected from the network or has any other issue, another Smart Stability House will become the Market Place Coordinator so that Smart Stability Network stays operational. When the previous Market Place Coordinator will be connected again then it just becomes a Smart Stability House. With this approach it can be guaranteed that the network is not relied on a centralized control unit, which can be harmful to the network if it has a fault. (Lann, 1977) calls this approach in a distributed network "Leader Election" and it is the process of designating a single actor as the leader of some task distributed among several computers (nodes) in a network. This means that before the task is performed, all nodes in a network are unaware which node will be the leader of the task or unable to communicate with the current leader. After the leader was elected in a network, each node knows which unique node is the leader of the task.

The Leader Election algorithm was not implemented in the simulation system because the simulation system is in particular used for evaluating the trading process itself after a leader was elected. Furthermore, there exist different Leader Election algorithms and each with its own advantages and disadvantages. The analysis and evaluation of those are beyond the scope of this thesis.

5.5 Trading Process

The trading process consists of five phases:

1. Requesting the energy demand of all Smart Stability Houses
2. Calculating the deviation from the schedule
3. Conducting the auction
4. Calculating the penalty fee
5. Announcement of the next cycle

The Market Place Coordinator is the responsible actor to handle the trading process for a specified time window, respectively trading window as known from NOBEL's approach in chapter 3.3. Each trading window is used to calculate the energy demand of the Smart Stability Network for the next time window what is referred in this thesis as a cycle. So when a new cycle starts then the Market Place Coordinator informs the Smart Houses that a new cycle has started and the houses should announce their energy demand and offers (tradable goods). Based on these announcements, the Market Place Coordinator calculates the deviation from the schedule based on the energy demand of all Smart Stability Houses:

$$d = \left| s - \sum_{i=1}^{n} e_i^f \right|$$

Equation 4: Deviation from the schedule

Where d corresponds to the deviation from the schedule, s to the schedule and e_i^f to the forecast of the energy demand for the house i.

The forecast function in the equation above is required to determine the energy demands of all houses. The ideal solution would be to forecast the energy demands of the next cycle to calculate the best possible deviation from the schedule. Because of some limitations in the simulation system, it is not possible to get the energy demands for the next cycle and instead the energy demands of the previous cycle are used as illustrated in Figure 9.

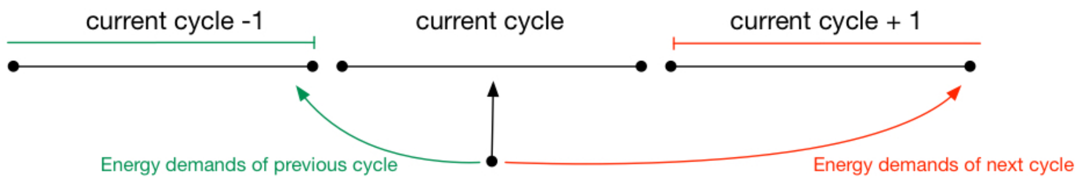

Figure 9: Energy demand forecast

This situation of course leads to the issue that the assumption may not correspond to the actual required energy demands of the next cycle. This means that the calculated deviation from the schedule is not as accurate as it could. However, this inaccuracy is dependent on the chosen time window for a cycle in the simulation system: the smaller the time window, the smaller should be the inaccuracy. Nevertheless, this thesis will not involve the solution for this issue and therefore uses the energy demands of the previous cycle to calculate the deviation from the schedule for the next cycle.

It is important to say that at this step all offers are accepted that provide energy, which were produced by photovoltaic systems. The reason for this action is the fact that produced energy must somehow be consumed (Kok et al., 2010). Of course, this condition has a big impact on the actual energy demand and the deviation from schedule for the next cycle. When for instance the Smart Stability Houses produced a high amount of energy then the situation could occur that actually no energy is required from the superior grid. Nevertheless, the Smart Stability Network has to comply with the schedule and therefore results in a deviation from the schedule.

$$d = \left| s - \left| \sum_{i=1}^{n} e_i^f - \sum_{i=1}^{n} o^i \right| \right|$$

Equation 5: Adjusted deviation from the schedule

Here corresponds *o* to all accepted offers that provide energy.

In the case where a deviation is present, the Market Place Coordinator looks for the best matching offers to decrease the deviation from the schedule. In order to achieve this goal, the Market Place Coordinator tries to use as many as possible offers while two different methods are applied:

1. Determine the best offer that expresses the deviation closest to zero.
2. Determine the best offer that expresses the deviation to zero.

These two methods are used because some of the tradable goods can only provide or consume the energy value that is proposed in the offer. For instance, a boiler can only be switched off for the whole time window of a cycle and not just for a couple of minutes during a cycle. On the other hand, a battery is only limited to its capacity and therefore it can either store more or provide less energy according to the charge of the battery in a cycle. Thus, tradable goods such as switching on/off a boiler are of course helpful to decrease the deviation form the schedule. But in some situation, it is only possible to bring the deviation to zero by consuming or producing a certain energy value. This certain energy value can for instance consumed by a battery although their capacity is far from being charged.

Any accepted offer by the Market Place Coordinator during these two phase has a defined price as described in chapter 5.3, which is credited to the house that proposed the offer.

As an example, the deviation from the schedule is equal to 3 kWh and there are three offers: 1st switching a boiler on for 2kWh, 2nd switching a heat pump on for 4 kWh and 3rd charging a battery with 5 kWh. Due to the fact that switching a boiler on has a higher priority than storing energy in a battery as described in chapter 5.3, the first method is used to determine the offer with the best energy value to use regarding its priority and the price. Here, the proposed energy value in the offer corresponds to the maximum amount of available energy that can be used. This method is repeated until the deviation from the schedule is closest to zero and no other offer can decrease the deviation anymore. Which means the 1st offer is accepted and the deviation is now equal to 1 kWh. The 2nd offer is not accepted because its use would instead increase the deviation from the schedule: $3kWh - 2kWh - 4kWh = -3kWh$. The Market Place Coordinator sends an acknowledge message to the House who sent the 1st offer.

Due to the fact that the deviation from the schedule is still greater then zero, the second method is applied. This method determines the best offer that can be used to decrease the deviation to zero by using the exact energy value that is required to achieve this goal. Also this method is repeated like the first method until no other offer can decrease the deviation anymore. Thus, the 3rd offer is accepted but the battery is only charged with 1kWh to bring the deviation from the schedule to zero. As before, the Market Place Coordinator sends an acknowledge message to the sender of the offer and informs the sender how much energy must be stored.

Now the deviation from the schedule is zero and the Market Place Coordinator continues with the next phase: calculating the penalty fee. In the case that the deviation is greater than zero, the Market Place Coordinator determines the penalty fee for the Smart Stability Network because the schedule is not complied: the higher the deviation, the higher the penalty fee. The penalty fee is divided to the number smart houses, which means that the participants share the penalty fee. As the next step, the Market Place Coordinator informs the houses if they have to pay a penalty fee and instructs them that they should get ready for the next cycle. Now the trading process starts anew.

6 Implementation

The implementation of the trading process is based on an existing simulation system through the use of the multi-agent framework JADE, as mentioned in chapter 4. This simulation system uses a model to represent an instance of a Smart Stability House. Each actor in the Smart Stability Network is represented as an agent in the simulation system, which has different behaviors and each behavior defines some actions under a given event.

6.1 Smart Stability House Model

This model represents a Smart Stability House (SSHM) in the network and provides several interfaces to devices such as photovoltaic system, boiler, heat pump and an energy storage facility (Lammel, 2014). Each instance of this model can be parameterized by an individual configuration to define which devices are available for the instance and what values, e.g. a battery and its capacity. Thanks to this model, different types of Smart Stability Houses can be created or rather used in the simulation system at runtime. Furthermore, the model includes several consumer profiles that cause a different behavior of the consummation of energy:

Consumer profiles
Couple under 30 years, with work
Couple, 30 - 64 age, with work
Family, 1 child, both at work
Family, 3 children, both with work
Single woman, 2 children, with work
3+ adults couple, 30- 64 years, both at work + Senior at home
Couple over 65 years
Single woman, 30 - 64 years, with work
Single man, 30 - 64 years, with work
Single man with 1 child, with work
Family with 2 children, 1 at work, 1 at home
H70 Couple over 65 years II
Student Flatsharing

Figure 10: Consumer profiles (Lammel, 2014)

The SSHM was developed in the Smart Stability Network Project University of Applied Sciences and Arts Northwestern Switzerland (FHNW) and provides a well-defined interface to send requests or commands to an instance of the model (Lammel, 2014). For example, a caller can ask the energy demand for the next cycle or send the command to switch the boiler off. The advantage of such an interface is that the caller does not need to know the business logic behinds this interface and needs to focus only on the use.

6.2 Simplifications

For the implementation of the trading process, some simplifications have been made in order to focus on the process.

6.2.1 Leader election

As mentioned in chapter 5.4, the leader election is not part of the simulation system because it is beyond the scope of this thesis. For this reason, the simulation system has a predefined agent which represents the Market Trading Coordinator as described in chapter 6.3.1. This actor only takes care of the trading process while the other agents are Smart Stability House Agents.

6.2.2 Schedule

For simplification of the simulation system, the Dispatch & Redispatch approach is not implemented to determine the schedule for the network. Instead, the deviation is calculated as the average of all energy demands for the last hundred cycles with the following equations:

$$j = \min(m, 100)$$

Equation 6: Number of performed cycles

This equation above returns the number of performed cycles m as j when the number of performed cycles is less than 100. The final equation calculates the schedule for the next cycle s, where d_{i-j} corresponds to the sum of energy demands for the cycle $j - i$.

$$s = \frac{1}{j} \sum_{i=0}^{j-1} d_{j-i}$$

Equation 7: Schedule

Although this approach is a strong simplification to determine the schedule, the calculated value serves well as schedule. Which is in fact the greatest challenge that a micro grid can compensate.

6.2.3 Wallet

A wallet is a simple implementation of a purse to transfer or withdraw money from it. Each Smart Stability House Agent has such a wallet to transfer the money from an accepted proposal or to withdraw money from it because the Smart Stability House Agent has to pay a penalty fee. Thus, there is no such an implementation of a money or rather baking account for a Smart Stability House. This means that the simulation system does not reflect the handing over of money between the actors of the community because it is beyond the scope of this thesis.

Nevertheless, the implementation of such a simple wallet system is important for the evaluation to see how many money can be generated through the trading of goods.

6.3 Agents

An agent is an actor in the simulation system that has different behaviors and performs some actions. Each behavior defines an action which will be executed by the agent when a specific event occurs, e.g. starting the trading process or receiving the proposals from the Smart Stability Houses. According to (Caire, 2003), the implementation of a behavior defines how often it is executed and what actions are performed. For instance, the action of cyclic behavior is repeatedly executed until the application terminates. This is the only used type of behavior in the simulation system because all actions such as the trading process are repeatedly executed.

6.3.1 Market Place Coordinator Agent

The Market Place Coordinator Agent (MPCA) takes the role of the Market Place Coordinator and executes the trading process for each cycle. The trading process is implemented as a cyclic behavior, which stays active as long as its agent is alive and will be executed repeatedly after every event. Because the trading process will be repeated for each cycle, this behavior allows the agent to fulfill the following steps for each cycle:

1. Call for energy demands
2. Receive energy demands
3. Call for proposals
4. Receive proposals
5. Handle energy demands
6. Handle penalty
7. Prepare for next cycle

In the first step, the MPCA calls all Smart Stability Houses Agents for their energy demands and waits until it receives all energy demands, which is dealt in the second step. Now the MPCA calls for all proposals of the Smart Stability Houses until each responds with its offers for their tradable goods. In the 5th step, the MPCA calculates the deviation from the schedule and tries to decrease the deviation as close as possible to zero through the offers from the Smart Stability Houses. When this step is done and the deviation is still greater than zero, the MPCA calculates the penalty fee for the Smart Stability Network and divides the fee among the houses. In the final step, the MPCA sends a message to all Smart Stability Houses that the next cycle will begun and that they should prepare themselves. In this final step, the MPCA and the Smart Stability Houses log some data for analysis and evaluation purposes.

6.3.2 Smart Stability House Agent

A Smart Stability House Agent (SSHA) represents an instance of the Smart Stability House Model in the simulation system and communicates with the MPCA over messages. A SSHA can perform several actions according to its behaviors, e.g. send offers to the MPCA. The behaviors are implemented as cyclic behaviors because each one is executed at least once per cycle. The following table shows the behaviors of the SSHA:

Behavior	Trigger	Description
Send Energy Demand	MPCA Step 1	Send the energy demand of the house to the MPCA.
Send Proposals	MPCA Step 3	Collect all tradable goods and sends them to the MPCA.
Receive Accepted Proposal	MPCA Step 5	Receive a message that a proposal was accepted by the MPCA.
Receive Penalty Fee	MPCA Step 6	Receive the penalty fee.
Prepare for the next cycle	MPCA Step 7	Receive a message from the MPCA that the house should prepare for the next cycle.

Table 8: Smart Stability House behaviors

As can be derived from the table above, each behavior is trigged by a step of the MPCA. The common flow of a behavior for a house is to receive a message (event) from the MPCA (trigger) and then to perform some actions:

Behavior	Actions
Send Energy Demand	1. Receive the “call for energy demand”-message from the MPCA 2. Get energy demand from the house 3. Send the energy demand to the MPCA
Send Proposals	1. Receive the “call for proposals”-message from the MPCA 2. Build a list of all possible proposals based on the available devices 3. Send the proposal list to the MPCA
Receive Accepted Proposal	1. Receive an “accepted proposal”-message from the MPCA 2. Transfer the money to the wallet of the house 3. Give a command to the house, e.g. switch the boiler off
Receive Penalty Fee	1. Receive the “penalty fee”-message from the MPCA 2. Pay the fee from the wallet of the house
Prepare for the next cycle	1. Receive the “prepare for the next cycle”-message from the MPCA 2. Log some data 3. Inform the house that the next cycle begins

Table 9: Smart Stability House behaviors and actions

In order to communicate with the SSHM, the SSHA uses a well-defined interface to perform requests or pass commands, which is part of the SSHM.

6.4 Communication

The agents communicate with each other through messages in the simulation system. A message belongs to a message type and can contain different type of data. For instance, a SSHA sends the offer to switch off the boiler for the next cycle in a “SwitchBoilerOffProposal”-message that includes the price and the sender of the message.

The agents use the following messages for their communication:

Type	Name	Sender	Recipient
Announcement	EnergyDemand	SSHA	MPCA
	PenaltyMessage	MPCA	SSHA
	PrepareForNextCycle	MPCA	SSHA
Proposal	PhotovoltaicEnergyProposal	SSHA	MPCA
	SwitchBoilerOnProposal	SSHA	MPCA
	SwitchBoilerOffProposal	SSHA	MPCA
	SwitchHeatPumpOnProposal	SSHA	MPCA
	SwitchHeatPumpOffProposal	SSHA	MPCA
	ChargeBatteryEnergyProposal	SSHA	MPCA
	DischargeBatteryEnergyProposal	SSHA	MPCA
	AcceptedProposal	MPCA	SSHA

The messages of the type “proposal” use the same formula for price formation as described in chapter 5.3. The other messages are used to trigger some events to control the flow of the trading process.

The multi-agent framework JADE provides the communication channel for sending and receiving the messages (Caire, 2003). The intercept of a particular message is thereby implemented in an agent’s behavior as mentioned in chapter 6.3.

7 Evaluation

In order to assess the impact of the energy trading it is necessary to perform simulations with different scenarios. These simulations should be informative if the electrical grid stability can be improved with trading of energy in a Smart Stability Network. Each scenario runs with different parameters to see their impact by comparison with the others.

7.1 Scenarios

The following scenarios are used to perform simulations in the Smart Stability Network.

Name	Description	Switch on/off devices	Photovoltaic system	Battery
Reference	In this scenario the energy trading is completely disabled. There are no energy production system such as photovoltaic systems and the energy consumption is taken at is demanded from the SSHM.	-	-	-
Reference with photovoltaic system	This scenario is based on the reference scenario but each house has a photovoltaic system that produces energy.	-	✓	-
Reference with different consumer profiles	In this scenario the energy trading is disabled but each house has a photovoltaic system. Furthermore, the houses have different consumer profiles.	-	✓	-
Trading	This scenario enables the trading of energy and the houses can send their offers to switch devices on or off.	✓	-	-
Trading optimization through photovoltaic system	This scenario is based on the second scenario but each house has a photovoltaic system available. With this approach a house can produce energy, which can be used in the Smart Stability Network to reduce the energy consumption.	✓	✓	-
Trading optimization through battery	In this scenario the energy trading is enabled but in addition each house has a battery in place to either store or provide energy to the Smart Stability Network. Compared to the previous scenario, a battery allows storing energy when the energy demand of the network is lower than the schedule.	✓	-	✓

Trading optimization through photovoltaic system and battery	This scenario is a combination of the trading and the optimization scenarios. The combination should further improve the stability of the electrical grid. Furthermore, this scenario verifies the impact and the influence of the energy trading to the stability with all optimizations enabled.	✓	✓	✓
Trading optimization with different consumer profiles	This scenario is based on the combined trading optimization scenario but the houses have different consumer profiles.	✓	✓	✓

Table 10: Simulation scenarios

7.2 Simulation

7.2.1 General Preferences

The size of the trading window or rather cycle time is set to 15 minutes. Each simulation run corresponds to the duration of one year or 35'136 cycles.

All SSHAs in a scenario are identically configured, except the SSHAs in the reference and trading scenario with different consumer profiles. This means each house in a scenario has the same configuration values for the boiler, heat pump, photovoltaic system and battery. The reason for this approach is to see the effect of the different tradable goods on the electrical grid stability and the generated profit compared to each other.

7.2.2 Results

The simulations were performed according to the described scenarios in chapter 7.1. Each scenario was run with a different number of SSHAs as indicated in the columns. The numbers in Table 11 show resulting values of the calculated average deviation per cycle over a period of a year.

Scenario	Average deviation per cycle over a period of a year with # SSHAs in kWh					
	5	10	20	30	50	100
Reference	1.141	2.283	4.566	6.850	11.416	22.832
Reference with photovoltaic systems	1.575	3.151	6.30	9.456	15.761	31.522
Reference with different consumer profiles	1.991	3.888	7.853	12.197	20.651	40.486
Trading	0.524	0.719	1.132	1.549	2.435	4.577
Trading optimization through photovoltaic system	0.907	1.559	2.892	4.229	6.886	13.513
Trading optimization through battery	0.0	0.0	0.0	0.0	0.0	0.0
Trading optimization through photovoltaic system and battery	0.0	0.0	0.0	0.0	0.0	0.0
Trading optimization with different consumer profiles	0.0	0.0	0.0	0.0	0.0	0.0

Table 11: Average deviation per cycle of a period of year in kWh

As can be derived from the table above, the trading of energy or rather goods dramatically decreases the average deviation from the schedule. The use of photovoltaic systems does not really support the stability of the electrical grid because its use increases the average deviation from the schedule. On the other hand, when each house has a battery then the deviation is reduced immensely because a battery is a powerful device to store or return a huge amount of energy. The use of batteries has therefore a positive impact on the deviation from the schedule due to these facts. These results are discussed more in detail in chapter 7.2.3 and 7.2.4.

The following tables show the resulting values of received and accepted proposals over a period of one year for all trading scenarios:

Scenario	Received proposals / Accepted Proposals with # SSHAs		
	5	10	20
Trading	155'007 / 4'312	263'829 / 11'394	470'184 / 26'504
Trading optimization through photovoltaic system	198'746 / 5'284	365'240 / 169'859	710'661 / 342'532
Trading optimization through battery	510'321 / 39'777	1'007'114 / 43'513	2'101'542 / 50'793
Trading optimization through photovoltaic system and battery	553'736 / 120'261	1'119'148 / 204'506	2'367'999 / 379'188
Trading optimization with different consumer profiles	505'431 / 55'552	978'535 / 59'862	1'991'181/ 82'531

Table 12: Received and accepted proposals for 5, 10 and 20 SSHAs

Scenario	Received proposals / Accepted Proposals with # SSHAs		
	30	50	100
Trading	673'571 / 42'334	1'107'214 / 73'617	2'175'837 / 151'748
Trading optimization through photovoltaic system	1'062'339 / 515'086	1'754'417 / 861'247	3'507'563 / 1'725'393
Trading optimization through battery	3'359'930 / 58'353	5'886'163 / 84'333	12'285'037 / 176'984
Trading optimization through photovoltaic system and battery	3'749'081 / 556'030	6'645'460 / 919'527	13'954'046 / 1'850'313
Trading optimization with different consumer profiles	3'160'898 / 99'966	5'474'870/ 136'767	11'285'623 / 229'924

Table 13: Received and accepted proposals for 30, 50 and 100 SSHAs

Scenario	Accepted proposals over a period of one year in % with # SSHAs					
	5	10	20	30	50	100
Trading	2.782	4.319	5.637	6.285	6.649	6.974
Trading optimization through photovoltaic system	42.113	46.506	48.199	48.865	49.090	49.190
Trading optimization through battery	7.795	4.321	2.417	1.737	1.433	1.441
Trading optimization through photovoltaic system and battery	21.718	18.273	16.013	14.831	13.836	13.260
Trading optimization with different consumer profiles	10.991	6.117	4.144	3.162	2.498	2.037

Table 14: Received and accepted proposals over a period in %

The figures show an interesting behavior regarding the accepted proposals in the different scenarios. In fact, the number of accepted proposals in the trading scenario is increased when the number of SSHAs is increased too. On the other hand, the same number decreases with the increase of SSHAs when each house has a battery. Moreover, the numbers of received and accepted proposals is immensely increased when the houses have a photovoltaic system because produced energy must be consumed at any price. Thereby, the deviation from the schedule increases because of this consumption but that leads to the fact that more offers can be accepted at the end to decrease the deviation again. This means that in a Smart Stability Network, the combination of batteries and photovoltaic systems have a major impact on the energy trading in terms of profit that can be made by the houses.

Scenario	Average profit of a house over a period of a year with # SSHAs in a monetary unit		
	5	10	20
Trading	-14'249.82	-3'275.55	195.91
Trading optimization through photovoltaic system	53'771.81	63'887.31	64'334.64
Trading optimization through battery	22'890.76	14'655.47	8'825.21
Trading optimization through photovoltaic system and battery	110'059.98	99'414.29	92'374.77
Trading optimization with different consumer profiles	38'782.48	21'756.38	17'983.02

Table 15: Average balance of a house over a period of a year for 5, 10 and 20 SSHAs (monetary unit)

Scenario	Average profit of a house over a period of a year with # SSHAs in a monetary unit		
	30	50	100
Trading	4'147.143	4'807.19	4'529.02
Trading optimization through photovoltaic system	65'929.19	69'462.45	69'293.77
Trading optimization through battery	6'164.04	5'051.29	4'847.21
Trading optimization through photovoltaic system and battery	89'837.25	88'499.47	88'044.77
Trading optimization with different consumer profiles	14'716.50	12'043.93	10'501.01

Table 16: Average profit of a house over a period of a year for 30, 50 and 100 SSHAs (monetary unit)

As mentioned before, the amount of batteries have a declining impact on the number of accepted proposals and therefore the same impact on the average balance of a house. But the use of photovoltaic system leads to an immense increase of the profit for a house over a period of a year. Nevertheless, these numbers are strongly depended on the prices and the priorities of the tradable goods in addition to the penalty fee as described in chapter 5.3.

7.2.3 Reference Scenarios

The reference scenarios provide the foundation to compare the results of the other scenarios. The results show that the deviation from the schedule is immensely increased with the number of SSHAs. Moreover, the use of photovoltaic systems increases the deviation even more in addition to the use of different consumer profiles.

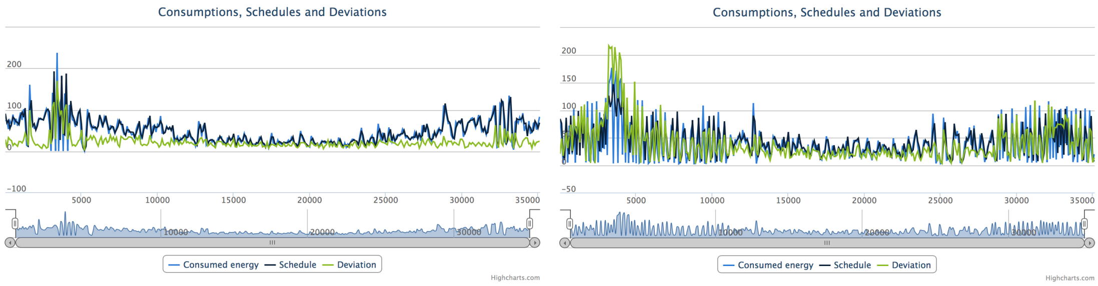

Figure 11: Reference scenario compared to reference scenario with different consumer profiles

This behavior for hundred SSHAs is shown in Figure 11 and can be explained with the additional fluctuations in the energy demand of the SSHAs because of the produced energy by the photovoltaic systems that must be consumed at any price.

7.2.4 Trading Scenarios

The results of the different trading scenarios show that the use of tradable goods has different impacts in a Smart Stability Network depending on the provided goods such as batteries and photovoltaic systems. While the use of batteries have an immense impact on improving the stability of the electrical grid, have the photovoltaic systems a positive effect on the profit of the houses.

7.2.4.1 Stability of the electrical grid

According to the results from Table 11, the average deviation from schedule is reduced through the use of tradable goods. Especially is to say, that the deviation can be significantly reduced even without having a photovoltaic system or an energy storage facility in place as shown in the figure below:

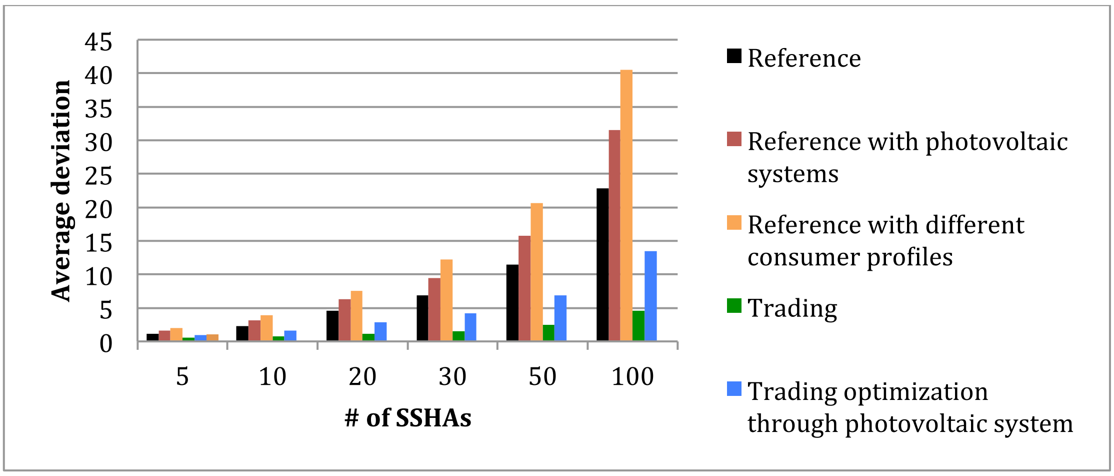

Figure 12: Average deviations from reference and trading scenarios

Figure 12 shows that the average deviation is especially reduced when the Smart Stability Network consists of more than 20 SSHAs. Thus, it can be assumed that a large numbers of SSHAs in a Smart Stability Network will have positive impact on the stability of the electrical grid and even with a reduced number of tradable goods.

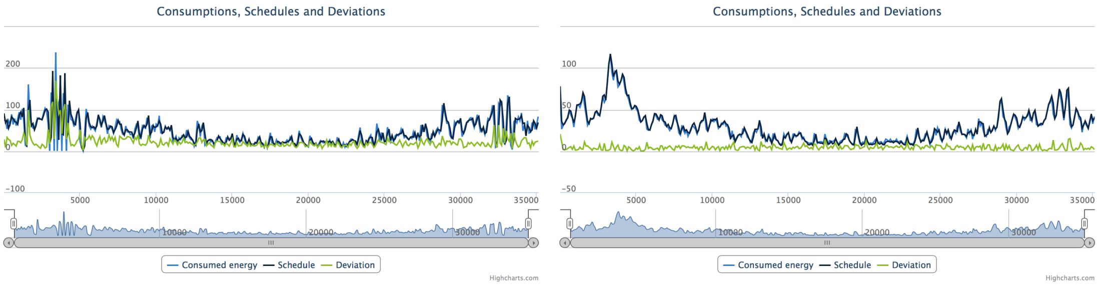

Figure 13: Reference scenario compared to trading scenario with 100 SSHAs

Nevertheless, in the scenarios where the houses have a battery, the deviation from the schedule is actually equal to zero. These results show that energy storage facilities have a positive impact on the stability of the electrical grid in a Smart Stability Network. The reason for this is the capacity of such a battery, which can either store or return a huge amount of energy. Furthermore, a battery can store or return just a specified amount of energy considering its capacity compared to the other tradable goods as described in chapter 5.2. Such a capability of a tradable good therefore allows the Smart Stability Network to reduce the deviation from the schedule even better.

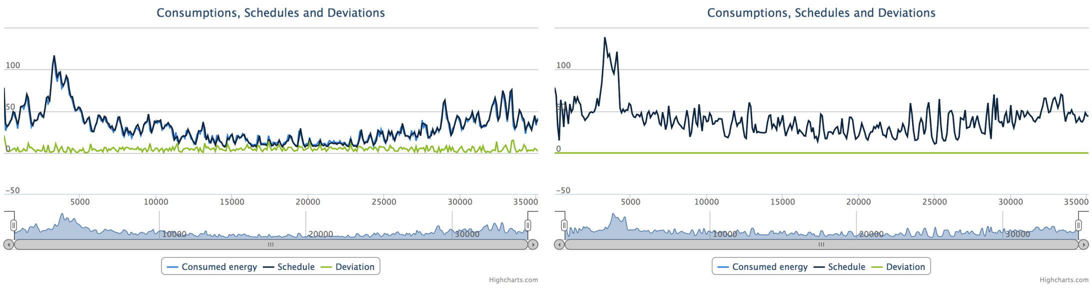

Figure 14: Trading scenario with 100 SSHAs compared to trading scenario optimized with photovoltaic systems and batteries.

On the other hand, the use of photovoltaic systems has a negative impact because it can increase the deviation from the schedule as shown in Figure 15.

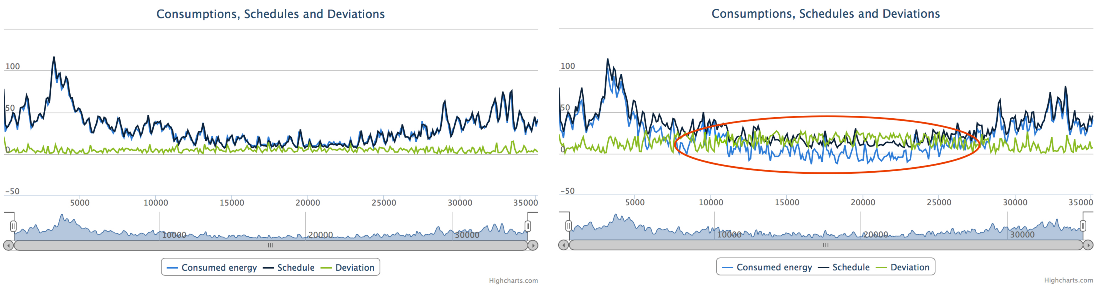

Figure 15: Trading scenario with 100 SSHAs compared to trading scenario optimized with photovoltaic systems

The reason for this behavior is that the produced energy from a photovoltaic system must be consumed and cannot be rejected. Thus, the energy demand for a cycle is critically decreased when the photovoltaic systems will produce a lot of energy. Such a situation can therefore have a negative impact on the deviation when the schedule foresees a high consumption for the Smart Stability Network.

7.2.4.2 Energy trading

The business impact or respectively the economic incentive is highly dependent on the following factors:

- Price formation of the tradable goods and the penalty fee
- Number of used photovoltaic systems
- Number of used energy storage facilities
- Number of SSHAs in a Smart Stability Network
- The different consumer types

These factors are critical for the success of the Smart Stability Network because those have a major impact on the earnings for a homeowner as can be derived from Table 15 and Table 16. While the batteries have a positive impact on reducing the deviation from the schedule, the uses of photovoltaic systems have a positive impact on the profit of the houses.

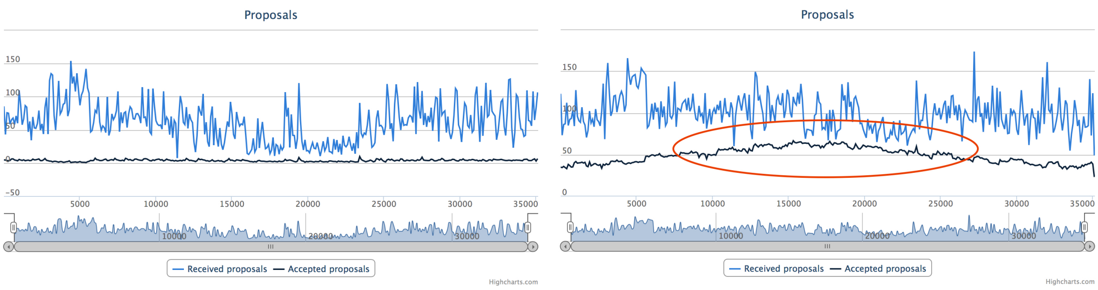

Figure 16: Number of received and accepted proposals in the scenarios: trading and trading optimization through photovoltaic system

The figure above is a comparison of the trading scenario and the trading optimization through photovoltaic system with 100 SSHAs. Due to the fact that the produced energy must be consumed in the Smart Stability Network at any price, the number of received and accepted proposals is dramatically increased. In other words, when more proposals are accepted the more homeowners get paid. This means for a homeowner that having a photovoltaic system is much more lucrative than having a battery as shown in the following figure:

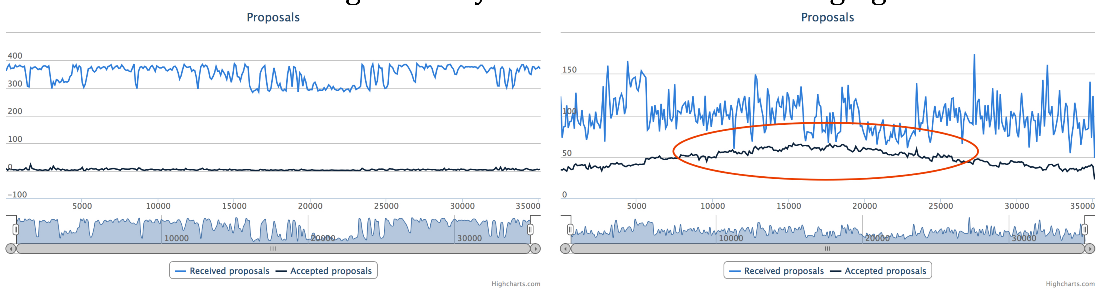

Figure 17: Number of received and accepted proposals in the scenarios: trading optimization through batteries and trading optimizations through photovoltaic systems.

Nevertheless, this disadvantage can be solved by a better price formation than the proposed in chapter 5.3. Moreover, the size of the participants in a Smart Stability Network influences the profit of the homeowners too. In the trading scenario for example, the average profit for a homeowner has the highest value when the Smart Stability Network consists of 50 SSHAs. This conclusion also applies for the trading scenario optimized through photovoltaic systems. In the other trading scenarios leads the size of 5 SSHAs to the most profit for the homeowners.

However, the different types of consumers have an impact on the stability of the electrical grid and the profit too. This means that a good consumption behavior of homeowners has a positive effect in terms of the stability of the electrical grid but a negative one on the profit if the there exist enough offers to decrease the deviation and vice versa. Thus, it can be said that the composition of a Smart Stability Network is critical to its success in terms of the stability of the electrical grid and the profit for homeowners.

7.3 Simulation environment

For the evaluation of the scenarios were two servers or rather instances from the Google Cloud Platform used and each instance had two CPU's and 13 GB memory (Google, 2015). The simulations of the different scenarios were performed in parallel on these instances, which took several hours as shown in the following figure:

Figure 18: CPU utilization in %

Although, the runtime to perform a simulation with a different number of agents for a scenario is sometimes pretty fast as can be seen in the example of the trading scenario optimized with batteries and photovoltaic systems:

# SSHAs	5	10	20	30	50	100
Runtime (min)	3	6	11	19	43	309

Figure 19: Runtime of the trading scenario optimized with batteries and photovoltaic systems

8 Conclusion

The designed mechanism to trade energy in the Smart Stability Network and the evaluation confirms the thesis statement:

"The use of distributed communication for trading energy between smart houses in a decentralized network can improve the stabilization of the electrical grid."

Hereby, the stability of the electrical grid can be achieved with different types of tradable goods such as switching on/off a boiler or a heat pump, use the energy of a photovoltaic system and store or receive energy from an energy storage facility. Nevertheless, not every tradable good has a positive effect on the stability of the electrical grid. While smart houses with a battery enable the Smart Stability Network to reduce the deviation from the schedule immensely, introduce smart houses with a photovoltaic system fluctuation and therefore increase the deviation. On the other side, smart houses with a photovoltaic system get more profit than houses with a battery because the produced energy of photovoltaic system has to be used at any price. However, the findings and results in this thesis show that the stability of the electrical grid can be improved and an economic incentive can be created for homeowners.

8.1 Requirements

Approach	Micro Grid	Distributed Communication	Decentralized Network	Trading Goods	Improve stabilization by trading energy
Smart Meter	-	-	-	-	-
Smart Grid	-	-	-	(✓)	-
Digital Grid	(✓)	-	✓	(✓)	-
NOBEL	-	-	(✓)	(✓)	(✓)
PowerMatcher	(✓)	-	✓	(✓)	(✓)
Smart Stability Network	✓	(✓)	(✓)	✓	✓

Table 17: Compare approaches with the Smart Stability Network

The Smart Stability Network is connected with the superior grid and has its own schedule. It consists of several smart houses that are connected with each other. The network itself **can operate even without a connection** to the superior grid for a certain time but an energy shortage can still occur depending on the available types of tradable goods. The smart houses, respectively the Smart Stability House Agents **elect an agent to become the Market Place Coordinator Agent**. This agent is responsible for the energy trading process. During the energy trading process **the SSHAs send their offers of their tradable goods** to the MPCA in each cycle whereby **the MPCA determines the best offer to decrease the deviation from the schedule and thus to improve**

the stability of the electrical grid. **Smart houses get paid for each accepted offer** according to on a general and specific price formation. These price formations take some risks into account, which can occur for a house by proposing an offer. In the case that **the Market Place Coordinator were disconnected from the network** or has any other issue, **another Smart Stability House Agent will become the Market Place Coordinator Agent** so that Smart Stability Network stays operational. Thanks to this approach, **no central control unit is required** to handle the energy trading process.

8.2 Further research

Despite the positive results in the evaluation of the energy trading in the Smart Stability Network, further research should be considered in the following topics:

- Energy demand forecast for the next cycle
- Concrete business model
- Leader election
- Information exchange

As described in this thesis, the forecast function for the energy demand of the next cycle is not accurate as it should be because the energy demands of the previous cycle are used. Therefore, further research to improve the used forecast function would lead to a more accurate result.

Although, this thesis shows that energy trading can improve the stability of the electrical grid and create an economic incentive for homeowners at the same time. A concrete business model is missing, which describes how such a Smart Stability Network can be introduced and sold to homeowners. Furthermore, it would be interesting too see what could be the best combination of tradable goods according to the size of participants in a Smart Stability Network.

As mentioned several times, the election of the Market Place Coordinator is still an issue. Although there exist a lot of research in this field, further research is required to choose or create and implement a solution for the Smart Stability Network. In addition, the performance, stability, reliability and scalability of the information exchange between the agents is not covered in this thesis. But these topics are important for a real implementation and could have a critical impact on the energy trading.

9 References

Abe, R., Taoka, H., Member, S., & Mcquilkin, D. (2011). Digital Grid : Communicative Electrical Grids of the Future, *2*(2), 399–410.

ACT, V. (2008). Challenge AND Opportunity: Charting A New Energy Future. *Citeseer*. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:CHALLENGE+AND+OPPORTUNITY:+CHARTING+A+NEW+ENERGY+FUTURE#0

Bundesamt für Energie BFE. (2012). Bundesrat bestimmt erstes Massnahmenpaket für die Energiestrategie 2050. Retrieved from http://www.bfe.admin.ch/energie/00588/00589/00644/index.html?lang=de&msg-id=44187

Caire, G. (2003). JADE Tutorial: JADE programming for Beginners. *Documentación de JADE*, (June), 1–23.

Chen, S., Shroff, N., & Sinha, P. (2013). Energy trading in the smart grid: From end-user's perspective. *Signals, Systems and Computers, …*, 327–331. doi:10.1109/ACSSC.2013.6810288

Cockburn, A., & Highsmith, J. (2001). Agile software development: The people factor. *Computer*, *34*(11), 131–133.

Communication, L. S. (2010). *the SMART GRID*. *Communication* (Vol. 99, p. 48). doi:10.1016/B978-1-59749-570-7.00011-X

Digital Grid Consortium. (2014a). Digital Power Trading. Retrieved from http://www.digitalgrid.org/en/about-digital-grid/benefits/48-digital-power-trading

Digital Grid Consortium. (2014b). Features of the Digital Grid. Retrieved from http://www.digitalgrid.org/en/about-digital-grid/technology

Digital Grid Consortium. (2014c). Problems with the Grid. Retrieved from http://www.digitalgrid.org/en/about-digital-grid/problems-with-the-grid

Dutchguilder. (2007). Iterative development illustration. Retrieved from http://commons.wikimedia.org/wiki/File:Development-iterative.gif#mediaviewer/File:Development-iterative.gif

Fairley, P. (2004). The unruly power grid. *Spectrum, IEEE*, (August). Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1318179

Fowler, M., & Highsmith, J. (2001). The agile manifesto. *Software Development*, *9*(August), 28–35. doi:10.1177/004057368303900411

Google. (2015). Google Cloud Compute Engine. Retrieved January 29, 2015, from https://cloud.google.com/compute/

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design Science in Information Systems Research. *MIS Quarterly*, *28*(1), 75–105. doi:10.2307/25148625

Highsmith, J., & Cockburn, A. (2001). Agile software development: the business of innovation. *Computer*, *34*(9). doi:10.1109/2.947100

Hinkelmann, K., & Kempthorne, O. (2007). *Design and Analysis of Experiments, Second Edition*. Hoboken, NJ, USA: John Wiley & Sons, Inc. doi:10.1002/9780470191750

Ilic, D., & Silva, P. Da. (2012). An energy market for trading electricity in smart grid neighbourhoods. *… (DEST), 2012 6th …*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6227918

JCC. (2013). *The Digital Grid*. Retrieved from https://www.youtube.com/watch?v=ArAib5qWU_o

Kok, J., Scheepers, M., & Kamphuis, I. (2010). Intelligence in electricity networks for embedding renewables and distributed generation. *Intelligent Infrastructures*. Retrieved from http://link.springer.com/chapter/10.1007/978-90-481-3598-1_8

Krosnick, J. A. (1999). Survey research. *Annual Review of Psychology*, *50*, 537–567. doi:10.1146/annurev.psych.50.1.537

Lammel, B. (2014). Dokumentation Haussimulation.

Lann, G. Le. (1977). Distributed Systems - Towards a Formal Approach. *IFIP Congress*. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Distributed+Systems+-+Towards+a+Formal+Approach#0

Marqués, A., & Serrano, M. (2011). NOBEL–a neighborhood oriented brokerage electricity and monitoring system. *… -Efficient Computing and …*, *2020*, 1–10. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-19322-4_20

Netherlands Organisation for Applied Scientific Research. (2014). The current situation in electrical networks. Retrieved from http://www.powermatcher.net/in-a-nutshell/current-situation/

Next Kraftwerke. (2014). Dispatch & Redispatch. Retrieved from https://www.next-kraftwerke.de/wissen/strommarkt/dispatch-redispatch

NOBEL. (2011). An innovative energy brokerage system.

Presse- und Informationsamt der Bundesregierung. (2014). Bundesregierung beschließt Ausstieg aus der Kernkraft bis 2022. Retrieved from http://www.bundesregierung.de/Content/DE/StatischeSeiten/Breg/Energiekonzept/05-kernenergie.html

Rahimi, F., & Ipakchi, A. (2010). Demand response as a market resource under the smart grid paradigm. *Smart Grid, IEEE Transactions on*, *1*(1), 82–88. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5454394

Swissgrid. (2014). Grid Stability. Retrieved from http://www.swissgrid.ch/swissgrid/en/home/reliability/grid_stability.html

Tabuchi, H. (2011). Japan Premier Wants Shift Away From Nuclear Power. Retrieved from Japan Premier Wants Shift Away From Nuclear Power

Teams, D. (2004). Rational Unified Process Best Practices for Software. *Development*, 1–21. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Rational+Unified+Process+Best+Practices+for+Software#4

U.S. Department of Energy. (2010). *the SMART GRID*. *Communication* (Vol. 99, p. 48). doi:10.1016/B978-1-59749-570-7.00011-X

Vijayapriya, T. (2011). Smart Grid: An Overview. *Smart Grid and Renewable Energy*. doi:10.4236/sgre.2011.24035

Villiger, A. (2014). *Applying self-organising algorithms in smart grids to achieve more autonomy in power supply on a micro level*. University of Applied Sciences of Northwestern Switzerland.

Yin, R. K. (2009). *Case Study Research: Design and Methods*. *Essential guide to qualitative methods in organizational research* (Vol. 5, p. 219). doi:10.1097/FCH.0b013e31822dda9e

Zheng, J., Gao, D. W., & Lin, L. (2013). Smart meters in smart grid: An overview. In *IEEE Green Technologies Conference* (pp. 57–64).

10 List of figures, tables and equations

10.1 List of figures

10.2 List of tables

10.3 List of equations