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Abstract English

Nowadays the power supply is a key issue in our society. A power supply system on the one hand determines the energy supply and on the other hand distribute the previously recovered energy over power lines to all consumers. A major problem with these processes is the loss and steadily increasing demand for energy. It would therefore be an urgent need, in addition to conventional sources, to use renewable energy sources. This technology division includes wind turbines, solar farms or an intelligent energy storage. In the future, our energy network will consist of a central supplier and a number of small additional reference sources to enable a more efficient handling of the produced energy.

To this day, many researches have been successfully implemented in this area. In addition, recommendations for dealing with renewable energy and the development of a smart grid system have been described. The smart grid technology can not be implemented within a short time, since the newly established technological and economic challenges must first be overcome. Central research questions that are often studied, deal with the microgrids, the integration of an intelligent demand management system or the communication between producer and consumer.

This thesis uses the mathematical concepts of game theory. Game theory is a very useful tool to analyze the rational actions of participants in the smart grid area. In general, this work is divided in a theoretical part and a simulation. The theoretical section deals with an introduction of Game Theory. The basic concepts of non-cooperative and cooperative games are explained in detail. Afterwards, an introduction to the concept of smart grids is given. This chapter also tries to underline the technological and economic advantages to a conventional grid system. The conclusion of the theoretical part is a summary of current research papers

that combine game theory with smart grids.

For a successful simulation, a separate game theory simulator was created. The main objective of the modeling and simulation process was the combination of game theory concepts in the field of smart grids and the energy markets. Therefore, a fictive numerical model was defined, which was then executed and analyzed. The model dealt with interactions between rational thinking actors on a separate local energy market and a government.

Abstract Deutsch

Heutzutage ist die Stromversorgung ein zentrales Thema in unserer Gesellschaft. Ein Stromversorgungsnetz hat einerseits die zentrale Aufgabe Energie bereitzustellen und andererseits die vorher gewonnene Energie über Spannungsleitungen an alle Konsumenten zu verteilen. Ein großes Problem bei diesen Prozessen ist der Verlust und ein stetig steigender Bedarf an Energie. Es wäre daher dringend notwendig, zusätzlich zu den herkömmlichen Bezugsquellen, erneuerbare Energiequellen zu verwenden. In diese Technologiesparte zählen Windräder, Solarfarmen oder auch intelligente Energiespeicher. In Zukunft soll unser Energienetzwerk aus einem zentralen Versorger und einer Vielzahl kleiner zusätzlicher Bezugsquellen bestehen, die ein effizienteres Umgehen mit der erzeugten Energie ermöglichen sollen.

Bis zum heutigen Tag wurden in diesem Bereich schon viele Forschungen erfolgreich realisiert. Zusätzlich dazu wurden Empfehlungen für den Umgang mit erneuerbarer Energie sowie dem Aufbau eines Smart Grid System beschrieben. Die Smart Grid Technologie kann natürlich nicht innerhalb einer kurzen Zeit realisiert werden, da die neu entstandenen technologischen und ökonomischen Herausforderungen erst bewältigt werden müssen. Zentralen Forschungsfragen, die oft untersucht werden, betreffen in diesem Bereich unter anderem die Entstehung von Mirco Grids, das Betreiben von Auktionen, die Integration eines intelligenten Nachfragemanagements oder die Kommunikation zwischen Produzent und Konsument. Um all diese Herausforderungen analysieren zu können, bedarf es eines fundamentalen Werkzeuges um aussagekräftige Behauptungen treffen zu können. Diese Masterarbeit verwendet dazu die mathematischen Konzepte der Spieltheorie. Spieltheorie ist ein ausgesprochen brauchbares Werkzeug um die zentralen Forschungsfragen im Smart Grid Bereich zu analysieren. Generell ist diese Arbeit in einen theoretischen Teil und in eine Simulation gegliedert. Der theoretische Part beschäftigt sich zu Beginn mit Spieltheorie. Dabei werden die Grundkonzepte

von nicht kooperativen und kooperativen Spielen genauer erläutert. Danach folgt eine Einleitung in die Thematik von Smart Grids, wo die technologischen sowie ökonomischen Vor- und Nachteile gegenüber einem herkömmlichen Versorgungssystem dargestellt werden. Den Abschluss des theoretischen Teils stellt eine Aufarbeitung von aktuell getätigten Forschungen dar, die spieltheoretische Konzepte mit Smart Grids kombinieren. Für eine erfolgreiche Simulation wurde ein eigener Spieltheorie - Simulator erstellt, mit dem ein numerisches Modell definiert und anschließend simuliert wurde. Das Hauptziel des Modellierungs- und Simulationsprozesses war die Kombination von spieltheoretischen Ansätzen im Bereich von Smart Grids und Energiemärkten, welche die Interaktionen zwischen rational denkenden Akteuren und einer Regierung oder einem Staat abbilden. Am Schluss der Arbeit werden dann alle Ergebnisse erläutert.

Statutory declaration

Ich erkläre hiermit an Eides Statt, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe.

Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht.

Die Arbeit wurde bisher in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

Wien, 22.01.2017

Benjamin Anderl

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Chapter 1

Introduction

1.1 Motivation & Problem

The traditional energy grid that is used by the consumer over the last decades will be now step by step replaced by a more intelligent system which integrates renewable energy sources. The awareness of global warming and its connections to CO₂ emissions has led to a change of thinking in the political sector. The current grids as well as the way of energy distribution and transmission will not be adequate for a stable and efficient future. [12,33]

Based on the awareness of increasing greenhouse gas emissions, researchers experiment with renewable energy sources like photovoltaic (PV) cells, solar cells (heating), geothermal units, wind turbines, etc. A smart grid can be a main driver to “[...] reduce greenhouse gas emissions by up to 211 million metric tons [...]”. [33] By the reason that global investors forces to put money in the development of intelligent grids, the global energy market is calculated to get a valuation of \$400 billion in 2020. [33]

The European electricity consumption is calculated to increase by a yearly rate of 1.4% in the next 20 years. Also, the share of renewable energy sources increases from 13% now to 26% in 2030. [12] The demand side (consumer) have set their

focus on a more efficient usage of electricity to achieve and support the concept of smarter homes. Therefore, consumer try to reduce the consumption of commodities or prefer cleaner means of transportation. Consequently, that the energy market will become more liberalized and dynamic, all stakeholders, from private consumer to electricity network companies, that are involved in a smart grid system have different needs and responsibilities. [12]

Nowadays, the most important needs for a private user are the quality and the value for money. In the future, the focus can expand to in-house generation and surplus sell back to a grid. To be able to cover all needs of the involved stakeholders, a smart grid make use of a user centric approach. [12]

The main driven factors that lead to a smart grid is the knowledge about climatic change as well as the current infrastructure and distribution of electricity. It is known that fossil fuels will have some limitations in the future or in the worst case will run out completely. Therefore, the EU set requirements that needs to be fulfilled to achieve a smarter and more intelligent energy distribution. [12]

1. The European internal market: More competition on the market will lead to an increasing efficiency as well as more innovative products and technologies. [12]
2. Security and quality of supply: The current infrastructure is confronted with increasing security and reliability issues as well as with the quality of supply. [12]
3. The environment: The major disadvantage of fossil fuels is the emissions of CO₂, SO₂, NO_x etc. The greenhouse gases, as mentioned before, is one of the biggest environmental and economic challenges for the humanity. [12]

Another important future technology improvement is the coupling of smart grids with smart metering systems. Consumers get the possibility to retrieve real time data about their energy consumption at any time. They are then able to adapt their demand by comparing the different energy prices throughout the day. This

freedom of consumption lead to lower costs and a more efficient energy usage. [11] The EU plans to replace 80% of electricity meters with smart meters until 2020. This will also have a huge impact in the annual household energy consumption, which is planned to be reduced at least by 9%. A report of the EU commission showed that “on average, smart meters provide savings of 160€ for gas and 309€ for electricity per metering point (distributed amongst consumers, suppliers, distribution system operators, etc.) as well as an average energy saving of 3%.” [11] A further financial motivation for consumer is the production and sell possibility of own produced energy. If the inhabitants generate their own energy for example through photovoltaic cells, solar cells or wind turbines, they can sell their surplus to the grid and find another income stream. [11]

As it can be seen above, the development of a smart grid is a key element for a stable future environment. At this stage a lot of researches were made to combine advanced economic and technological instruments with smart grids. The main topics in this area concern auction-based pricing, demand side management, communication technologies and the integration of information technologies.

1.2 Contribution

The main goal of this master thesis was the investigation of the possibilities of game theoretic methods in the area of smart grids. In these days, smart grid related topics are more important than before. Actual trends like auction-based systems have great impact of the exploration of the commercial benefits of a smart grid. Game theoretic methods in the area of smart grids implicate a lot of complex topics which need to be handled within the research. By supporting the usage of renewable energy sources through smart grids, private consumers get a motivation to be an important part in the whole process. Thus, it is from interest to investigate the concept of a competitive local energy market with multiple players in the role as seller or buyer. For a clear and understandable overview of game theoretic methods in the context of smart grids, a detailed analysis of existing tools and research work in both topics was needed.

With the knowledge gained in this thesis, a detailed research work of game theoretic methods in smart grid has been investigated. In addition, a non-cooperative game was formulated, which covers the idea of different players competing on a local energy market and selling their own generated energy to other game participants. For solving the game, a java based simulator has been implemented, which tried to reach a Nash equilibrium point between the locals.

1.3 Structure

The thesis is divided into four main chapters. After the introduction, the second chapter deals with the concept of non-cooperative and cooperative game theory. It starts with a short history summery of game theory and explains then the basic concepts of strategies, players and different equilibrium methods. All of this models are described with an explanatory example.

The third chapter can be seen as theoretic research of smart grids. Primarily the idea and the function of a grid system are analyzed. Furthermore the differences between traditional power system and smart grids are discussed.

The fourth chapter provides an overview of the existing researches in the application of game theory in combination with smart grids. The published research work helps to understand different concepts of game theory in the context of renewable energy systems and grid technologies.

In the next chapter, the simulation part of the thesis is described. Therefore a non cooperative game in a local energy market with three different scenarios is formulated. After the game definition process, a java based simulator was implemented to find a Nash equilibrium point between the players.

The sixth chapter shows the results of the simulation process. All simulation rounds are analyzed and described with graphics and result tables.

The last chapter deals with the conclusion of the thesis. Here, a short summary of the design, the implementation and simulation process is given.

Chapter 2

Game Theory

In this chapter the basic rules, strategies and game types of game theory are introduced.

2.1 History of Game Theory

The beginning of game theory was in the early 20th century, as some mathematicians began to analyse different games. First, they studied simple games to become familiar with the analysis. Later on, they were able to understand much more complex games, like Chess or Nim. [21] In the history of game theory there is one well known scientist, John von Neumann. He was the first mathematician who extended the previous work to the game of poker. Poker differs from other games like Chess and Nim as the players do not know anything about the next moves from their opponents. An important element of poker is "bluffing". You do not really know, if your opponent's bet or raise is made with a strong or a weak hand. In comparison to Poker, Chess and Nim give you perfect information about the players next move. This was the first big step in the history of game theory when Neumann introduced the difference between imperfect and perfect information games. [21] A few years later he decided to work with Oskar Morgenstern, a german mathematical economist who was well known for his economic know how in

national defense and space travel issues. In the 1940s, they published a book with the title "*The Theory of Games and Economic Behavior*". In this book they tried to analyse games which are subjects of the daily life, for example military conflicts or economic competition. [21] The games described are all one-shot games. That means that players will play this game only once. [15] In the 1950s John Nash developed and introduced a new concept, which is called Nash Equilibrium.

Today, game theorists specialise more in classical theory questions rather than the practical application of game theory. Nevertheless, it has a wide spectrum of application. Fields like psychology, biology, genetics, politics or scholars use game theory and their concepts to solve problems in their own domain. [15]

2.2 Foundations of Game Theory

The fundamental elements of game theory concern the strategies and tactics of the different players. Most of the games lead to a winner and a loser. [15] How is game theory actually defined? Roger A. McCain defined game theory as a : "*study of the choice of strategies by interacting rational agents[...]*" [21]. A key element in game theory is to find the best strategy for oneself as response for the strategy of the opponent player. [21].

According to McCain:[...] *we define the best response for a player as the strategy that gives that player the maximum payoff, given the strategy the other player(s) has chosen or can be expected to choose.*" [21] This concept is a good example for the rationality in game theory. As it was described before, a game consists of the following elements:

1. Players

If someone describes players in games of game theory, he speaks from rational economic agents. [15] Their job is to find an individual decision from a precisely defined set of strategies. Their unique goal is to choose a strategy which will lead to the best available benefit. [15]

2. Strategies

According to [15] a strategy is "*an order of moves determined in advance of some event by an individual player*". In a game a player can choose out of a predefined set. The players will pick a specific strategy depending on the availability of different informations. [15]

3. Information

Another key element of game theory is information. Without information a player can not choose the best strategy. The information set contains the number of participants, the set of strategies and actions as well as informations about the moving sequence. Game theory includes games with different types of information [15]:

(a) Perfect or imperfect information

McCain defines a game of perfect information as a game where a player makes his own strategy decision based on the knowledge of all previous moves and other influences of his opponents. [21]

A game with imperfect information is defined as a game where sometimes player do not know anything about the chosen strategies. Either both players choose their strategy simultaneously or the strategies are concealed. [21]

(b) Complete or incomplete information

A game with incomplete information is very similar to a game with imperfect information. A good example is when a user choose his strategies randomly or when probabilities are included in some parts of a game. [15]

(c) Symmetric or asymmetric information

In a symmetric information game, both players have the same information about the sequence of a game or the details of the payoffs. Logically, a game with asymmetric information is defined as game where

both players don't have the same information about the sequence of moves or payoffs. [15]

4. Payoffs

The payoff is the value or benefit what a player receives at the end of the game. Usually the payoff depends on the chosen strategy. [15] For example imagine the following payoff matrix for player A [15]:

$$\begin{array}{cc} & \begin{array}{cc} B1 & B2 \end{array} \\ \begin{array}{c} A1 \\ A2 \end{array} & \left(\begin{array}{cc} 5 & 10 \\ 2 & 1 \end{array} \right) \end{array}$$

Table 2.1: Payoff matrix for Player A [15]

Player A can choose between two different strategies A1 or A2, based on the decision of B. For example if Player B chooses strategy B1, A can decide either to get a payoff of 5 with strategy A1 or a payoff of 2 with strategy A2. Because of his rational behaviour he will decide to play strategy A1. [15]

5. Normal form vs. extensive form

To be able to handle and interpret the process of sequential and simultaneous games, there are two forms for the graphical representation. [15] First, we can use the extensive form. According to McCain: "*A game is represented in extensive form when it is shown as a tree diagram in which each strategic decision is shown as branch point.*" [21] If a decision node has more than one following branch, it is defined as an information set. [21]

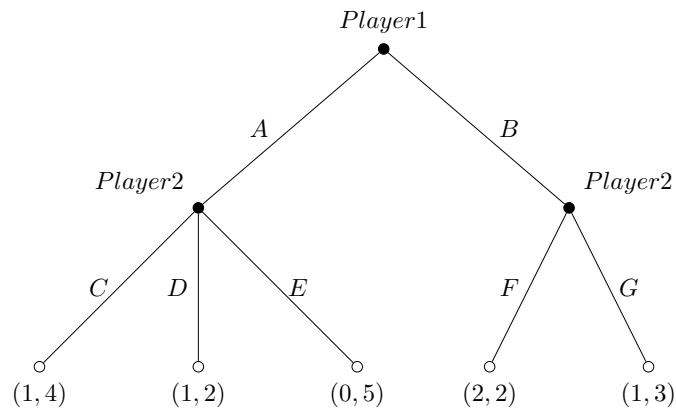


Figure 2.1: Tree diagram - Extensive form [21]

Furthermore, the payoffs and strategies of the players can be shown in table form. The table is separated in rows and columns. [21] In a 2-person game the rows represent the strategies of Player A and thus the columns the strategies of Player B. In addition, the values in the cells show the payoffs of both. [21] For example imagine this table:

		Player B	
		A	B
Player A	A	(3, 5)	(7, 1)
	B	(5, 6)	(2, 2)

Table 2.2: Table form - Normal form [21]

If table 2.2 is analysed, it can be seen that *Player A* can get a profit of 3 or 7 if he chooses strategy A. Logically the same application rules apply for the profits of *Player B* and for the strategy B of *Player A*.

2.3 Strategies and Nash Equilibrium

In the previous section a strategy was defined as an order of moves, which depends on the actions made by the opponent player. [15] We know now that in a game a player always tries to maximize his profit by choosing the best strategy. If a player, no matter what his opponent choose, at all times takes the same strategy, he has a dominant strategy. [21]

2.3.1 Dominant Strategy

- Dominant strategy:

A dominant strategy is characterized as a strategy that is preferred in each situation, because it allows the player to get the best profit in each situation. [21]

- Dominated strategy:

A *Strategy A* dominates another *Strategy B*, if it offers a better payoff than the other strategy, equal what the opponent player chooses. [21]

- Dominant strategy equilibrium:

In a game where all players develop a dominant strategy, the combination of these strategies and their associated payoffs, form the dominant strategy equilibrium. [21]

To get a better understanding of these definitions an example is given.

2.3.2 The Dumping Game - Dominant Strategy example

		Mr.Smith	
		<i>Dump</i>	<i>HireTruck</i>
Mr.Jones	<i>Dump</i>	(4000, 4000)	(5000, 3500)
	<i>HireTruck</i>	(3500, 5000)	(4500, 4500)

Table 2.3: The Dumping Game [21]

Table 2.3 demonstrates that both *Mr.Jones* and *Mr.Smith* can choose two strategies, *Dump* or *Hire Truck*. From the perspective of Mr Jones, his best answer, if *Mr.Smith* plays *Dump*, is also *Dump*. Furthermore, the payoff matrix shows that *Mr.Jones* will again choose *Dump*, if Mr.Smith decides to play *Hire Truck*. Because of the reason that *Mr.Smith* has the same payoff values like *Mr.Jones*, his dominant strategy is also *Dump*. [21] This simple example is a perfect illustration of the definition of dominant strategies.

Strategy of Mr. Jones	Best Response of Mr.Smith
Dump	Dump
Hire Truck	Dump

Table 2.4: Best Response Mr.Smith [21]

Strategy of Mr. Smith	Best Response of Mr. Jones
Dump	Dump
Hire Truck	Dump

Table 2.5: Best Response Mr. Jones [21]

2.3.3 Nash Equilibrium

In the last subsection the concept of a dominant strategy equilibrium was introduced. But in some games there are sometimes situations where no dominant strategy is reachable. Therefore, another powerful instrument is needed, the concept of *Nash*. [21]

The concept is named after a famous mathematician, called John Nash. It is said that no other of all the famous game theorists had such an impact on game theory than John Nash. [21] In comparison to the dominant strategy equilibrium, a *Nash equilibrium* is more general. In general, a *Nash equilibrium* is defined in the following way: *"For any game in normal form: if there is a list of strategies, with one strategy per player, such that each strategy on the list is the best response to the other strategies on the list, that list of strategies is a Nash equilibrium."* [21]

If a game has a dominant strategy equilibrium, it indicates at the same time a Nash equilibrium. If it is said that every dominant strategy equilibrium is a Nash equilibrium, it is the same as it would be stated that every cocker spaniel is a dog. Now the question is, if it is also true to say that every Nash equilibrium is a dominant strategy equilibrium. [21]

This conclusion is generally known as false. In general, a dominant strategy equilibrium is always a Nash equilibrium but not every Nash equilibrium is a dominant strategy equilibrium. [21]

A Nash equilibrium has one further important property. It is said that every Nash equilibrium strategy is rationalizable. A strategy is a rationalizable strategy if

: "[...] a strategy can be rationalized as a best response to a strategy that the other player rationally might play[...]" [21]

In summary, if a game has a Nash equilibrium no player has an incentive to leave this stable equilibrium. [15]

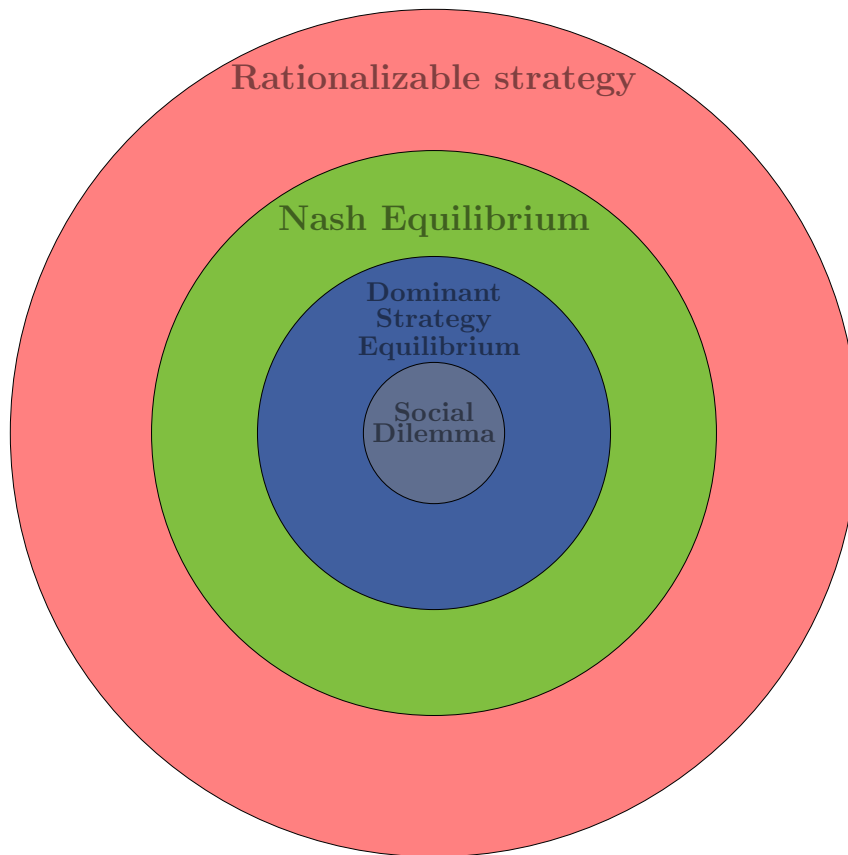


Figure 2.2: Non-cooperative Solution Diagramm [21]

2.3.4 Multiple Nash Equilibrium's

Sometimes games tend to have more than one Nash Equilibrium. Then two types of games with multiple Nash Equilibrium's can exist: [21]

- Coordination Game:

This game happens if two or more Nash equilibrium's are available and both players choose the same strategy. [21]

- Anticoordination Game:

An anticoordination game is defined as a game where two or more Nash equilibrium's exists but both players choose different strategies. [21]

2.3.5 Textbook Game - Nash Equilibrium example

		Prof.Heffalump		
		400p.	600p.	800p.
Dr.Boingboing	400p.	(45, 45)	(15, 50)	(10, 40)
	600p.	(50, 15)	(40, 40)	(15, 45)
	800p.	(40, 10)	(45, 15)	(35, 35)

Table 2.6: Textbook Game 1 [21]

		Prof.Heffalump		
		400p.	600p.	800p.
Dr.Boingboing	400p.	(45, 45)	(15, <u>50</u>)	(10, 40)
	600p.	(<u>50</u> , 15)	(40, 40)	(15, <u>45</u>)
	800p.	(40, 10)	(45, 15)	(<u>35</u> , <u>35</u>)

Table 2.7: Textbook Game 2 [21]

After analyzing this game, one Nash equilibrium at $(35/35)$ was found. This is for both players a state, where no one has the intention to leave. [21]

2.3.6 Mixed Strategy Nash Equilibrium

In game theory there are situations where the instrument of probability is very useful to get a better reward. Probability is defined as the measurement of the likelihood that an uncertain event will take place. A probability of 1 means that an event will certainly occur, whereas a probability of 0 illustrates that a statement is certainly false. In case of game theory, the concept of expected values and probabilities is used to deal with uncertainty from the player or nature. [21]

Uncertainty is a situation that can result either from the players themselves or from the nature. At the beginning of a game a player has a list of pure strategies where he can choose from. But there are moments where it is not useful to play a specific pure strategy, because it can make a player vulnerable to exploitation by the other player. Therefore a rational player will try to make himself unpredictable by choosing his pure strategies in combination with probabilities. The goal of using strategies with probabilities, or better known as mixed strategies, is to reduce the chances of exploitation by its opponent. [21]

Roger McCain defines a game with mixed strategies as a game where "[...] a player chooses among the list of normal form pure strategies according to given probabilities [...]". [21] Thus it is clear that an equilibrium of mixed strategies can be reached, where at least one player chooses a mixed strategy. In the early years John Nash defined the theory that each two person game has an equilibrium in mixed strategies, even though there is no equilibrium in pure strategies. [21] To illustrate a mixed strategy Nash equilibrium, the game *Battle of Sexes* is a good example. [31]

		Player <i>B</i>	
		<i>A</i>	<i>B</i>
Player <i>A</i>	<i>A</i>	(2, 1)	(0, 0)
	<i>B</i>	(0, 0)	(1, 2)

Table 2.8: Battle of Sexes [31]

The analysis of the game shows two Nash equilibrium's in pure strategies, (A,A), (B,B). This result demonstrates that A as well as B must be the best response for both players no matter what the opponents strategy is. In a next step it is interesting to check the construction of a mixed Nash equilibrium. [31]

Therefore it is necessary to differ between the column's expected payoff and the row's expected payoff.

Row Calculation:

Player A Strategy A: $(2 \cdot p) + (0 \cdot (1-p))$

Player A Strategy B: $(0 \cdot p) + (1 \cdot (1-p))$

Column Calculation:

Player B Strategy A: $(1 \cdot p) + (0 \cdot (1-p))$

Player B Strategy B: $(0 \cdot p) + (2 \cdot (1-p))$

As a result for strategy A, Player 1 chooses this strategy with $p = 2/3$ and Player B chooses strategy A with $p = 1/3$. After the calculation of the probabilities, there is a mixed strategy equilibrium at: $[(2/3), (1/3); (1/3), (2/3)]$ [31]

In summary, mixed strategies give the players new chances to be unpredictable in his strategy choice. Simultaneously, it should also help to neutralize the player's possibilities of vulnerability. [21]

2.3.7 Correlated Equilibrium

As it was discussed before, players can use a coin flip to decide which strategy they will choose. [2] In general this assumption automatically leads to some problems. The concept that a person with serious attitude would choose a certain strategy for an important decision, because of a flip coin, is not easy to accept. In 1974 Robert Aumann introduced the concept of a correlated equilibrium. [1, 2] It is defined as *"[...] an arrangement that assigns probabilities to the joint strategies in a game with two or more Nash equilibriums in pure strategies. [...]"* [21] An arrangement can be achieved if the players both use the information from the outside to choose a specific strategy. [2] For a more demonstrative definition of this concept a practical example is given. [21]

		Player B	
		A	B
Player A	A	(2, 2)	(<u>12</u> , <u>7</u>)
	B	(<u>7</u> , <u>12</u>)	(10, 10)

Table 2.9: A Mall Location Game [21]

In this game, there are two retailers who are looking for new possibilities to open a store. One strategy is to choose a mall, otherwise they can open a shop in the Route 40 commercial corridor. [21] This game shows two pure Nash equilibriums $([2, 7], [7, 2])$. The question which now arises is, if both players can get a better reward if they correlate their strategies. This game makes the assumption that a third party, the mall, tries to get both retailers. This could be possible if the mall gives them some additional information, so that both can rethink their decision. [21] As Robert Aumann states, this special information can be seen as a signal from the outside. It should help to improve the outcome of both players. This game supposes that both players together get the information with a probability of 0.5. With a probability of 0.25 only a single player will receive a special

information. The case of no information is send to both players has a probability of 0. If a player gets a specific information he will choose the strategy "mall", otherwise he will go with the strategy "stand alone location". Now there are multiple possible scenarios which need to be analyzed. [21]

1. Player A does not get a specific information. Now he knows that Player B has the specific extra information and therefore he must choose the strategy "stand alone location" [21]
2. Player A gets an extra information from the mall. $P = 1/3$ if only Player A got this information. Whereas p changes to $2/3$ if both got the information. [21]
3. If now both players follow the predefined rule they can get a payoff of $(1/3)*7 + (2/3)*10 = 9$. If both players deviate from this rule they can only achieve a payoff of 8. [21]

By providing information to both players, the mall gives a new opportunity of an equilibrium. This example is important for understanding the concept of correlated strategy equilibrium. Because of a third party it is in some cases possible to achieve better payoffs as any pure Nash equilibrium's. [21]

The aim of this subsection was to show that coalitions can also happen in non-cooperative games but only under the condition that all player choose their best possible response. [21]

2.4 N-Person Games

A one person game has the characteristic of a standard decision problem, where the uncertainty arises from the nature. Games with two or more players are quite

different to a one person game. By the reason of the free choice of the agents another form of indetermination occurs. If three or more players interact in a game, coalition forming is a new important characteristic of n-person games. [30] N-person games show the fact that each of them has to deal with the following issues: [30]

- Coalition
- Organizational structure
- Commitment
- Trust
- Compromise
- Threat
- Social and cultural environment

Nevertheless, games, for example with 10 players, can get very complicated because of the reason that there are 3.628.800 relationships between these 10 participants. Therefore in N-Person theory some helpful assumptions are made. [21]

The first simplification is called Representative Agent. The idea of the representative agent scenario is to assign each player the same list of strategies and accordingly the same payoffs. The main point of this idea is that although the players can choose from the same strategies and earn the same profit, they will differ in their actions in an equilibrium. Another powerful tool is the state variable. The state variable can help a player provide all the informations he needs to choose his best response strategy. Roger A McCain defines a state variable as a *"[...] single number or one of a small list of numbers, that together express the "state" of the game [...]"* [21] A good example for this method is a pursuit game, where one player will catch the other play through the shortest possible way. The

best response for the pursuer is a strategy which makes the distance as small as possible. On the other side, the best response for the second player is a strategy where the way is as long as possible. In both cases the distance can act as a state variable. [21] This two simplifying concepts did not arise from game theory. Actually it is used in the context of economics, especially when supply meets demand. In this case there are two agents, supply and demand, and a state variable, the market price. [21]

This section shows that games with more than three players can lead to a very complicated situation. If a player starts to check each strategy that another player can choose, he will understand that this process is not time effective. The reason of this problem is, that the possible combinations of players and strategies increases much more than the number of players itself. [21] Therefore, game theorist decided to make some simplifying assumptions, that should help to analyse n-person games. Both introduced concepts in this section, the representative agent and the state variable, help agents to gain important information to choose their best response strategy.

2.5 Cooperative Game Theory

The non-cooperative part of game theory was described in the previous chapters, now the cooperative solutions of games will be analyzed.

If non-cooperative games are compared with cooperative games, then the main difference is in the commitment of the participants. In the non cooperative case players make no commitments to coordinate their strategies. The main goal is to make a rational decision based on the question what the opponent's best response will be. The cooperative approach tries to use the concept of commitments to coordinate the players strategies. In comparison to the non cooperative way, the

main question here is to find a common strategy that will maximize the benefit of the whole coalition. [21]

Formally a cooperative game is described in the following way: [5]

1. a set of players $N = \{ 1, 2, 3, \dots, n \}$
2. a characteristic function v , which defines the value created by a coalition

First of all a *coalition* is defined as a group of players who interact together and coordinate their strategies to get the best payoff for the coalition. [21]

In general two different types of coalitions are defined: [21]

- Singleton Coalition:

In a *Singleton Coalition* a player goes alone and makes no cooperation. [21]

- Grand Coalition:

The *Grand Coalition* consists all players of the game. [21]

A *side payment* is a transfer of a payoff from one member to another within the coalition, so that no player will gain a worse result as before. [21]

At the end there is a concept needed which will find an the optimal solution.

Therefore, two different approaches will be introduced:

1. **The Core:** Roger A McCain defines the core as a set of all possible stable imputations, so that no individual or group has the intention to drop out and build a new coalition where a better payoff might be the result. It is important to note that there are cases where the core is empty and results in a set without any members. [21]

An example is now given to underline the concept of the core.

K, L, M	10
K, L	7
L, M	7
K, M	6
K	3
L	3
M	3

Table 2.10: Coalition functions or characteristic functions [21]

The table 2.10 provides some conditions for the stability of a solution of this 3-person game. It is obvious that all players must get at least a payoff of 3.

Furthermore, Player K and Player L together can earn a payoff of 7. The coalition $\{L,M\}$ and $\{K,M\}$ can get a payoff of 6.

The Grand Coalition $\{K,L,M\}$ can provide a surplus of one in comparison to the sum of the individual payoffs. This fact provides the players with the information that within the grand coalition they might get a chance of a higher payoff. The only question that arises from this fact concerns the distribution of the values. From the constraints which are defined below, it is obvious that Player L will get a payoff of 4 and Player K and M will get a payoff of 3. To find a result like this, it is necessary to check the constraints. First, if all payoffs of the 2-person coalitions are added and at the end divided by 2, the payoff is the same as in the grand coalition. This demonstrates that the grand coalition generates enough payoff to satisfy all 2-person coalitions. [21]

$$y_K + y_L \geq 7$$

$$y_L + y_M \geq 7$$

$$y_K + y_M \geq 6$$

$$2 * (y_K + y_L + y_M) \geq 20,$$

$$(y_K + y_L + y_M) \geq 10$$

Secondly, all players in the case of a single coalition must receive a payoff of at least 3. By the constraints below this conditions can also be satisfied by the grand coalition.

$$y_K, y_L, y_M \geq 3$$

$$(y_K + y_L + y_M) \geq 9$$

With regards to the constraints, if Player M will get a payoff > 3 , Player K and L will earn together < 7 . They will drop out of the grand coalition and create their own coalitions to get a payoff ≥ 7 . Therefore, the payoff of Player M must be 3, to fulfill all constraints. To find the solution for Player K, it is necessary to argue in the same way. If the payoff of K is > 3 , Player L and M can only receive a value of < 7 . The result will be that L and M drop out of the grand coalition and form their own coalition, where they can get a payoff ≥ 7 . Reasoning in this way brings Player K a payoff of three. Finally, the value of Player L is still missing. With the value information of Player K and M, the only suitable value for L is four. [21]

The resulting imputation $y_K = 3, y_L = 4, y_M = 3$ will be in the core of this 3-person game. The core of this game consists of a one single imputation, because it is the only allocation of values where no one of the participants has the intention to leave the grand coalition and form a separate coalition. [21]

2. **Shapley Value:** Another important solution concept, in addition to the core, is the Shapley value. This concept is based on the idea of marginal contributions. The Shapley value shows some interesting properties when it is compared to the core. [21]

(a) The Shapley value has the property to be unique. That means that in

every game there can only be exactly one solution.

- (b) If the Core is empty, the Shapley value anyway creates a solution.
- (c) If the game is symmetrical the Shapley Value will also be symmetrical.

The Shapley value deals with different possibilities of orders in which the participants can be added. The average value of all orders lead to the Shapley value. The calculation for the example above can be done in the following way. [21]

- (a) Generate all possible orders
- (b) Calculate the relevant value for each player
- (c) Average the values for each player

	K	L	M
K, L, M	3	4	3
K, M, L	3	4	3
L, K, M	4	3	3
L, M, K	3	3	4
M, K, L	3	4	3
M, L, K	3	4	3
Average	$3\frac{1}{6}$	$3\frac{2}{3}$	$3\frac{1}{6}$

Table 2.11: Calculation of Shapley Value [21]

The result of the Shapley value shows that it disagrees with the core of the game. If the grand coalition is created by the payoffs of the Shapley value, then Player K and L can get a maximum payoff of $6\frac{5}{6}$. If they build their own coalition they will earn a payoff of seven. The same procedure can be done with the coalition $\{L, M\}$. This example demonstrates that the Shapley value is not in the core for this game. [21]

Both concepts, the Core and the Shapley value, have some pretty good qualities but also some weak points. That is the reason why there exist a lot of different solution concepts in cooperative game theory.

Cooperative game theory represents a specific type of games where players use the tool of commitments to choose and coordinate their strategies. A few different tools exist to create a suitable solution for a cooperative game. [21]

In this thesis two widely known concepts, the Core and the Shapley Value, have been introduced.

2.6 Auction Games

In the field of auctions a lot of researches are made within game theory. There are a few familiar types of auctions. In this section the focus will be on the English Auction.

Before highlighting this type more closely, the different well known types are introduced.

1. English Auction:

This type requires buyers who bid sequentially higher prices as long as no one bid higher. Important to note is that the auction starts with a low price and evolve to a higher price. The person with the highest offer will get the item. [21]

2. Sealed-bid Auction:

A sealed-bid auction is an auction where all bidders bid at the same time, so that no one knows anything about the opponents bid. [21]

3. Second price Auction:

This type of auction requires the highest bidder to pay the price of the second

highest bid. This auction allows the bidders to choose a price, which they think the item is worth and so allows them to get a benefit. [21]

4. Dutch Auction:

This auction starts at a high price. The price is then reduced step by step until someone is willing to pay the item at a specific lowered price. [21]

Now the focus is set on the English auction and its connection to game theory. This type is described as the most familiar auction. If there are two bidders who increase the price step by step, the highest price will win at the end. The question that arises is at which price a bidder will step out and stop increasing the price. Therefore, there has to be a personal limit of a bidder. It is called the person's value. The concept of the person's value is easy to understand. If a person buys an item at the price of his personal value, he will neither be better nor worse off. If he pays a price at a lower level than his personal value, he will be better off. Reasoning in that way will lead to a worse payoff, if he pays a price which is higher than his personal value. [21]

Another interesting characteristic of English auctions are their efficiency. Efficiency can be described as a situation, where "*[...] no one can be made better off without making someone else worse off.*" [21] If both players bid in a rational way, the player with the higher personal value will get the item. If there is a situation where someone can be made better without making someone worse, then there is an inefficient situation. [21]

To illustrate English auctions in combination with Game theory, an example should help to understand the concept.

Assumptions:

- 2 Players: {A,B}
- Use the concept of backward induction

- Find the perfect equilibrium

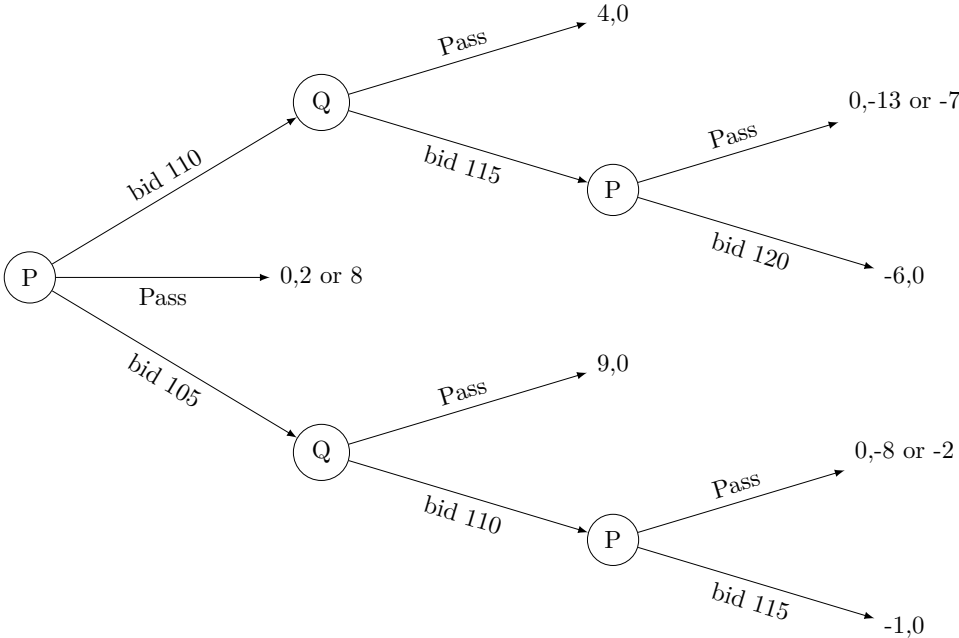


Figure 2.3: Tree diagram - English Auction Game [21]

First, the initial game can be split into two basic proper subgames finding a solution for the opportunities of Player P. [21]

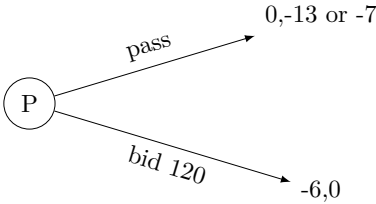


Figure 2.4: Subgame 1 - English Auction Game [21]

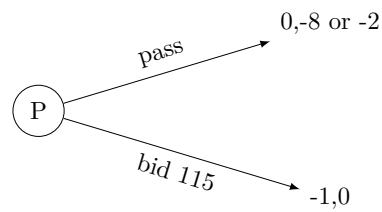


Figure 2.5: Subgame 2 - English Auction Game [21]

In the first subgame P chooses to pass instead of increasing the price to 120. The same result appears in the second subgame. With the information of the results of these two subgames, the initial game can be reduced to the following form. [21]

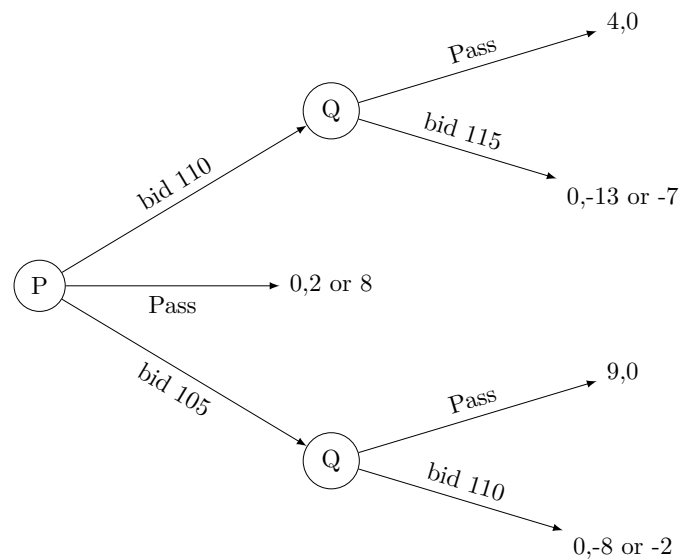


Figure 2.6: Tree diagram - English Auction Game [21]

The next step is to find the best solution for player's Q opportunities. In both subgames Q will choose to pass to get a payoff of 0 instead of a negative payoff. [21]

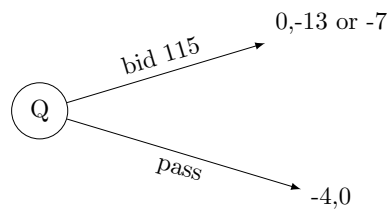


Figure 2.7: Subgame 3 - English Auction Game [21]

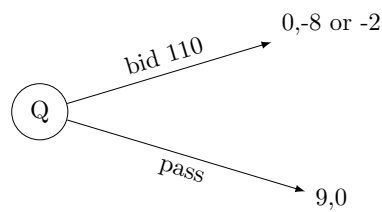


Figure 2.8: Subgame 4 - English Auction Game [21]

Now it is possible to reduce the initial game a second time. This is the final decision tree of this auction game. [21]

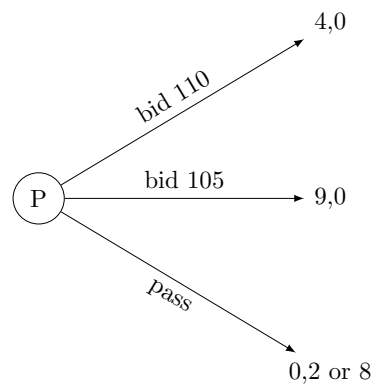


Figure 2.9: Reduced Game 2 - English Auction Game [21]a

The subgame's perfect equilibrium for player P is to bid 105 and for player Q to pass. This example of an English auction game demonstrates that it is always subgame perfect to increase the price step by step as long it does not exceed the

personal value. [21]

This chapter gave an introduction to the concept of game theory. Non cooperative as well as cooperative techniques were presented with theoretic definitions and practical examples.

Chapter 3

Smart Grids

A smart grid is defined as the next generation power grid. [13] The world wide industry tries to handle a lot of challenges including demand response, energy conversation or strategies for the optimal use of energy. Therefore an intelligent working electricity grid is necessary. [14] A smart grid or intelligent grid is needed to get solutions for the shortcomings of the classical existing grid. [14]

The next chapter deals on the one side with the functionality of a smart grid, its advantages and improvements compared to the current energy solution and on the other side presents a comparison between the present grid and the next generation electricity grid. At the end security issues and threats are also shortly discussed.

3.1 Evolution of the electricity Grid

The generation process of electricity is done through gas, coal, nuclear power, sun or wind technologies. The principle of electricity generation, discovered in the 19th century by the British scientist Michael Faraday said, that electricity can be produced by the motion of a loop of wire or a piece of copper between the poles of magnet. [13] Today, there are many ways how to generate energy. Figure 3.1 gives an overview of the main electricity generation in Europe.

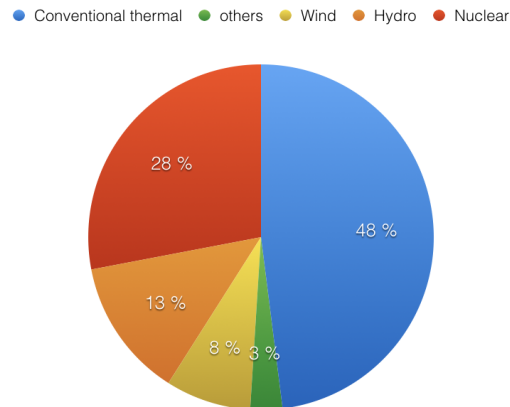


Figure 3.1: Energy Sources [13]

The current existing electricity grid is characterized as *"[...] a product of rapid urbanization and infrastructure development in various parts of the world in the past century."* [14] This grid system evolved on economic, political and geographic reasons. The power industry is based on a hierarchical system, where each process from the power generation to the power delivery is strictly defined. Figure 3.2 shows the structure of the existing electricity grid. [14]

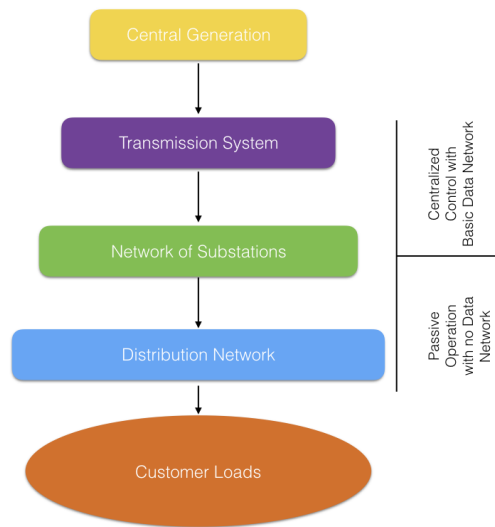


Figure 3.2: Hierarchical Structure [14]

The figure demonstrates that on the top of the chain, power plants are responsible for the production of energy. This generated energy is then transported via transmission lines to the distribution network and at the end sent to the customers. This unidirectional process leads to a few serious problems. [14]

The first problem is, that the source has no information about any service parameters of this end point. The system works inherently inefficient, because it is build "[...]to withstand maximum peak demand across its aggregated load". [14] The System stability decreases step by step, because of an extremely rise in power demand in touch with high investments into the electrical power infrastructure. [14] Another problem is the loss of energy which occurs during the transport via transmission lines. [13, 14]

All this facts lead to the global need for a modernized electrical grid system, which will use new technologies to handle demand side management in an efficient way. [14]

3.2 Functionality of a Smart Grid

The previous section provided an introduction on the main functionalities of the existing grid. If it is compared to a smart grid some essential differences can be seen. Figure 3.3 presents a comparison between these two types of grid systems.

Existing Grid	Intelligent Grid
Electromechanical	Digital
One Way Communications	Two Way Communications
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self Monitoring
Manual Restoration	Self Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

Figure 3.3: A comparison between Smart Grid and Classic Grid [14]

In the traditional way, a power grid works unidirectional. Energy is created by a few central distributed generators, which are driven by flowing water or head engines equipped with nuclear power. Normally the generation plants are quite big and far away from the populated area. After the generation, the electric power is transferred with a higher voltage to the transmission grid. If the power arrives at the substations, it is stepped down to a lower voltage level to be able to enter the distribution grid. The last step deals with the supply of the customers. Therefore a step down to a lower required voltage level is necessary. Figure 3.4, shows an example of the traditional grid system. [13]

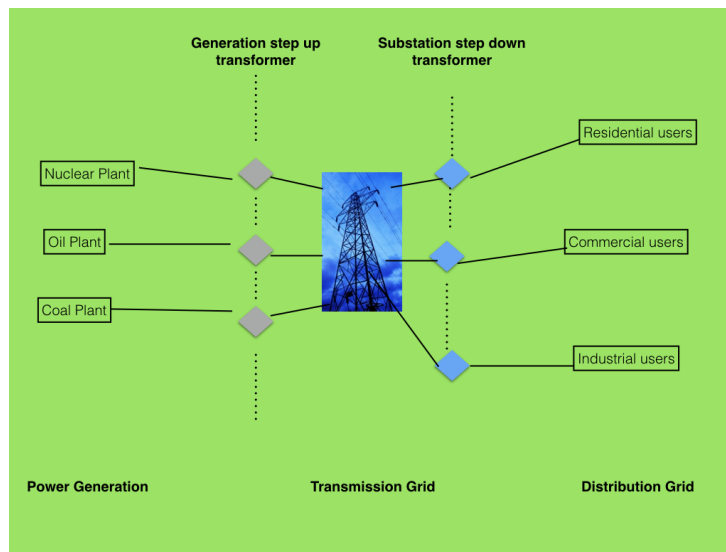


Figure 3.4: Traditional Grid System [13]

The biggest difference of a smart grid to the traditional power generation is, that this system enables a two-way flow of information and electricity. This helps to create a system that is safe, clean and efficient. Another big advantage of a smart grid is how it handles peak demand hours of power. With the possibility of real time pricing, customers should be convinced to adapt their demand profiles, that will automatically lead to a reduction of peak demands. [13]

To ensure the requirements and achieve the benefits of a smart grid, the U.S. National Institute of Standards and Technology (NIST) proposed a conceptual model, which should help to understand the mechanisms of a smart grid. The NIST concept divides the smart grid in seven different parts. Within each part smart grid actors, devices, systems or programs are included to make decisions, exchange information and make sure that applications are performed without any problems. [13]

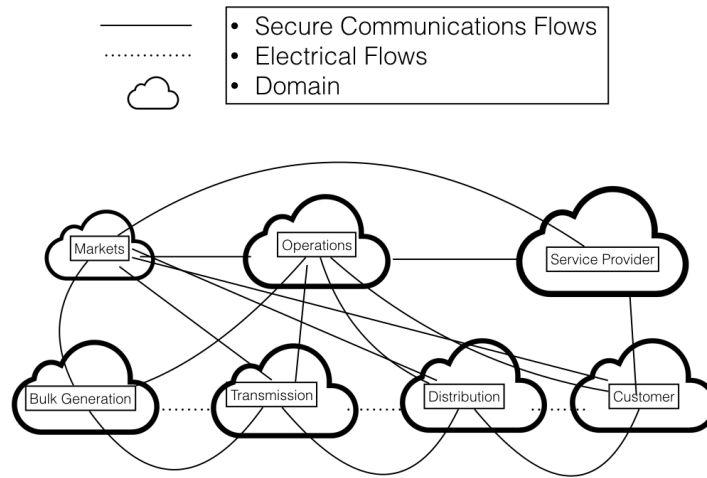


Figure 3.5: NIST Smart Grid model [13]

The customer domain represents the end user of the power chain. Although they are customers of the energy, they may also generate and store additional energy. Markets are defined as a place where operators and participants will meet. The service domain provider has the function to offer services to end users and provide secure communication flows to the markets and the operations domain. The operations domain includes managers which are organizing the transfer of energy. [13] The generation of electricity is done by the bulk generation domain, which is not only responsible for the generation but also necessary for the storage of energy for future distribution. The transmission and distribution domain role carries the generated energy over long distances to be able to distribute it later to the customer. Within this distribution and transmission process, also energy storage is done. [13]

The NIST model gives an overview of the roles which are included in the processes of a smart grid. Xi Fang et al. provided a more technical survey of a smart grid. They split a smart grid in three main parts. This work discusses the smart infrastructure system in more detail. [13]

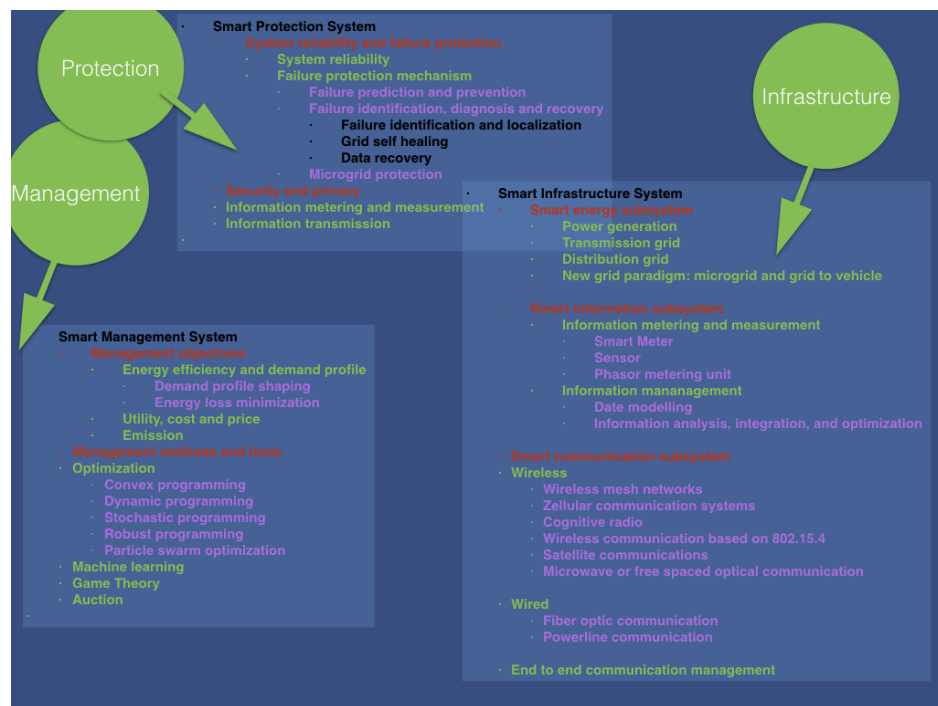


Figure 3.6: Smart Grid System Xi Fang et al. [13]

1. Smart Infrastructure System:

The smart infrastructure system is responsible for the generation process, the transportation via transmission lines and the distribution to the customers. The authors divided the smart infrastructure system in three more specific subsystems. [13]

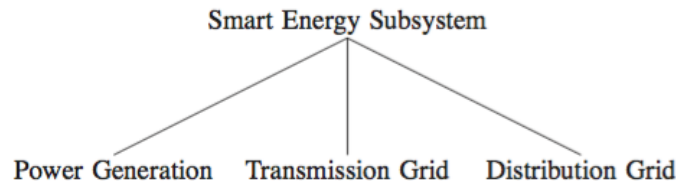


Figure 3.7: Smart Infrastructure System [13]

(a) Smart Energy Subsystem:

The smart energy subsystem is the most important sub process of the infrastructure system. It is responsible for the generation, transport and consumption process of energy. [13]

The power generation process is handled with a two way flow of electricity and information. Smart grids support the so called distributed power generation. Distributed generation offers the use of distributed energy resources, for example solar panels or wind turbines. This generators has the advantage to provide better power quality and reliability to the grid. [13]

Nevertheless, the use of distributed generators is related also to some problems in real life. First, the use of solar and wind generators are influenced by a lot fluctuations. Second, the cost of installing and operations costs of such generators for one unit of electricity is higher than with traditional central power plants. To make a change in the today's power system, it is on the one side necessary to find solutions for the installation costs of distributed energy resources and on the other side more targeted promotion must be done. [13]

The development of the transmission grid depends on infrastructure challenges like increasing demands and also on the supply of new technologies like materials or communications technologies. The future

smart transmission grid consists of a smart control center, a smart power transmission network and smart substations. All together should help to improve the power quality and reliability as well as provide more flexibility in the control and operation process. [13]

For the distribution grid the today's most relevant problem is a more efficient power supply to the customers better. It is clear that an increase of distributed generators in the grid system will lead on the one side to more flexibility, but also create more complexity for the power flow control on the other side. Hence, a smart power distribution and delivery system is required. Until today a lot of researches are made within this topic. An interesting approach was introduced by Takuno et al., where *"[...] information is added to the electric power itself and electricity is distributed according to this information."* [13] Xi Fang et al. said that this system could lead to a more efficient and easier in-home power distribution. [13]

(b) Smart Information Subsystem:

The smart information subsystem deals with the information metering, monitoring and management process, which is an essential part of a smart grid. [13]

Smart metering has two important functions within a smart grid. First, it is responsible for collecting information from the users' devices. Second, it is also responsible for controlling the performance of the devices. One of the best know system, is the automatic metering infrastructure (AMI) which is built on the idea of automatic meter reading (AMR). It is seen as a logical and effective strategy to automatically collect diagnostic, consumption and status data from the users' devices. The collected information are then analyzed and troubleshooted. A big advantage of AMR is that it allows to communicate in two ways. Hence,

data are available in real time and on demand. The availability of the information helps to improve system operations and the demand management of the users. On the customer side, a lot of benefits are offered from a smart metering system. First, users can manage their bills. If their estimated bill will be higher than expected, they can reduce their energy consumption to optimize their overall costs. Furthermore, by using real-time pricing, users can shift their demands in peak load hours. All in all a smart metering system offers a lot of benefits for the optimization of the customer side. [13]

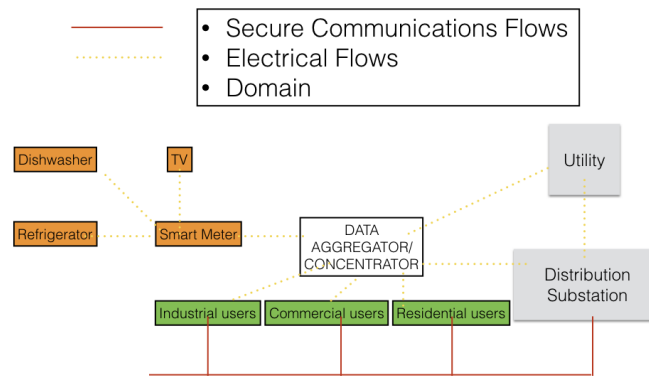


Figure 3.8: Smart Metering Structure [13]

The monitoring and measurement process is an important activity to obtain grid status information. Two of the most known concepts are sensors and phasor measurement units. [13]

Sensor networks are a mechanism that was already used in power grids to detect mechanical failures, for example conductor failures. [13] A research work proposed by Leon *et al.* presents the idea that sensor

networks are included in a power grid to obtain real time mechanical and electrical conditions of transmission lines. It should help to get a complete overview of the power system in real time. [13, 20] A more cost effective technology are wireless sensor networks (WSNs). WSNs provide a feasible and effective sensing and measurement platform for monitoring and diagnosis. Some researches are made in this area. Gun-gor *et al.* presented an approach, where wireless sensor networks can help to identify a single system contingency, before it can make any damage within the whole power grid. [13, 16]

The use of sensor networks in smart grids also implicates some requirements: [13]

- Quality of Service requirements
- Resource constraints
- Remote maintenance and configuration
- Security requirements
- Hard environmental conditions

The second concept deals with the use of phasor measurement units (PMU). The main goal of a PMU is to ensure a stable and reliable transmission and distribution system. A phasor measurement unit is responsible to measure the electrical waves on the grid and evaluate the health status of the system. PMU's are widely discussed by the industry and researchers. The main challenges here deals with the installation of a PMU, the collection of data and also with the protection for a grid. [13]

(c) Smart Communication Subsystem:

The smart communication subsystem tries to ensure a stable communication connectivity and an efficient information flow among all devices and systems within a smart grid. Communications technologies can be

divided in two major parts: wireless and wired communication. [13]

Wireless technologies offer a lot of benefits in the daily life of a customer. It is not only related to lower installation costs and rapid mobility but also offers a perfect fit for remote end applications. [13]

Wired technologies play also an important role and are also integrated in a smart grid system. One world wide used communication technology is fiber optic communication. Fiber optic infrastructures offer a high speed communication, which is more expensive than other communications structures but with its high bandwidth capacity and immunity properties it is nevertheless a cost effective communication medium. [13]

Another known technology is powerline communication. It is used to carry data on a conductor, which are then used for power transmission. Many people think that powerline communications are a good option for a lot of applications. The reason why powerline communications are a good option, is that they have similar installation costs like wireless technologies because they can make use of already installed lines. On the contrary other people have some doubts about the security performance of PLC, but in general it is a qualified candidate for smart grids. [13]

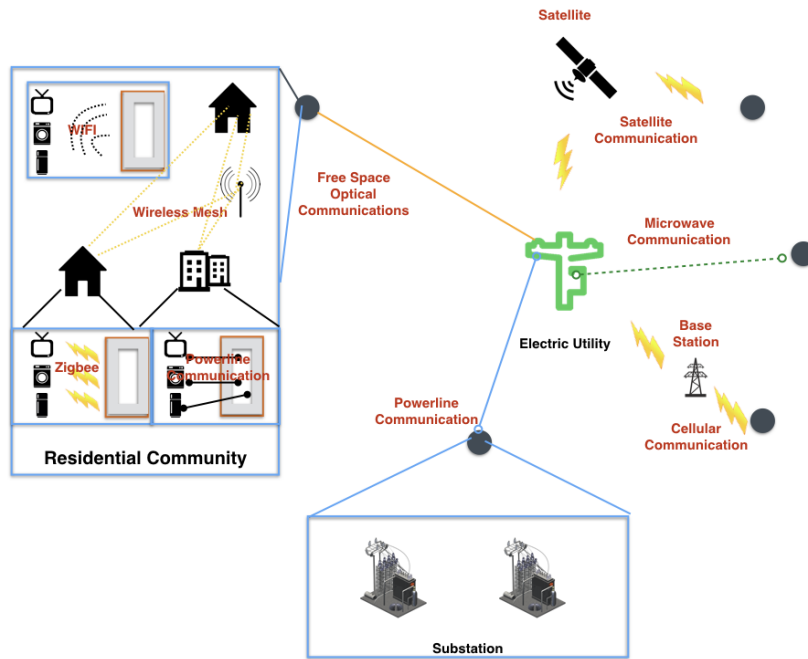


Figure 3.9: Communication technology example [13]

Figure 3.9, is an example of a communication network. User devices are connected via WIFI, ZigBee and powerline communications. The users can interact and exchange information with wireless mesh networks. A public utility also uses powerline communications to interact with different substations. [13]

2. Smart Management System

The smart management system is responsible for enabling more specific management and control services within an smart grid infrastructure. The main objectives deal in most cases with improvements of energy efficiency, cost reduction, utility maximization and balancing supply and demand of energy. Management tools use programming technologies, machine learning, game theory or auction theory to achieve its goals. [13]

3. Smart Protection System

The smart protection system has the duty to enable advanced analysis about the reliability of the grid and to protect the system against any failures and cyber security problems. The security task is also related to provide information privacy of the customers. A smart failure identification and analysis should lead to a self healing process of the grid, which is much more efficient than in the traditional grid. [13]

Xi Fang *et al.* presented a more technical view of the smart grid infrastructure. The published work focused on the differences between the classical grid system and a smart grid solution, the benefits of a new grid designs as well as on the technology behind this concepts.

3.3 Microgrid

Microgrids can be seen as a cornerstone of the future development of smart grids. [13] It is defined as *"[...] a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode."* [23] The customers of a microgrid are able to produce low voltage electricity by renewable resources like solar panels, wind turbine or fuel cells. [13]

A microgrid enables new solutions to provide reliable energy for a customer. Microgrids provide, by the possibility of locally generation of energy, a balance load situation in the grid. If it is part of the general grid, microgrids can help to improve the quality of power distribution. [23] If the grid disconnects because of disturbance, microgrids switch into the island mode, where distributed generators continue to supply the customers with energy. The possibility of energy production via distributed generation and the disconnection in case of disturbance, leads

to the assumption that microgrids can provide highly reliable energy to the customers. [13]

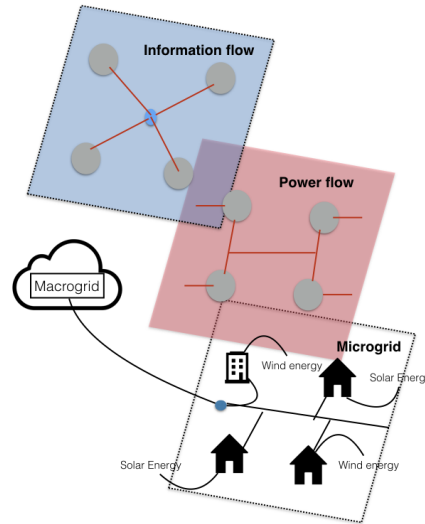


Figure 3.10: Microgrid [13]

Figure 3.10 shows an example of a microgrid. The blue layer describes the information flow, while the red layer illustrates the power flow within a grid. In this example the microgrid consists of two solar panel generators, a wireless access point and two wind generators. The supply of energy is done via powerlines. Each building is connected via powerlines to the generators. [13]

This example demonstrates a more complex topology of a microgrid. A more simpler example of a topology is a customer's premises. This type has only one point of connection to the utility grid and can be controlled by a single user. [13]

A third concept that is related to microgrids is the zero-net-energy substation. The idea is, that the utility tries to build a concept where each distribution substation is connected to sufficient generators and storage possibilities. At the end, two goals need to be reached: [23]

1. "Net zero energy flow from distribution substation to the subtransmission

system over the course of a year[...]" [23]

2. *"[...] the ability to form a microgrid separate from the subtransmission system by leveraging the connected generation and storage, coupled with demand-side management and distribution automation" [23]*

A further benefit of a microgrid can be realized by implementing a powerful distributed management system. It is able to build a platform that can form instantly viable microgrids. For priority customers this DMS will try to form as many microgrids as possible to minimize the loss and the resulting effects of larger systems. [23]

Another important topic of microgrids is its storage property. There will be only a few number of microgrid designs which are able to create a good balance of generation and load. Therefore, it is necessary to look for storage possibilities during the whole process. One attractive source are batteries of electric vehicles during their charging process. The only negative aspect about vehicle to grid energy flows, is the fact that it reportedly reduce the life time of the vehicle batteries. Anyway, it provides a nice concept to balance microgrids. [23]

Michael Montoya *et al.* provided four key components each microgrid needs to have to be an effective solution: [23]

1. A robust telecommunication that is resistant against latency and offer a high bandwidth capability. [23]
2. To ensure the rules of interconnection, high speed data processing is necessary. [23]
3. Systems must be controlled and monitored to send instructions to connected devices. [23]
4. A solid cyber security system must be implemented to protect the control system. [23]

3.4 Security and Threats

The last section of the smart grid chapter deals with security issues and grid security challenges.

Smart grids, as previously described, enable intelligent transmissions and distribution networks. To ensure a good quality of energy, an improvement of the system reliability and security quality is necessary. Figure 3.11 demonstrates the different communications and control systems in a smart grid. Smart grids collect and process a lot of data during their daily activities. This graphic should give a first impression, in which domains a cyberattack can happen. [19]

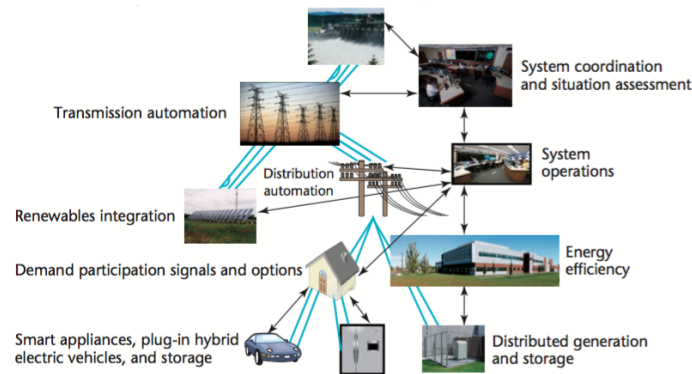


Figure 3.11: Domains of possible Cyberattacks [19]

Cyberattacks on operating systems can have huge consequences for a smart grid. For example power system blackouts, IT infrastructure failures or damaged consumer devices can all lead to an energy market chaos. To ensure human safety, some security challenges need to be handled within a smart grid. [19]

1. Trust:

The customers of a smart grid environment define trust for a control system as confidence that data, which are collected by a specific device, hasn't been changed or modified. If some users become unsure about this method, new trustful monitoring approaches are needed. [19]

2. Communication and Device Security:

Existing grid systems use serial communication to provide monitoring and control information. The user knows that serial communication is reliable and predictable and therefore a trustful solution. New smart grid solutions use Internet or broadband communication technologies. These technologies implicate some security and reliability problems. The traditional grid involves devices which are locked in high security buildings. The new two way communication are free accessible for all consumers and adversaries. [19]

3. Privacy:

The traditional grid system deals with problems like availability, integrity or confidentiality. With metering and monitoring tools, which were discussed above, privacy of a user becomes more and more important. The collection of data encompasses not only consumption information of a user, it also provides information about when a user is at home, at work or elsewhere. This leads to a huge increase of criminal targeting of homes. [19]

Effective cybersecurity solution must ensure that data about power flows will be handled in secret. Therefore developers should also think about efficiency and scalability of a system and must create a design that is adaptable and evolvable for future developments. Ning Lu *et al.* gave an overview of the important security problems of a smart grid. Especially the user privacy was introduced as a new big factor of security discussions. [19]

This chapter dealt with the evolution of the grid system. In a first step, the classic grid was compared to a smart grid to find the biggest differences of both systems. Afterwards the main functionality of a smart grid was introduced. In addition, different important smart grid related areas such as microgrids, smart metering, communication technologies or cyber security problems were surveyed.

Chapter 4

Smart Grids analyzed with Game Theory

This chapter deals with an analysis of the existing researches of smart grids in combination with game theory. The main topics are demand side management, pricing techniques, electric vehicles and communication technologies.

4.1 Demand side management

For a future smart grid system, demand-side management will be an important technique to control the energy consumption at the customers premises. Two major players are involved in this process: [28]

- Utility companies:
Utility companies are typically the big energy supplier. [28]
- Consumer:
Consumer can be electric cars, user premises or a company. [28]

Demand-side management tries to reduce the energy consumption by providing specific energy efficient tools to the end-users. This interactions can happen on a

technical level or on a social level. The technical level concerns interactions between smart meters and the control center of the utility company. At the social level there can be different service agreements between these players. [28]

Therefore, a good demand-side management system must enable pricing techniques that ensures efficient load management, implements a scheduling mechanism for all devices and controls the user behaviour. Game theory provides a lot of useful tools for developing pricing strategies and scheduling mechanisms or "[...] enabling efficient interconnection of heterogeneous nodes." [28]

Within demand-side management also demand-response models are described. Demand-response models focus on the process where a utility company tries to change the consumption behaviour of the grid users. This can happen with a specific signal, for example a pricing information. [6, 28]

Lijun Chen *et al.* present two abstract market models to match on the one side power demand and power supply and shape on the other side the demand. [6] They consider a situation where a supply deficit or surplus of energy exists. A deficit can happen when climatic changes lead to a decrease in power generation with solar farms or wind generators. A surplus arises from an improvement of the weather conditions. Chen *et al.* assume that an increase and a decrease of the power supply, depending on the particular situation, is related to high costs. Hence, the power supply is inelastic. In a first step, they observe an inelastic supply deficit situation, where a specific bidding scheme should help to create a load shifting mechanisms among the customers. Therefore, the utility company needs a supply function from each consumer, to make a decision based on the market price and the user bids. The consumer then is committed to shed his load. [6] Lijun Chen *et al.* demonstrate that in an competitive market where grid user are typically price takers, their bidding mechanism leads to an efficient equilibrium with a maximization of the social welfare. A market with oligopolistic properties achieves an unique Nash equilibrium. Hence, they suggest an iterative and distributed supply bidding mechanism for achieving an equilibrium in the demand

response model. [6]

In a next step, they consider an elastic power supply situation. This time the consumers have knowledge about the real time prices and according to this, they will adapt and shift their demands. The daily objective for a consumer is to maximize his aggregate net utilities. It is important to note, that this demand response scheme needs a two way communication between the users and the companies, as described in chapter 2. Lijun Chen *et al.* achieved a situation with an efficient equilibrium and a maximized social welfare, when users are price takers. If they are price anticipating and think strategic, then a unique Nash equilibrium is achieved. [6]

Christian Ibars *et al.* present a distributed load management mechanism to reduce and control the power demand at peak hours. [18]

The authors make use of a specific type of a non-cooperative game, the congestion game. Their general idea of the model is, that user get the capabilities of managing their own demand. In many cases the need of electricity has a variability in time and quantity. Therefore, they argue that user should hold a control device which monitors the total power demand and manages all appliances or storage devices. Then the internal management is handled by the consumers. Usually they know their daily demand and can filter it within 24 hours time slots. Each time slot refers to a user specific demand vector. In a next step all consumers take place in a bidding process by sending their personal demand vector to the network. Based on this information a price is generated and the user get the chance to adjust their need and shift their consumption priorities. If all participants entered the system and updated their bids so that convergence can be reached, the process will end. Christian Ibars *et al.* argue that this bidding process will take place once every 24 hours. [18]

M is related to the total number of users. The network is modeled as a directed graph (V, E) , where the generating vertex V_0 is connected to the customer specific vertex V_1 . The graphic below shows two vertices connected with parallel edges

$e_{0,1}^1, \dots, e_{0,1}^N$ The power needed by user i at a specific time slot j is described by the edges. [18]

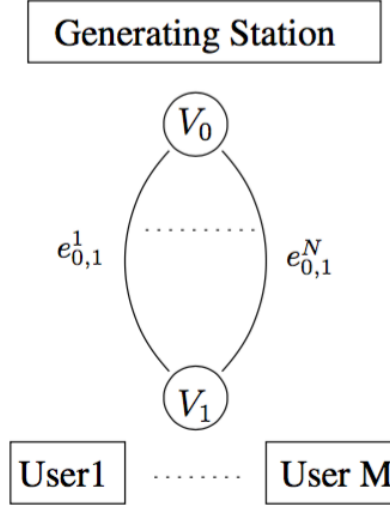


Figure 4.1: Demand Management Networkmodel [18]

For the load management the network model additionally consider load constraints. The goal is to optimize the distribution process and minimize the capacity margins. [18]

After presenting their idea of demand and load management, Christian Ibars *et al.* formulated for both models a congestion game. The setup of the demand management game was defined by the authors in the following way: [18]

- "the players are the M users demanding resources during the day;" [18]
- "the resources E are the N available edges $e_{0,1}^j$, representing the n time slots, through which the power demanded by user i flows;" [18]
- "the strategy of player i is the demand vector d_i ;" [18]
- "the cost of each resource in E is $c_e = c_{e0,1}^j$ " [18]

Each player will define his strategy and adapt it based on the chosen strategies of the other player. It is repeated until an equilibrium is reached. A Nash equilibrium in the demand management game is reached, if all players adapt their strategies to minimize their costs. From the above network model an equilibrium is reached when the cost flow from vertex V_1 to V_0 is minimized. [18]

For the load management game the authors argue that the congestion game loses its symmetric characteristic. Nevertheless, a Nash equilibrium can be found according to Christian Ibars *et al.* It can be reached, if all other players have fixed strategies and a single player minimizes its cost function. [18]

After simulating the proposed games, the authors were able to demonstrate that their model leads to a stable equilibrium point. Furthermore, they showed that simulations for different users result in a smoother demand curve while also satisfying the demands of each user. [18]

Another approach for game theory and demand side management was presented by Amir-Hamed Mohsenian-Rad *et al.* They defined a model for autonomous and distributed demand management by using an energy consumption scheduling game. In addition, they take advantage from the future two way communication technology. [22]

The basis scenario consists of an energy source which is connected to the grid and is used by several users. Each customer owns a smart meter with an automatic energy consumption schedule (ECS) function to find its best energy consumption strategy. [22]

Figure 4.2

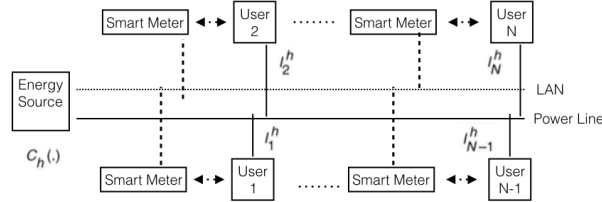


Figure 4.2: Basis Scenario Energy Consumption [22]

For the cost model it is important to note that the cost of the same load can be different at different times. For example, the energy consumption at night could be less than during the day. A further model assumption is, that the individual needs of a user are included. Therefore, each smart meter must be able to analyse and schedule the household energy consumption. [22]

In this paper the authors set a focus on optimizing the energy costs problem. Each player tries to take a strategy, which will minimize his payments to the utility company. The proposed solution of the energy consumption game lead to a unique Nash equilibrium. The players fall in a situation where there is no intention to deviate from the demand schedule. Amir-Hamed Mohsenian-Rad *et al.* also present a second theorem that find an optimal solution for the energy cost minimization problem. The proof of this theorem says that the optimal solution is also the unique Nash equilibrium. Furthermore, the authors realized that an efficient pricing mechanism incite the users to cooperate with each other to reduce their own payments. [22]

Amir-Hamed Mohsenian-Rad *et al.* presented a solution concept where the min-

imization of the energy consumption costs leads to a reduction of the peak to average ratio and therefore to an overall system improvement. Furthermore, a game theoretic approach with a simple pricing system helps, that users have the incentive to cooperate with each other to choose optimal strategies. By this reason a Nash equilibrium of the presented energy consumption game can be seen as an another example for the energy demand management problem. [22]

Sarvapali D. Ramchurn *et al.* introduced a new model of decentralised demand side management, where large populations can be coordinated by using autonomous agents. The main idea of the agents is, that they control the deferment of the loads to maximize the user's comfort and minimize at the same time their energy costs. Therefore in the future, more tools getting electrified and new challenges of peak hours arise. The authors provide the opinion that, if there are no appropriate strategies for smart meters, more significant peak situations will arise due the reactive behaviour of smart meters. [26]

Therefore Sarvapali D. Ramchurn *et al.* presented the idea of an adapting instead of a reacting behaviour. The agent's deferment of loads lead to an increase or decrease of energy consumption during different times of a day. The authors propose that if agents try to defer loads, it is always preferable to converge to the competitive equilibrium. [26] *"This means that they converge to an equilibrium price for electricity if there is enough storage, at which point social welfare is maximised."* [26]

In recent researches most of the presented demand side management approaches used a central controller to send information to a small group of users to reduce their energy consumption during peak demands. The problem is that if there is a large pool of users this approach will not be effective enough to reduce peak situations. The authors define two key components to receive significant performance benefits within smart grids. First, an agent needs a price signal to start thinking about deferring loads. Second, in addition to the price signal the autonomous and adaptive behaviour of the agent will result in a performance increment. [26]

The best known pricing mechanisms include fixed price techniques, where real time costs are hidden from the users, time-of-use (TOU) techniques, which bias the real time energy price and real-time-pricing (RTP) mechanism, where a signal for the next 30 minutes are sent to the customers. The following graphic shows the demand and its optimization by using the presented pricing techniques. [26]

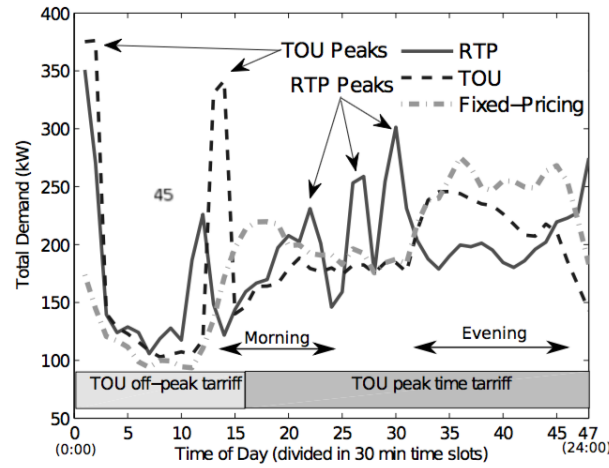


Figure 4.3: Demand of electricity with different pricing techniques [26]

From the graphic above it can be seen that by using a fixed price mechanism the demand is higher during morning and evening hours. This is due to the presence of the customer at home. Time of use techniques lead to an optimization of their demand at peak time but increase so the demand in off-peak hours. In a similar way, the RTP mechanism shifts the demand to different time slots during a day and create so new peaks demand. [26] Sarvapali D. Ramchurn *et al.* present a pricing model where agents defer their loads based on a predicted market price for the next day in comparison to the 30 minutes pricing model. The big difference to the classic RTP mechanism is, that all DSM-capable agents do not optimise their consumption at the same time. This decentralized demand side management technique can be very attractive, if millions of consumers are involved. In addition, the price signal

is sufficient for the communication between the generator and consumer. [26]

The results of an empirical evaluation show that for a model simulation with 5000 homes and load profiles of 26 million homes, a reduction of 17% of peak demands and 6% of carbon emission was reached. By using the concept of game theory, the authors gave economic incentives for consumers, to make use of agent based smart meters. [26]

4.2 Applying Game Theory in Microgrids

Microgrids, as previously described, consists of a network of distributed energy sources which provides energy to multiple small areas. In this section cooperative games for energy trading between multiple microgrids and non-cooperative games for load and source control are discussed. [28]

Microgrids have the function to minimize the demand on the main grid, by providing energy to consumers of different small geographic areas. But sometimes there are moments, where the consumers demand can not be satisfied only by a microgrid and additional energy is needed from the main grid. A good and efficient working future smart grid consists of a large number of microgrids, which can exchange energy with each other instead of requesting additional energy from the main grid. This concept optimizes the loss of energy during the transport over the distribution lines and reduces so the demand of the main grid. [28]

The authors of [27] proposed a cooperative game for exchanging energy in future microgrids. They consider a distribution network that consists of n microgrids, a main grid and a substation that is connected to both. In a specific situation, depending on the consumer's demand, each microgrid may creates a surplus or requests a surplus of energy to meet its demand requirements. Microgrids with a surplus have the intention to sell its additional power. Microgrids which meet the demand perfectly do not participate in the exchange process. To meet the additional demand and acquire the missing energy, a cooperative and non-cooperative

solution can be used. [27, 28]

First, the demand can be satisfied by exchanging energy with the main grid. The authors define the non-cooperative utility for any microgrid, as the total power loss over the distribution lines. The power loss consists of several factors, for instance the distance between the microgrid and the substation, the transfer voltage or the amount of energy. Another possibility is a cooperation between the microgrids. It can be seen as a coalition which participates at a local energy market. These microgrids can then exchange energy locally among themselves, optimize the loss of power during distribution lines and reduce at the same time also the distance of power transfer. [28]

Figure 4.4 shows the idea of multiple microgrids cooperating with each other.

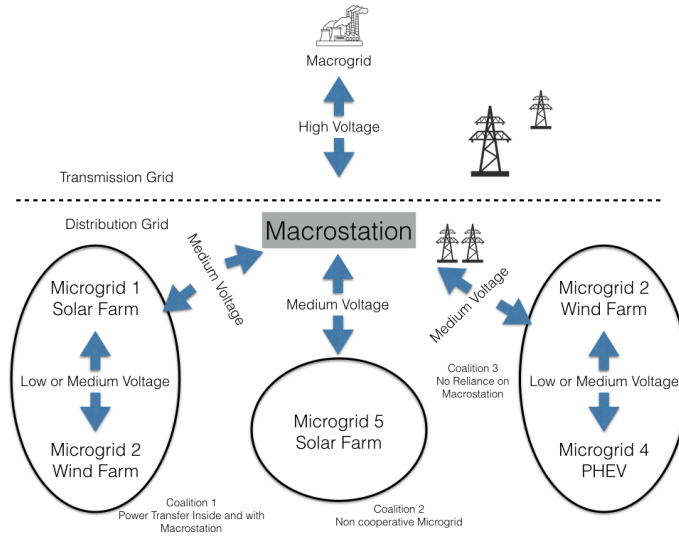


Figure 4.4: Microgrid Cooperation [28]

For simulating a cooperative energy exchange model, some definitions are needed. A coalition S in a cooperative microgrid game can be divided into two subgroups. First S_s is characterized by the group of sellers and S_b is defined as the group of buyers. A coalition utility is a function of the relationship between sellers and buyers. The question is now, how can sellers and buyers be matched and how can

microgrids form coalitions to reduce the power loss over the distribution lines? [28]

Two game theoretic approaches can help to solve these questions. [28]

First, auction theory is a strong tool to analyse the relationship between sellers and buyers. The arrangement between both is the price at which the trade will happen. The authors present the framework of a double auction. It means that a coalition can form a double auction game, where the players corresponds to buyers and sellers. The strategies of the players are of the one side the price at which energy will be traded and on the other side the quantity of energy that a player needs or wishes to sell. The optimal solution is a quantity of energy and a defined price which optimize the objective function. [28]

The second presented concept, is a coalition formation game to match buyers to sellers and vice versa. The authors of [27] presented a solution concept by using a communication network, where microgrids can at any time signal their needs by using for example an agent. If other microgrids are also willing to join a coalition, they can start to cooperate immediately. Within the coalition the involved microgrids must accept the matching process of buyers and sellers. It must also be clear, that microgrids will form a larger coalition if the new formation increases the payoff for at least one microgrid. W. Saad *et al.* presented interesting results by using their solution concept of a coalition formation game. The following graphic shows a comparison of the results between a classic non-cooperative game and the cooperative approach. It can be clearly seen that the cooperative solution leads to a reduction of the average power loss while the number of microgrids increases. [27, 28]

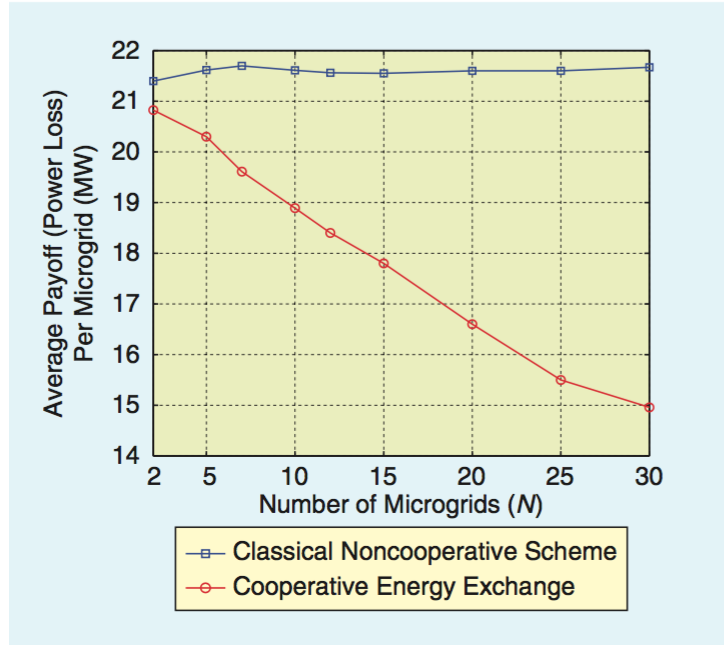


Figure 4.5: Non-cooperative Concept vs. Cooperative Approach [28]

In comparison to the previously discussed cooperative solution concepts, also non-cooperative games can be used to simulate microgrids. In the existing literature either demand management or supply management are discussed. A smart grid that is able to handle multiple microgrids must create a framework that “[...] capture both the competition over the energy resources that arises between the loads as well as the competition over the supply of energy that arises between the sources.” [28] The authors in [34] proposed a non-cooperative game where the set of players N consists of L loads and S power sources. A source S choose its strategy to regulate the voltage. A load L chooses a strategy to control its shunt resistance on the ground level. The key question of the load and source interaction game involves the selection of a strategy of a load or source to optimize its objective function. W. W. Weaver *et al.* proposed the Nash equilibrium as solution concept for the load and source game. The authors consider a simple one source and one load example to find a Nash equilibrium. Within this game a source tries to regulate

its terminal voltage, whereas a load tries to regulate its input voltage. Thus the authors discovered an equilibrium when a load as well as a source can regulate their power and optimize at same time their utilities. [28,34]

W. Weaver *et al.* showed that non-cooperative games can also be used to model and simulate the interactions between a source and a load in microgrids. [28]

4.3 Energy trading

The world's population is growing extremely fast and therefore additional energy is required. To be able to meet the requested demand, it is important to consider energy efficiency. Recent achievements of smart grids have shown, that there is a big potential to use the energy in an efficient way. This can be reached by using decentralized generation and storage mechanism. Customer can then be a part of an energy trading market to request additional energy to fulfill their needs. By using a concept like that, customers get away from stressing the main grid. Bayram *et al.* provide their concept for energy trading in smart grids. [3]

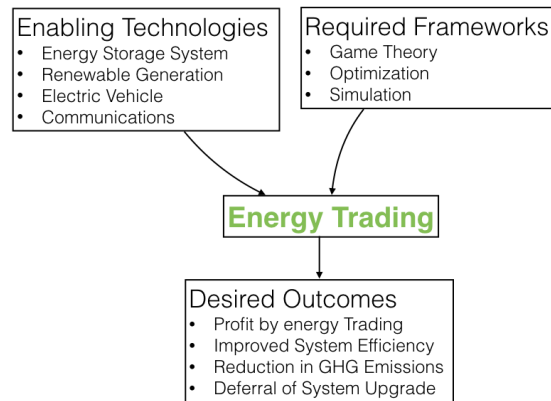


Figure 4.6: Components of energy trading [3]

The following section deals with the benefits of energy trading, an introduction to enabled technologies and game theoretic solution concepts for auctions games.

The concept of energy trading depends on the willingness of customers to participate in such a trading market and of course the availability of matching technologies. Customers will get a higher motivation to participate if they can save costs and improve their own profits. In general there are four economic benefits. [3]

1. Improved System Efficiency: The efficiency of a smart grid can be improved by distributed generation, storage units and the use of electric vehicle to store additional amount of energy. Energy trading can help to meet the demand of each user locally and decreases at the same time the use of high capacity generators. Furthermore congestions of transmission lines can be reduced and this will minimize the line losses. [3]
2. Reduced System Operation Cost: Another motivation is the reduction of the operation costs. Normally they arise during peak hours which are about 10% of a day, to meet the high electricity demand. The following graphic demonstrates a typical cost curve in the US. It can be easily seen that during peak hours the system operation costs increases. The trading energy concepts can help customers to reduce their costs at peak hours by trading energy locally and also can lead to better profits. [3]

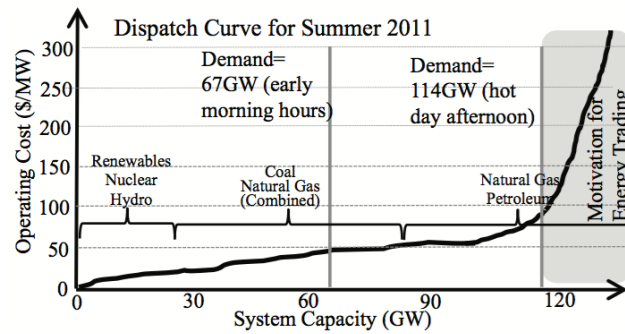


Figure 4.7: Energy Trading between Micro grids [3]

3. Reduction in GHG emissions: One of the major goals of the European Union is to reduce the GHG emissions in the next years. By the year of 2020 the green house gas emission should be cut by 20%. To reach this goal micro grids have the potential to improve the overall system stability by allowing the energy trading process at peak hours. For example, power generation during peak hours often leads to significant amounts of waste heat. If the waste is then recycled, it could be possible to cool and heat buildings or to heat water. Such a process can improve the customers energy efficiency from 35% to 85%. [3]
4. Energy Profiling: The last economical benefit is the arising network of user demand profiles. For micro grids it is easier to integrate renewable energy sources if a stable user network exists. Furthermore, the balance of supply and demand can be handled in a different way, which then again lead to lower line losses. [3]

Energy trading, as it was described above, enables new technologies and models for improving the energy efficiency. For micro grids it is useful to integrate renewable energy sources such as panels or wind turbines. The use of such technologies can reduce peak loads and improve the whole energy system. [3]

Another energy trading approach deals with the storage mechanism. With the

ESS (energy storage systems) technology users can store off peak demand energy and exchange it during peak hours demand. A similar technology can be found by using electric vehicles. It is a cost-effective and friendly means of transport. EV's with bidirectional chargers can exchange energy to the main grid or to other EV's. [3]

With that in mind three scenarios are possible. Stored energy can be now traded from Vehicle-to-Home (V2H), from Vehicle-to-Vehicle (V2V) or from Vehicle-to-Grid (V2G). [3] Figure 4.8 shows a energy trading market scenario.

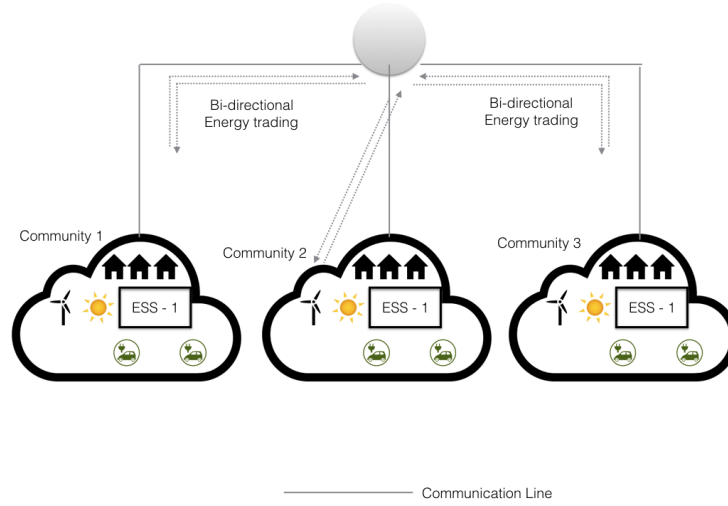


Figure 4.8: Generation Costs [3]

The energy trading scenario often includes multiple players who are trying to optimize their utility. For solving such games game theory especially in combination with auctions can help to find an optimal trading price and trading quantity. In the following step different auction approaches will be introduced.

In fact, there are two questions that needs to be answered within an auction matching game. For a coalition S , how can sellers be matched in an optimal way to buyers within the same coalition? To answer this question a suitable framework

is needed. Auction pricing is a popular game theoretic instrument that is used for demand and supply matching games. With auction games it is possible to study the interactions between a seller, who sells in this case power, and a buyer who needs additional power. In a next step, all participating players need an auction process to determine a price and the amount of good at which the trade will take place. Their strategies are defined through the price and the quantity they are willing to sell or buy. The end of an auction mechanism is characterized by an optimal quantity and price, that maximizes the players objective function. [28]

The work of Saad *et al.* [28] introduces the concept of a double auction. In every coalition S a double auction game is characterised by a group of sellers and buyers. The players strategies depend on the price at which the good will be traded. Therefore each player is looking for the optimal quantity and the optimal price so that at the end the objective function is optimized. [28]

Saad *et al.* studied the use of a double auctions in the plug-in hybrid electric vehicles (PHEV's) market. PHEV groups trying to sell part of their stored energy in a different energy market. The double auction mechanism shows the interactions between the PHEV groups and the smart grid distribution network. At the end of an auction a price has to be determined at which a buyer buys and a seller sells energy. [29]

Therefore, the authors defined a non cooperative game to model the competition between the PHEV groups that are willing to sell part of their produced energy. The non cooperative game consists of three main components. First of all there are the players, which have the roll of a seller. The second part is the strategy, which is for all players to sell their surplus of energy. The last part characterizes the utility function of each seller. It is defined through the benefits and the costs from selling their surplus. Costs could arise from discharging the batteries of the PHEVs' or from storage devices. [29]

In the work of Saad *et al.* [29] the concept of a double auction should determine a trading price and the trading amount. To optimize the sellers profits it is necessary

that each player truthfully reveals his reservation price, so that at the end of the game no player has the incentive to overbid or underbid his reservation price. This would lead to an outcome, which supports a truthfully bid report. [29]

The introduced double auction model can be now described in a few steps.

1. Order the sellers: In a first step all sellers are ordered in an increasing sequence of their own reservation bid. [29]
2. Order the buyers: Similar but in contrast to the first step, all buyers are ordered in a decreasing order of their reservation bid. If two sellers or two buyers have the same reservation bid, then they are aggregated into one virtual player. [29]
3. Supply and demand curves: After the ordering of sellers and buyers, the aggregated demand and supply curves can be generated and some intersection points will be found. At an intersection point a specific seller L and buyer M will be now found. [29]

To be able now to match the total supply and demand, a rule of the double auction indicates that $L-1$ sellers and $M-1$ buyers will participate at the trading market. In general this rule determines that sellers with an index of $i \leq L$ and buyers with an index of $k \leq M$ are allowed to join the double auction process. The authors state that a suitable trading price can be found in the range of $[s_L, b_M]$. Saad *et al.* define all sellers as indifferent between all buyers. This leads to the fact that the sellers utility is characterized only by the amount of energy. Therefore a potential seller has no interest in the identity of the buyer. [29]

At the end of an auction a tradeable quantity needs to be found. As described before the trade will occur at a specific trading price. There are now two scenarios that can occur from the players perspective. The first scenario concerns with an outcome where the total demand of all buyers exceeds the total supply. In this case every seller would sell the whole energy that it puts on the market. [29]

The second scenario deals with the assumption that the total supply exceeds the

total demand. In this case the sellers can not sell all of their energy. Therefore it is necessary that their oversupply is divided equally between the remaining sellers. To ensure that a seller sells a non-negative amount of energy, the process described above must be repeated. [29]

The proposed energy market game from Saad et al. can be solved by using the concept of the Nash equilibrium. In this specific energy trading market game the Nash equilibrium is defined as a state where no PHEV group can improve its position by unilaterally changing the amount of energy that it will put in the market. [29]

To find such an equilibrium the authors of [29] introduced a best response algorithm. This algorithm works in two separated steps.

1. Best response dynamics stage
2. Energy trading stage

At the first stage, each seller needs to choose an initial strategy. It is clear that in this round all sellers will choose that strategy where it can sell all of its energy surplus. Afterwards, the sellers participate in an iterative and sequential process where they have to choose a strategy for each turn. And similar to the assumption above, the sellers here will again choose its best response strategy. This process is continued until convergence is reached. After the suitable Nash equilibrium was found, the next stage is the actual energy trading process where the double auction mechanism starts. [29]

For a more practical approach, the authors introduced another use case. For the role as an auctioneer an energy company will be chosen. In general the auctioneer serves as monitor for all interactions between the PHEV groups. In addition it is equipped with two more functions. On the one side it should sort the sellers and buyers, as described above, in an increasing or decreasing order. On the other hand, at the best response dynamic stage, the auctioneer is responsible to inquire the strategies of the sellers at each turn. [29]

To summarize the work of Saad *et al.* [29], the authors introduced an interesting approach for solving the interactions between a group of PHEVs' and a smart grid. They solved the optimal price finding process by using the concept of a double auction model. Furthermore, they formulated a non-cooperative game between the PHEV groups, where each participating group defines as strategy, the amount of energy which should be offered on the trading market. In a next step each PHEV group will choose that strategy which optimizes their utility function. The proposed solution concept of the defined non-cooperative game, is then a Nash equilibrium. [29]

Another interesting approach of auction theory was introduced by Wijaya et al. in 2013. In their paper they presented the idea of cutting the peak to average ratio from the supply side. The corresponding loads are then distributed via a multi-unit auction to the customers. The work of the authors tries to correspond with the expectations of the future smart grid by matching the demand side with the supply side. [35]

The design of an electricity market is characterized by a supply side which should satisfy the conditions of the demand side. If the demand increases rapidly, additional high costs generators are needed to fulfil demand for short time periods. For this scenario Wijaya et al. presented a solution concept, where the USP is the explicitly cut of the PAR and the new distribution of the load with an auction system. [35]

Before introducing the model of Wijaya *et al.* some basic definitions are given. First, peak to average ratio (PAR) is a measurement which compares the peak with the average load. As auction system the author make use of an uniform price auction. One of the key characteristic of this method is, that: "*[...] each bidder pays the same price for each item/resource they win.*" [35] The price is then defined through the highest non-winning bidder. For the scenario that all winners pay a price of zero, the auctioneer can define at the begin a reservation price. In

other words a minimum price that each bidder needs to pay at least. [35]

After the winning bidders are defined the resource distribution starts. The following example gives an overview of the distribution process. A company A offers six units to the market. Now all bidders determine their bids and their needs.

- player 1 needs 2 resources and bid a total price of 12\$
- player 2 needs 3 resources and bid a total price of 10\$
- player 3 needs 3 resources and bid a total price of 8\$
- player 4 needs 1 resources and bid a total price of 6\$
- player 5 needs 2 resources and bid a total price of 5\$

The result of the auction is that player 1 gets two resources, player 2 gets three resources and player 3 gets also one resources. Each player has to pay 6\$ for one resource. In the case of player 3, where only a part of the load can be received, the player can now decide to take the deal or to withdraw. [35]

As described previously the authors of [35] make use of a multi-unit auction model. The presented model of Wijaya *et al.* works similar to the example above, but has some extra modifications. It can for example happen, that at a specific time slot t a customer do not get any load. This happens if other bidders won the whole energy before. For this scenario the authors build a condition where each consumer at least gets a minimal amount of load. To protect the companies from getting paid a price of 0, a minimum reservation price was defined. [35]

In general, the auction process could run over multiple rounds. This is relevant for the case, that not all loads are distributed in one single round x . In the next round, $x+1$, only the loads from x are distributed. For each round the winners are determined and the auction only ends if no loads are longer available. [35]

The authors made also a proof to fulfill the conditions of truthful bidding. With truthful bidding no consumer has the incentive to lie about their valuation. [35]

For the proof two different situations are now analysed.

1. The load available on the market is larger than the required load of the agent. For this case the agent will definitely bid on it. Now there are two outcome scenarios of the auction process. [35]
 - (a) The agent won't win. If he chooses to bid a smaller price than her valuation for the load in time slot t ($v_i(t)$), he will not make the deal. Otherwise if the agent bids higher than $v_i(t)$, he could win but could also pay a price which is higher than $v_i(t)$. The agent will then lose this case, because he pays a higher valuation price than expected. [35]
 - (b) The agent will win. If the price to pay for the required loads is defined with v' and the agent bids b' , and $v' \leq b' < v_i(t)$, then he has to pay v' . In the case of underbidding v' , he will lose the auction. If he chooses to overbid he won't get any benefits for a higher price, because he still has to pay v' for it. [35]
2. The load available on the market is smaller than the required load of the agent. In this case the agent chooses a different time slot, which is close to t . t' then fulfill the load requirements of the agent. Afterwards, one of the above described cases are applied. [35]

In the following, the authors presented a proof for the consumer's load shifting. The authors consider the fact that a consumer is interested in obtaining his load for specific time slot t' . If there are no loads available, he can bid for a different time slot t'' . And if he wins the auction he is allowed to shift his energy consumption from t' to t'' . [35]

The utility for a consumer is defined through two properties:

- costs
- shift percentage

Wijaya *et al.* used the concept of auction to reduce the overall costs by increasing the PAR cut percentage. In addition they showed that consumers with lower valuations has a higher shift percentage than consumers with higher valuations. At the end, they also mentioned that the total electricity costs for the consumers are lower in comparison to the original generated energy costs. [35]

H.Bosetti *et al.* presented a survey of illustrations and limits of game theory for energy system. One section deals with auction games in energy markets. They introduced a single auction game theoretic approach to demonstrate a straight forward concept of finding a Nash equilibrium within an auction game. [4]

A single round auction is characterized by three players. Two of them are on the supply side, also known as sellers, whereas the third player is defined as a buyer and represents the demand side. The buyers main activity is to buy electricity at a specific maximum acceptance price. Both sellers can produce a surplus of electricity and can so supply additional energy to the buyers. For the generation both producers have costs of c_1 and c_2 . [4]

The resulting bid prices are defined such that:

$$c_1 < p_1 \leq P$$

$$c_2 < p_2 \leq P \text{ and}$$

$$c_1 < c_2$$

The mechanism of the auction works in a similar way as other auction games above. First, the seller gives a signal that he is willing to sell energy on the market. In a next step, the buyer chooses a price and announces a first bid. In general, buyers bid for some extra energy if they can not satisfy their own demand or if they want to buy additional energy for economical reasons. After the bidding process is done, the sellers choose buyers according to their specific bids. [4]

The authors presented a numerical approach to find a Nash equilibrium and a Pareto optimal point at an auction game. The game consists of two companies G_1 and G_2 . Both sellers have costs of $c_1 = 5$ and $c_2 = 7$. The buyers acceptance price P is at $P = 11$. [4]

The strategy set for p_1 is: $\{7,8,9,10,11\}$ and for p_2 : $\{8,9,10,11\}$. The respective profits are defined as u_1 and u_2 . [4]

- $u_1 = G_1$ wins the auction $= p_1 - c_1$, $u_2 = 0$;
- $u_2 = G_2$ wins the auction $= p_2 - c_2$, $u_1 = 0$;
- G_1 and G_2 tie the auction $= (p_1 - c_1)/2$, $(p_2 - c_2)/2$;

		P2			
		8	9	10	11
P1	7	(2, 0)	(2, 0)	(2, 0)	(2, 0)
	8	(1.5, 0.5)	(3, 0)	(3, 0)	(3, 0)
	9	(0, 1)	(2, 1)	(4, 0)	(4, 0)
	10	(0, 1)	(0, 2)	(2.5, 1.5)	(5, 0)
	11	(0, 1)	(0, 2)	(0, 3)	(3, 2)

Table 4.1: Payoffs for the auction game

[4]

Table 4.1 gives an overview of the payoff values u_1 and u_2 . Using general game theoretic techniques for finding a Nash equilibrium it can be seen that at $p_1 = 7$ and $p_2 = 8$ no player can improve its payoff by changing to another strategy. Furthermore $p_1 = 11$ and $p_2 = 11$ demonstrate a situation where no player can improve its payoff without downgrading the payoff of the other player. This state is also known as Pareto optimal point. In the described case above the buyer will then buy energy from company₁, because of the lower energy price. [4]

4.4 Communication technologies

For a smart grid communications technologies are an essential part to provide reliable information flows between different participants. The following sections deal with a game theoretic approach for communications technologies.

In general, elements of a smart grid have different communications partners. Smart meters need to exchange important data with the utility company control center. On the other side, a smart meter also needs to exchange data with the control centers of its neighborhood, to send pricing data, read meter data or other control other types of data. [28]

A further approach of a smart grid communication is the information flow from a plug-in hybrid electric vehicle to the main grid. Several research works presented the concept of a two way communication between these two elements. In most cases it was used for diagnosis or vehicle roaming. The popular communication technology concepts are power line or wireless communication. [28]

For example power line communication(PLC) is often: “[...] *considered for deployment by utility companies around the world of smart metering, load control, or other applications.*” [28]

On the other hand, different communication approaches, for example cognitive radio, proposed wireless networks as the main network technology. [28]

In general, a future smart grid needs to integrate a myriad of communications technologies that work together in an efficient way. The junction of these networks increases the network design and analysis complexity. Therefore, game theory is a useful tool to proof the efficiency of wireless and wireline communication. [28]

In the following the work of Saad *et al.* introduced a network formulation game for multihop narrowband PLC communication between the elements of a smart grid. [28]

PLC is as described above one suitable solution for large scale networks like a smart grid. However, PLC does have reliability problems and that is the moti-

vation to investigate alternative communication technologies. Furthermore, PLC tries to face technical challenges such as channel modelling, data transmission or network planning. [28]

Although these challenges exist, narrowband PLC is a preferred solution for smart grid elements. In Europe it is widely implemented for deploying advanced metering infrastructure. One of the biggest problems of narrowband PLC is its limited channel capacity with increasing communication distance. The limited capacity was the starting point of developing intelligent algorithms that solve this problem and is so an important enabler for smart grid applications. [28]

The game theoretic model consists of M connected smart grid elements. A smart grid element can be any object that consists of any communication element like a smart sensor. The main task for a smart grid element is to send important data to a common access point (CAP). Data could consist of pricing inquiries, load reports or control data. A control point can be a general control center of a grid operator or a repeater that is responsible for transmitting data to other parts of the smart grid. By using narrowband PLC the communication is enabled over a specific frequency. In Europe the maximum frequency is 148.5 kHz, whereas in the United States the limit is at 500 kHz. [28]

During the communication process between a smart grid element and a CAP, a capacity $C_{i,CAP}^K$ is transmitted. [28]

- i...Smart grid element
- k...Frequency
- CAP...Access point
- C...Capacity

As it was said before, the capacity is only suitable for small distances and can decay with increasing communication distance. One consequence of this limited

capacity is an increasing delay during the communication between the smart elements and the CAP. Therefore, it is of big interest to design an architecture that allows smart grid elements to use narrowband PLC, send their data and expect reasonable delays. [28]

Saad *et al.* proposed multihop power line communications as a solution concept. With multihop PLC smart elements can use PLC to communicate with the control center, the utility company or with other elements. [28]

The main question of the multihop PLC technique is to find a suitable next hop to optimize the delays of the smart elements. To find an optimal solution for his problem Saad et al. introduced a network formulation game. [28]

A network formation game is defined by a situation where: "[...] a number of players need to interact to decide on the formation of network graph among themselves." [28] In a smart grid environment where the elements use multihop PLC, a network formation game consists of M smart elements who communicate over a communication tree structure with the CAP. For this game the authors make the assumption that all participating elements are physically interconnected so that PLC can be used without problems. [28]

Within this game each smart element will find and choose a path that minimizes its transmission delay. The resulting cost function for each player $i \in M$ is defined as:

$$c_i(G) = \sum_{(i_l, i_{l+1}) \in q_i} \tau_{i_l, i_{l+1}}^* \quad [28]$$

- $q_i = i_1, \dots, i_L$ shows the multihop path from an smart element i to the CAP. [28]
- $\tau_{i_l, i_{l+1}}^*$ defines the delay which occurs during the transmission from an element i_l to another smart element i_{l+1} [28]
- the delay is given by: $\tau_{i_l, i_{l+1}} = (R \cdot L_i) / (C_{i_l, i_{l+1}}^K)$ where L_i is the number of packets of R bits that a smart element needs to transmit. $(C_{i_l, i_{l+1}}^K)$ defines

the capacity that can be send via a channel k with a narrowband PLC transmission from one smart element to another. [28]

For this game Saad *et al.* defined the rule that each smart element can only accept a specific number of connections. This is because of a limited capacity of available frequencies and amounts of bandwidth. Now each player's objective is to find an optimal partner that will transmit its packets. [28]

It is important to note that each smart element will act on its own. If element A finds an optimal partner B , then A will not coordinate his choice with any other players who could be involved, in a positive or negative way, by his choice. [28]

Although a network formation game has a cooperative characteristic, the authors preferred a non cooperative solution. In a non cooperative game the players strategies are defined through the next hops. [28]

A smart element chooses its next hop by using best response dynamics, so that the next link will minimizes the above defined delay. [28] For a network formation game, a Nash equilibrium is a network where: "[...] *no smart element can improve its delay by changing its chosen path.*" [28]

Figure 4.9 gives an example of a network formation game.

The graphic shows a network with $M = 10$ smart elements. In this game there are smart elements, for example 3 and 9 who prefer to communicate directly with CAP instead of using a multihop. This is the result of their close position to the CAP. On the other side there are smart elements, such as 6 and 7 which can achieve a better delay by using a multihop link. [28]

The results presented by Saad *et al.* show that this network is a Nash network. No smart element has the incentive to change its current link. For example smart element 6 could disconnect from element 5 and connect to one of the other available smart elements. In each case the authors of [28] show that the delay from element 6 will increase. They also demonstrated that the average delay per smart element can be reduced by using multihop powerline communication. [28]

In general communication technologies such as PLC or wireless communication

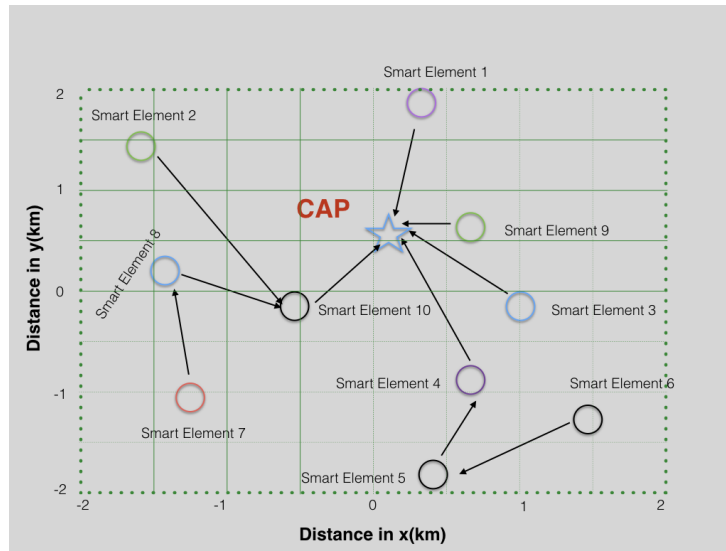


Figure 4.9: Nash network - Network formation game [28]

have an huge impact to smart grids. Especially multihop PLC that was introduced above is a promising technique to reduce the overall delay of transmission and also enables advanced metering functionality. Furthermore, a reliable communication network is the basis for a demand side management, a microgrid or a trading process. A communication network is also responsible for the efficiency of a smart grid. By using the concept of game theory different future communication architectures, such as cooperative networking or cognitive radio could be proved. [28]

This chapter gave an overview and introduction of the applications of game theory in smart grids and tried to show the huge potential of game theory as solution concept for this area. The literature survey consists of different scientific approaches for demand side management, microgrids, energy trading or communication networks. For each section different approaches for non cooperative or cooperative games were used.

Chapter 5

Game Design & Implementation

This chapter deals with the implementation of a Game theory simulator as well as with the design of Cournot games. First of all, the functionality and the structure of the implemented simulator is described. Afterwards, the design and definition of a Cournot game on a local energy market is proposed.

5.1 Implementation

Before the development of the simulator started, the idea was to use a modelling software that includes game theoretic behaviour. There are just a few tools available that are specialised for the energy market, which offer also a lot of functionality. But most of them have more advantages for consulting firms or governmental agencies to make predictions for the development of the future energy demand, than testing game theoretical models. This was the main reason to develop a game theoretic simulator.

For this thesis a tool was needed, where non cooperative games can be defined and executed. That was the starting point of the implementation of a the following simulator.

For the implementation of this simulator Java was used as programming language. It was used because it has some advantages in development over other program-

ming languages. Java programs are robust, have a good performance and the object oriented character helps to understand the language easily. In addition, there are many available API's to be able to get faster results. For the whole coding process Eclipse Mars was used as development environment.

The basic idea of the application was to simulate non cooperative games on a local energy market. Therefore, the Nash equilibrium was chosen as the main solution concept. In addition, the solver is able to find dominant strategies of each player as well as a dominant strategy equilibrium if it is available. In a second part, the simulator makes an economic analysis for all players with corresponding recommendations.

For the start of the computation process the simulator needs a few input data, which needs to be done manually. First of all, the simulator needs the number of players and its strategies. After the data input is complete the program can create automatically strategy profiles and the corresponding payoffs for each player. A detailed description is given in the next section.

The simulator was designed in a way that n-persons with n-strategies can be defined and executed. The more strategies and players the higher is the complexity of the game. In general, the possible strategy profiles are calculated as n^m , where n is the number of strategies and m the number of players. The number of the corresponding possible profile payoffs are defined through $n^m * m$.

In addition to the analysis of the game results, data about the execution time of the simulation process is collected to get also results of the efficiency of the simulator with increasing complexity.

The architecture of the proposed solver is divided in three different java scripts. *Main.java* includes all input data, which are necessary for the game setup. Input data are typically the number of players or all different possible strategies. The class is responsible for the execution of the main function and the display of the simulation results.

The *simulator.java* file is responsible for the construction of a non-cooperative game as well as for the computation of dominant strategies and Nash equilibrium.

This script does also execute the economic calculation of the game.

The third file, *profile.java* includes important helper functions, which are needed for the construction of a game and for the finding of a Nash equilibrium. In addition, *profile.java* does make the economic computation based on input data and defined formulas in the class.

5.2 Functionality of the Simulator

This section describes now how the simulator actually works. Therefore, some pseudo code is presented to get a smart overview of the application.

In a first step the game setup must be created. In order to start this process, the number of players and the strategies are required. Afterwards the game can be created.

The possible profiles are calculated through the number of players and the number of strategies. All possible profiles are then saved into an array. For each player in this game the corresponding payoff for a specific profile is calculated through a defined formula.

Payoff $u = p * q$

Price $p = x - i * q$.

As it can be seen the price is defined via a demand function where x and i are constant parameter. By the time that all profiles are equipped with specific payoffs the game creation process ends.

Algorithm 1 Game Creation Process

Precondition: Number of players and number of strategies are entered**procedure** CREATE POSSIBLE PROFILES $n \leftarrow \text{Numberofplayers}$ $m \leftarrow \text{Numberofstrategies}$ $z \leftarrow \text{Numberofstrategyprofiles}$ **for** $i \leftarrow 0$ to x **do***Create an entry of profile with size n in Profiles array***function** CHANGEPROFILETYPE(0, n)**end function****end for****for** $i \leftarrow 0$ to Profiles.length **do** $\text{payoff} \leftarrow \text{Profiles}[i].\text{getPayoff}[\text{player}]$ *Save payoff for each player for a specific strategy profile***end for****end procedure**

After the input process was successful the Nash equilibrium calculation starts. In general this function is executed for each player in the game. Each possible profile, which was created before, is now compared. This means that for a player i a profile with its corresponding payoff is taken and checked against the other strategies of player i . For example, if there are three players, a possible strategy profile could look like this: $\{ 1 \ 1 \ 1 \}$.

Now for player1 the value for strategy 1 from the above profile is saved and compared to the payoff values for the profiles $\{ 2 \ 1 \ 1 \}$ and $\{ 3 \ 1 \ 1 \}$. If then the value of the profile $\{ 1 \ 1 \ 1 \}$ is higher than both of the others, strategy1 is marked, otherwise this profile is skipped because it can not be a Nash equilibrium. This process is then repeated for all profiles.

Algorithm 2 Nash Equilibrium

Precondition: Number of players and number of strategies are entered**procedure** CREATE POSSIBLE PROFILES $u \leftarrow 0$ $payVal \leftarrow 0$ **for** $i \leftarrow 0$ to $NumberOfPlayers$ **do** **for** $j \leftarrow 0$ to $NumberOfProfiles$ **do** $u \leftarrow$ payoff of player i for strategy profile j $payVal \leftarrow$ payoff of player i for strategy $j+1$ **if** $u > payVal$ **then** mark strategy from profile j of player i **end if** **if** $u < payVal$ **then** go to next strategy profile **end if** **end for** *Save profile index of a Nash equilibrium* **end for****end procedure**

The next functionality deals with finding dominant strategies and a possible dominant strategy equilibrium. In theory a dominant strategy is a strategy that a player always chooses regardless which strategy his opponent takes because it always gives him the best payoff. A dominant strategy equilibrium occurs where each participant selects his own dominant strategy. This simulator tries to find a dominant strategy in a similar way to the above described Nash functionality.

First of all, for each player all possible strategy profiles must be compared to find a possible dominant strategy. In general, for a player i a strategy profile j is taken to find the best answer in this moment. The index of the best strategy is then saved in a new arraylist. If the list contains only the same strategy then a player

has a dominant strategy. This step is repeated for each player. If each player has a dominant strategy, then the simulator also found a dominant strategy equilibrium.

Algorithm 3 Dominant Strategy

Precondition: Number of players and number of strategies are entered

```

procedure FIND DOMINANT STRATEGY
   $u \leftarrow 0$ 
   $payVal \leftarrow 0$ 
  for  $i \leftarrow 0$  to  $NumberOfPlayers$  do
    for  $j \leftarrow 0$  to  $NumberOfProfiles$  do
       $u \leftarrow$  payoff of player  $i$  for strategy profile  $j$ 
       $payVal \leftarrow$  payoff of player  $i$  for strategy  $j+1$ 
      for  $k \leftarrow 0$  to  $Strategy.length$  do
        if  $u > payVal$  then Save strategy index of  $u$ 
        end if
        if  $u < payVal$  then Save strategy index of  $payVal$ 
        end if
      end for
       $dominantStrategy \leftarrow Profiles[index].addStrategy$ 
    end for
  end for
end procedure

```

The last part of the simulator deals with the economic computation of the model. For this part a new player, the government, is added. The economic analysis deals with the question which form of financial support is better for the government. For each Nash equilibrium the total investment and yearly subvention costs are calculated. For the government an economic recommendation will be done based on a specific time horizon.

In addition, the simulator calculates data about the inhabitants profit, the return rate and the amortisation time. At the end of the calculation each producer also can get an economic recommendation.

5.3 Game Design

In this chapter the concept of Cournot is used to define a non cooperative game between different energy producer in a local energy market.

5.3.1 System Model Cournot Game

A graphical overview of all participants in an energy model can be seen in the following figure 5.1.

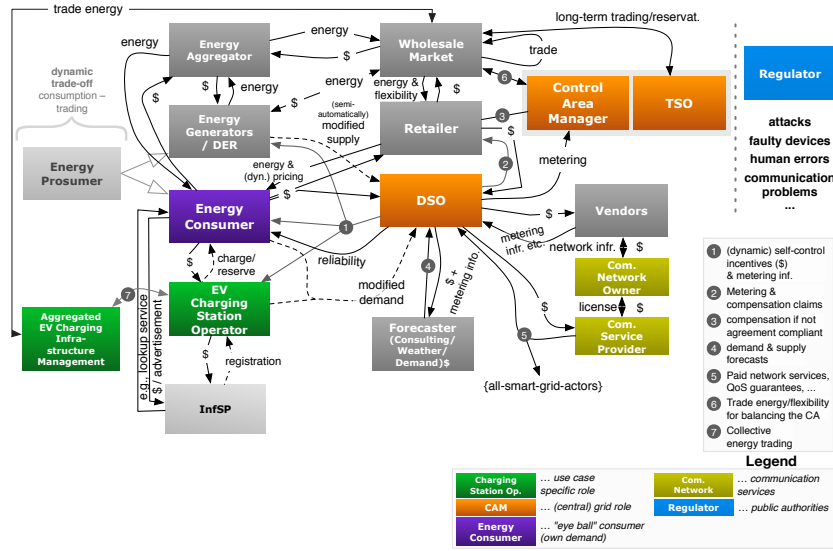


Figure 5.1: Players in a Smart Energy Market [9]

The market model is characterized by lot of different player interactions. This thesis set the focus on the relationship between *retailers* and the *wholesale market* as well as between *retailers* and the *government*. More specific, the competition

between different energy producers is simulated. The best concept for simulating a model where different generators sell the same product, in this case the product is energy, is the Cournot model.

A Cournot game is characterized by an industry demand curve, which has the property of a downward slope. Multiple producers, also called industry, compete on a market with a similar product. Their strategies are defined through the quantity they are willing to sell on the market. [21]

Figure 5.2 shows a demand curve of a Cournot model that has the main characteristic of a downward slope.

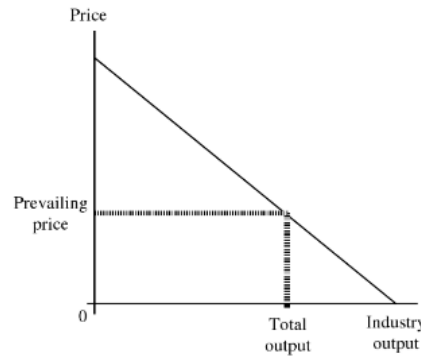


Figure 5.2: Demand Curve of Cournot Model [21]

In general, there are two common interpretations for the demand curve. First, the price which predominates in the industry is given through the total output of all producers and its corresponding point on the curve. Second, if the prevailed price is given the distance from the vertical axes through the demand curve defines the maximum quantity that can be sold on the market. [21]

Before the simulation process can start, the Cournot model is described in a formal mathematical way.

The demand function is defined as $p = a - bQ$ with $Q = q_1 + q_2 + \dots + q_n$.

As it was said before, the strategies are the amount of a product a player will sell on the market. Thus, a competitor on the energy market chooses a specific

quantity of energy which he is willing to sell.

For this game simulation the assumption of complete information is taken. The costs c are the charge for the production of one unit energy. [32] It is assumed that they have always a positive value: $c_{tot} = cq_i \geq 0$

The main goal for a player is to maximize its utility function or in this case its profit π . Now a formal derivation of the payoff is given. [32]

$$\begin{aligned}\pi_i(q_i, q_j) : \\ &= pq_i - cq_i = (p - c)q_i \\ &= [x - y(q_i + q_j)]q_i - cq_i \\ &= xq_i - yq_i^2 - yq_iq_j - cq_i\end{aligned}$$

A well known solution concept for a Cournot game is a Nash equilibrium. As it was described before, each player chooses its best strategy that will maximize its payoff. Now a formal approach will help to find a solution for a Nash equilibrium. [32]

$$\max \pi_i(q_i, q_j)$$

Assuming now q_i to Producer A:

$$\frac{\partial \pi_1}{\partial q_1} = x - 2yq_1 - yq_2 - c = 0$$

Now the same procedure is done for Producer B:

$$\frac{\partial \pi_2}{\partial q_2} = x - yq_1 - 2yq_2 - c = 0$$

The corresponding Nash equilibrium can be found by setting both equations equal to each other.

$$\text{NE} : q_1 = q_2 = \frac{x-c}{3y}$$

In a next step the solution of q can be used to find a outcome for p and for the profit π .

$$p = \frac{(x+2c)}{3}$$

$$\pi = \frac{(x-c)^2}{9y}$$

One assumption of the proposed Cournot Game model is the perfect information condition. In other words, a Player i chooses its best response strategy on information of the strategy of a Player j . In a formal way the best response conditions can be solved with the above defined first order conditions for q_1 and q_2 . [32]

$$B_{\text{response1}} : q_2 = \frac{(x+2c)}{3} - 2q_1$$

$$B_{\text{response2}} : q_1 = \frac{(x-c)}{2y} - \frac{1}{2}q_1$$

In order to test the Cournot model with the proposed Simulator a numerical experiment is described in the next section.

5.4 Game Formulation

5.4.1 Cournot Game

A non cooperative Cournot game on the energy market can be formalised as 3-tuple: $M = (n, S, u)$

- $n \in \mathbb{N}$ is the number of players that competes against each other in the game;
- S is the set of actions each participant can choose from;
- $u : X \rightarrow \mathbb{R}^n$, $X = \{ (x_1, x_2, \dots, x_n) \mid x_i \in S \}$

For the first part of the simulation the basic concept were taken from the *IEEE 30 - Bus Test System* [7,8]. Figure 5.3 shows the basic structure of the *IEEE 30 - Bus Test System*.

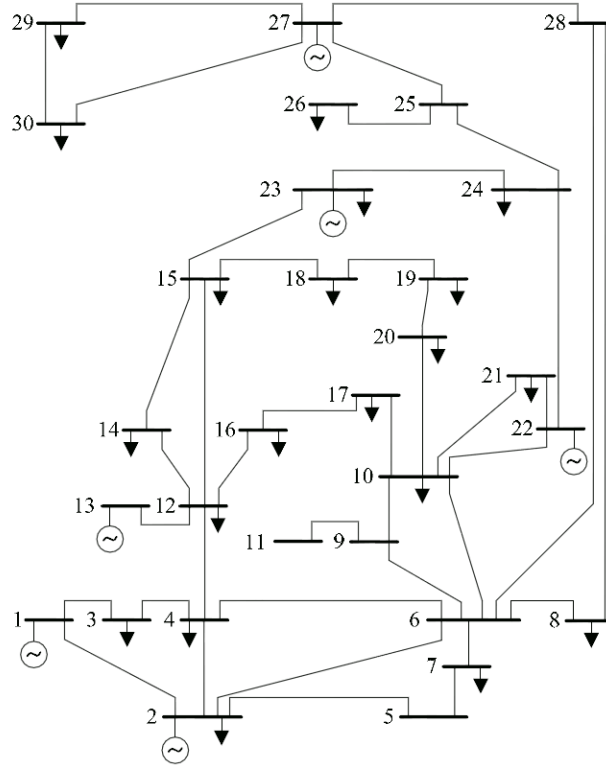


Figure 5.3: 30-Bus IEEE Test System [7]

For the game setup some assumptions were made. First of all, the game takes place in a small fictive neighborhood, where some of the inhabitants invest in solar energy technology for selling additional energy on a local market. The investments lead to a new local energy market where residents compete against each other to sell their additional produced energy. Each competitor on the market has a specific number of energy generators with different start up costs. In addition, each resident is only allowed to produce a specific amount of energy with its generators. If the limit is exceeded the producer must pay a penalty fee. Table 5.1 shows the general distribution of the generators with their corresponding limits. Table 5.2 displays the different penalty categories.

Player	Generator #	$P_g^{\max}$	$P_P^{\max}$
		[MW]	[MW]
A	1	20	20
B	2	18	30
	3	12	
C	4	17.5	35
	5	7	
	6	10.5	
D	7	25	25
E	8	17.5	35
	9	17.5	
F	10	25	25
G	11	18	30
	12	12	
H	13	35	35
I	14	18.8	37
	15	22.2	
J	16	21	35
	17	7	
	18	7	

Table 5.1: Market Model

Category	Range	Penalty
<i>1</i>	[20 - 25 MW]	400
<i>2</i>	[26 - 30 MW]	600
<i>3</i>	[31 - 35 MW]	800
<i>4</i>	[36 - 40 MW]	1000

Table 5.2: Penalty Categories

Generator #	$c_i[\text{€}/MW^2]$	$d_i[\text{€}/MW]$	$e_i[\text{€}]$
1	0.04	2	200
2	0.04	1.75	140
3	0.125	1	120
4	0.03194	1.354	220
5	0.03194	1.354	135
6	0.03194	1.354	150
7	0.03194	1.354	240
8	0.0166	3.25	275
9	0.0166	3.25	130
10	0.0166	3.25	380
11	0.05	3	290
12	0.05	3	230
13	0.05	3	400
14	0.0125	1	270
15	0.0125	1	300
16	0.06	2.5	500
17	0.06	2.5	250
18	0.06	2.5	250

Table 5.3: Generator Costs

The general costs for each generator consists of production costs $[c_i, d_i]$ and start up costs $[e_i]$ which can be seen in detail in table 5.3. The cost information from [8] were slightly changed and extended to fit better for this simulation process. In addition data for penalties and number of generators are assumed to be random. The strategy of each resident is the quantity of energy which he is going to sell on the market. In this game setup each player can choose from three different quantities. In the following listing the Cournot setup is described in a formal way supplemented with numbers.

- $N = \{A, B, C, D, E, F, G, H, I, J\};$
- $S = \{20, 30, 40\};$
- $C_i = \frac{c_i}{2} P_{gi}^2 + d_i P_{gi} + e_i$
- $u_i = p x_i - C_i$
- The industry demand function has the following structure:
 - $Q = 189,2 - 0,66p$
 - $p = 378,4 - 1,5Q$

The simulations process consists of different simulations levels. Each simulation level has a different number of participating players. The difference in the size of the competitors should give an insight of the development of the market share and the profits of each resident if more competitors enter the market.

The main goal of the first simulation round is a non-cooperative Nash-Cournot equilibrium solution. The solution should consist of a distribution of the energy quantity and a sales calculation for each player, so that no player has the intention to change his chosen strategy.

After the Nash equilibrium calculation is done, the economic part of the simulation starts. Therefore a new player, the government, joins the game. From the resident view each of them should have the chance to get a financial aid for using

and supporting renewable energy and smart technologies. For a government it is interesting to know whether it is better to fund the start investment of the solar generators or to pay a yearly financial aid for the produced quantity of energy. In general data for financial aids and investments costs were taken from the Internet [10, 25] and slightly adjusted. Table 5.4 gives an overview of the investment costs and calculation of financial aids.

Player	Generator Investment Costs x	Service Costs [per year]	Financial aid per MW[in €]
A	15000	$0.015 \cdot x_i$	30
B	40000	$0.015 \cdot x_i$	30
C	75000	$0.015 \cdot x_i$	30
D	15000	$0.015 \cdot x_i$	30
E	50000	$0.015 \cdot x_i$	30
F	15000	$0.015 \cdot x_i$	30
G	40000	$0.015 \cdot x_i$	30
H	25000	$0.015 \cdot x_i$	30
I	50000	$0.015 \cdot x_i$	30
J	75000	$0.015 \cdot x_i$	30

Table 5.4: Investment Costs and Financial Aids

During the economic analysis the simulator calculates for each resident the time of amortisation, the profit and the return rate. For the government the investment and subvention strategy is compared and analysed to make afterwards a strategic political recommendation. The economic analysis is always calculated for a different time period t which depends on the durability of the solar energy generators. Different assumptions for t are made to point out the different strategy choices of a government for different time periods. The results also show the development of the return rate and the profit of each resident.

The simulation process should answer in general the following question:

1. Does more competition or in other words more players on the energy market have a strong impact on the participants profit?
2. How does the Nash equilibrium changes if more players compete against each other?
3. How does the strategy selection varies if more players are on the market?
4. How does the strategy recommendation for a government changes within different time calculation periods t ?

The simulation is done with different numbers of players to manifest the fitness of the simulator with increasing complexity. It is also important to note that this experiment consists of fictive players and strategies and therefore no explicit predictions will be done. The numerical experiment has three different levels of simulation and complexity.

1. Three players compete on an energy market with three different strategies of quantities;
2. Six players compete on an energy market with three different strategies of quantities;
3. Nine players compete on an energy market with three different strategies of quantities;

Chapter 6

Results & Analysis

The following chapter deals with the presentation of the results of the simulation process. For each simulation level the results are saved in table form to get a better overview.

6.1 Simulation & Results Level 1

For the first simulation round the simulator is configured with three players and three strategies.

- $N = \{A, B, C\};$
- $S = \{20, 30, 40\};$

The first simulation round found a Nash equilibrium where all three players produce the quantity of 40 *MW*. In addition, the Nash equilibrium is also a dominant strategy equilibrium which can be seen in table 6.3. Player 2 has the highest sales outcome per year in comparison to the other competitors. This advantage can also be seen in figure 6.1, where the distribution of the market share is illustrated.

Nash Equilibrium	Player	Strategy	Sales [€]
1	A	40	4680.00
	B	40	6754.48
	C	40	6515.284

Table 6.1: Nash Equilibrium Simulation Round 1

Simulation Round	Player	Dominant Strategy	Dominant Strategy Equilibrium
1	A	40	[40;40;40]
	B	40	
	C	40	

Table 6.2: Dominant Strategies

Table 6.3 show the results if the government decides to choose the subvention model. It shows that in comparison to the above results Player 3 has now the highest yearly income. Furthermore, it can be said that in most of the different time periods for all producers it is better to take the subvention instead of the first investment aid. For the government the decision is not always 100% clear. Table 6.5 and figure 6.2 show that for a subvention case over 15 years the government should prefer the investment strategy.

Nash Equilibrium	Player	Investment costs[€]	Financial Aid [€/year]	Profit [€/ year]	Armoti-sation Time[years]	Return rate [in %]
1	A	15000	1200	5655	2.55	39.2
	B	40000	2400	8554.48	4.36	22.8
	C	75000	3600	8990.28	7.41	13.4

Table 6.3: Economic Analysis - Subvention Model

Nash Equilibrium	Player	Investment Costs	Profit [€ /year]
1	A	0	4455.0
	B		6154.48
	C		5390.28

Table 6.4: Economic Analysis - Investment Model

t	Total investment costs[€]	Total subvention costs [€]	Strategy Recommondation
5	130.000	36.000	Subvention
10	130.000	72.000	Subvention
15	130.000	108.000	Subvention
25	130.000	180.000	Investment

Table 6.5: Strategy Selection Government

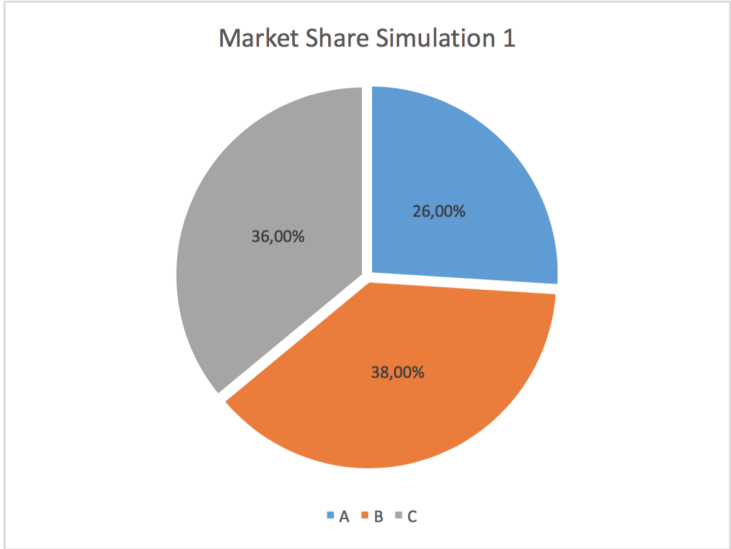


Figure 6.1: Market Share Round 1

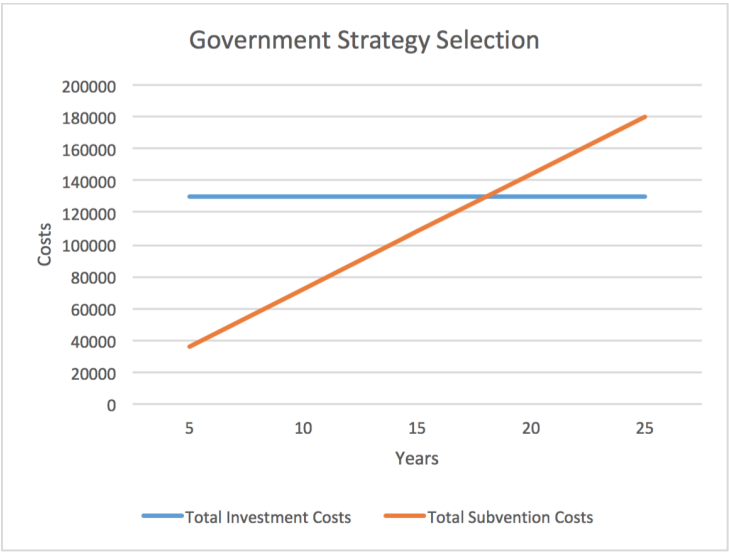


Figure 6.2: Comparison Investment vs. Subvention Strategy

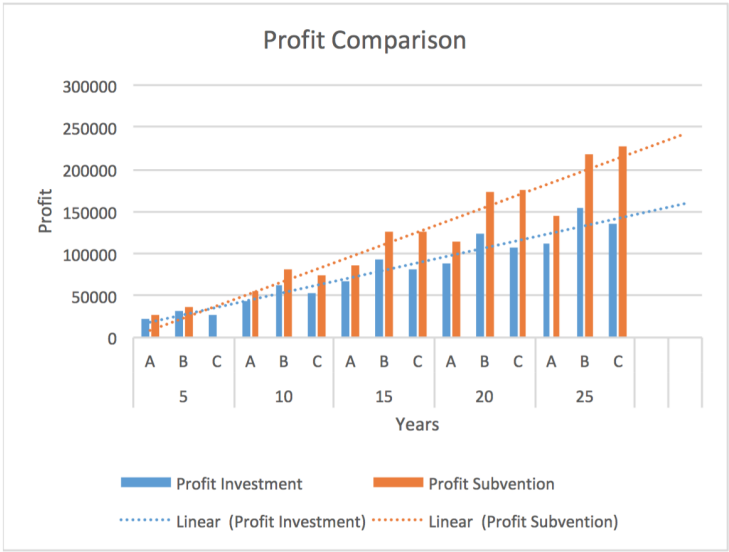


Figure 6.3: Profit Development with different government scenarios

6.2 Simulation & Results Level 2

For the second simulation round the local energy market has now six energy producers. All other assumptions are the same like before.

- $N = \{A, B, C, D, E, F\};$
- $S = \{20, 30, 40\};$

The model of the simulation round 2 successfully found a Nash equilibrium. The strategy selection and corresponding payoffs of each player can be seen in table 6.6. In comparison to the first round no dominant strategy equilibrium could be found and also only player F has found a dominant strategy. More players on the market leads to lower generation quantities for most of the competitors. Figure 6.4 displays the new proportions of the market shares.

Nash Equilibrium	Player	Strategy	Payoff[€]
1	A	20	1520
	B	30	2921.02
	C	30	2688.92
	D	40	3241.74
	E	30	2733.77
	F	30	2272.74

Table 6.6: Nash Equilibrium Simulation Round 2

Simulation Round	Player	Dominant Strategy	Dominant Strategy Equilibrium
2	A	-	No dominant equilibrium
	B	-	
	C	-	
	D	-	
	E	-	
	F	30	

Table 6.7: Dominant Strategies

In the case of the subvention model the amortisation time increases in comparison to the first round which is also a consequence of the lower yearly profit. Figure 6.6 show that for all players instead of *D* and *F* the investment model is a better choice within a calculation time of five years. For a time period of 15 years all players would prefer the subvention model to the investment scenario. The result differs from the first round by the fact that more players on the market increases the time for finding a common scenario which would be suitable for all producers.

Nash Equilibrium	Player	Investment costs [€]	Financial Aid [€/year]	Profit [€/ year]	Armoti-sation Time[years]	Return rate [in %]
1	A	15000	600.0	1895.0	7.0	14.13
	B	40000	1800.0	4121.02	8.4	11.8
	C	75000	2700.0	4263.92	13.9	7.1
	D	15000	1200.0	4216.74	3.37	29.6
	E	50000	900.0	2883.76	13.75	7.2
	F	15000	1800.0	3847.74	3.68	27.1

Table 6.8: Economic Analysis - Subvention Model

Nash Equilibrium	Player	Investment Costs	Profit [€ / year]
1	A	0	1520.00
	B		2921.02
	C		2688.91
	D		3241.73
	E		2733.76
	F		2272.74

Table 6.9: Economic Analysis - Investment Model

t	Total investment costs[€]	Total subvention costs [€]	Strategy Recommondation
5	210.000	45.000	Subvention
10	210.000	90.000	Subvention
15	210.000	135.000	Subvention
25	210.000	225.000	Investment

Table 6.10: Strategy Selection Government

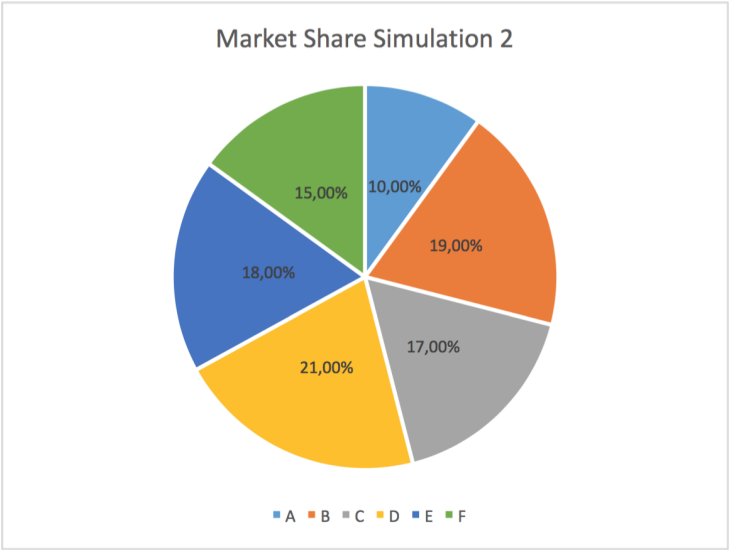


Figure 6.4: Market Share Round 2

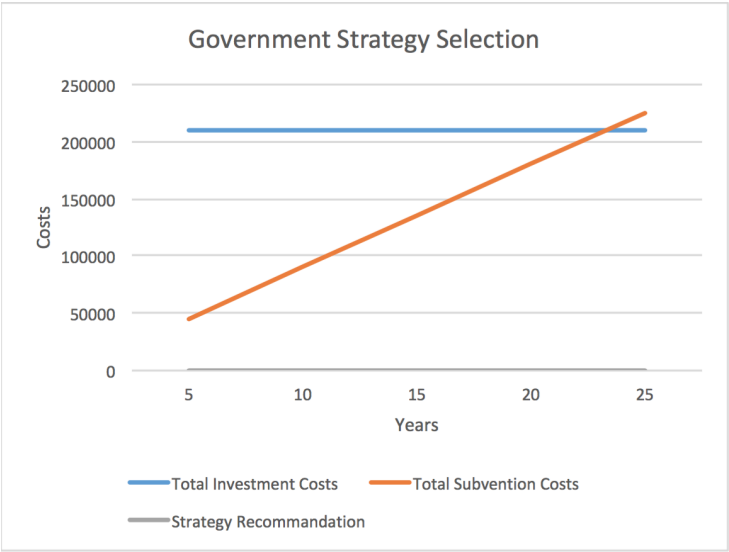


Figure 6.5: Comparison Investment vs. Subvention Strategy

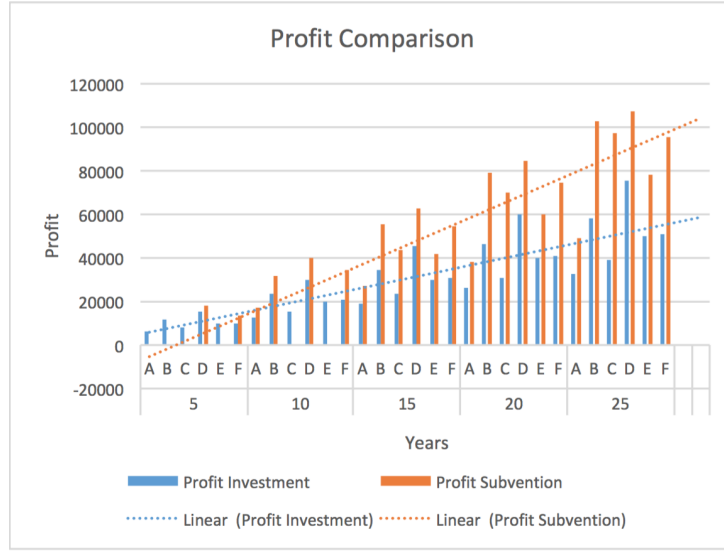


Figure 6.6: Profit Development with different government scenarios

6.3 Simulation & Results Level 3

The last simulation round has nine different actors which are competing against each other on a local energy market. This section also covers the results of the different execution times, the return rates and also the amortisation times.

- $N = \{A, B, C, D, E, F, G, H, I\};$
- $S = \{20, 30, 40\};$

The last simulation round reached 3 different Nash equilibrium's. Each of them is displayed in Table 6.10 - 6.12. The dominant strategy analysis found neither a dominant strategy for a player nor a dominant strategy equilibrium. By the reason of this fact no table was created. In general, the smaller payoff results from the Nash equilibrium's indicate a lower market price and a higher amount of produced energy on the market. This fact is one main characteristic of the Cournot game

and can be also seen in figure 5.2.

Nash Equilibrium	Player	Strategy	Payoff [€]
1	A	20	320.0
	B	30	1121.02
	C	30	888.91
	D	20	686.53
	E	30	933.76
	F	20	511.68
	G	20	374.8
	H	20	490.0
	I	30	887.07

Table 6.11: Nash Equilibrium Simulation Round 3 [#1]

Nash Equilibrium	Player	Strategy	Payoff [€]
2	A	20	320.0
	B	30	1121.02
	C	30	888.91
	D	20	686.53
	E	20	488.34
	F	20	511.68
	G	30	818.3
	H	20	490.0
	I	30	837.07

Table 6.12: Nash Equilibrium Simulation Round 3 [#2]

Nash Equilibrium	Player	Strategy	Payoff [€]
3	A	20	320.0
	B	30	1121.02
	C	30	888.91
	D	20	686.53
	E	20	488.34
	F	20	511.68
	G	20	374.79
	H	30	927.5
	I	30	837.07

Table 6.13: Nash Equilibrium Simulation Round 3 [#3]

The market share of all participants has changed slightly in comparison to the first two rounds. More interesting is the time of amortisation. It is the period that each player needs to get a positive profit. In average each player needs about 18,7 years to make a positive profit. In general, a solar energy generator has a durability of between 15 - 25 years. Figure 6.10 shows that only player *E* has a very high amortisation time at Nash equilibrium two and three. This indicates that it would be better for *E* to leave the local energy market or to think about the entry at the beginning.

The Rate of return which can be seen in Figure 6.11 shows that a higher number of players on the market leads to a smaller percentage for each competitor. In other words, a player gets a smaller value back from his generator investment per year.

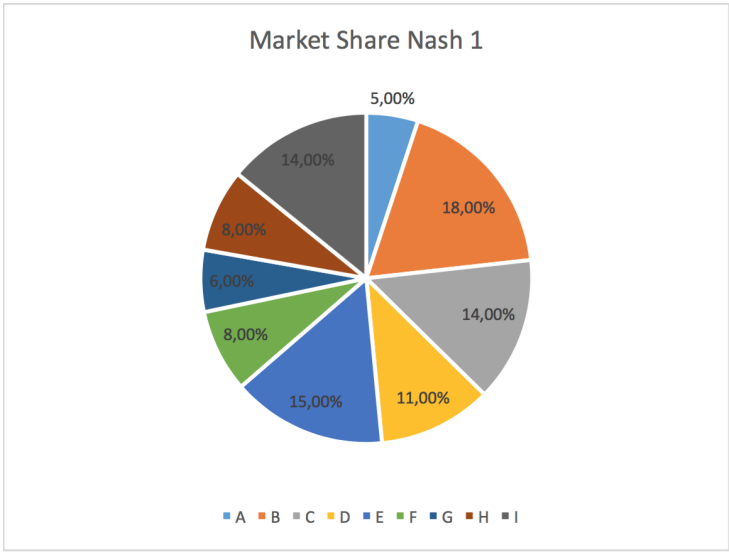


Figure 6.7: Market Share 1

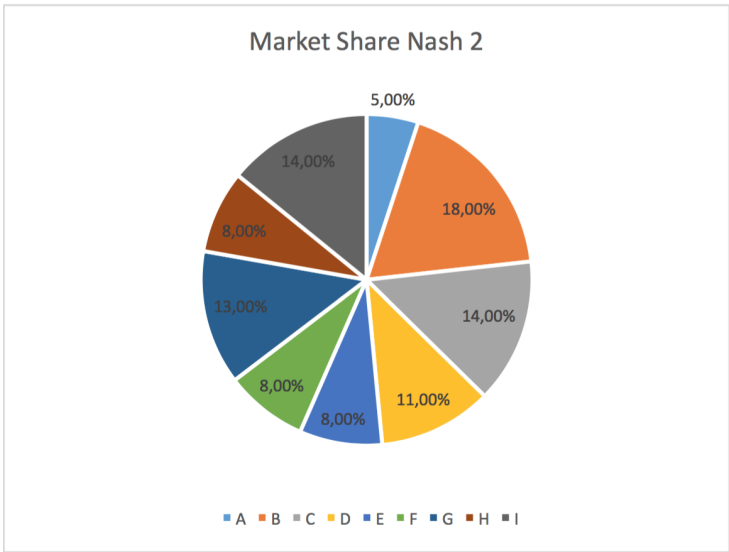


Figure 6.8: Market Share 2

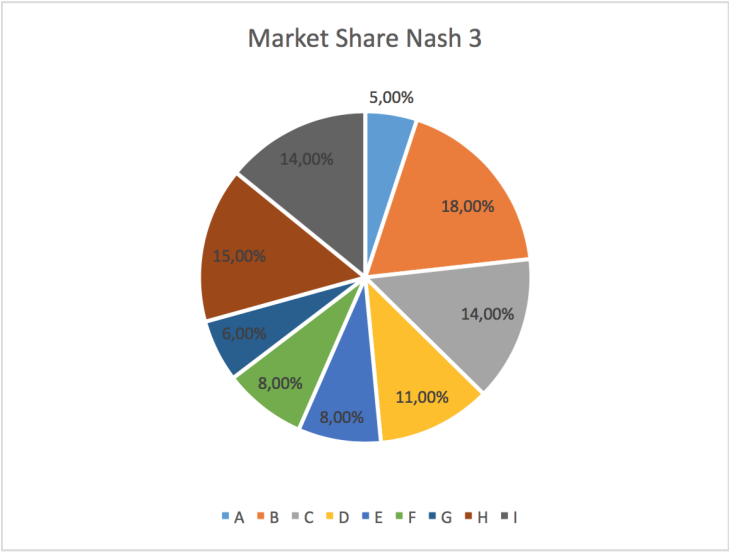


Figure 6.9: Market Share 3

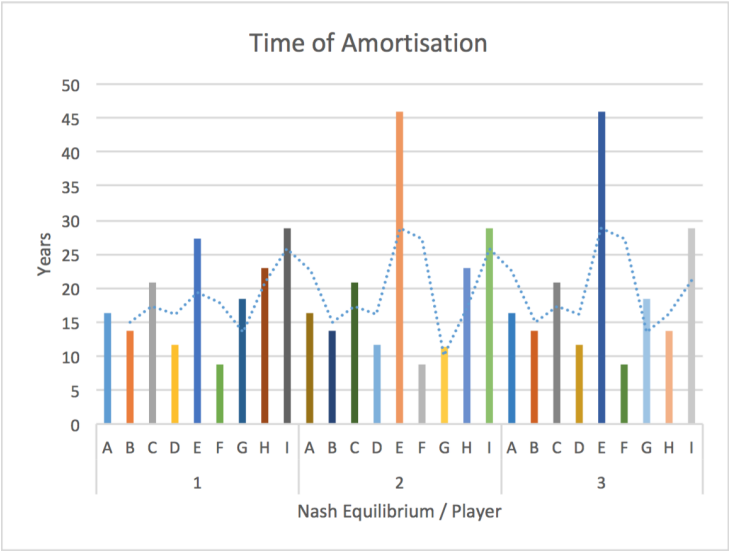


Figure 6.10: Time of Amortisation for each player

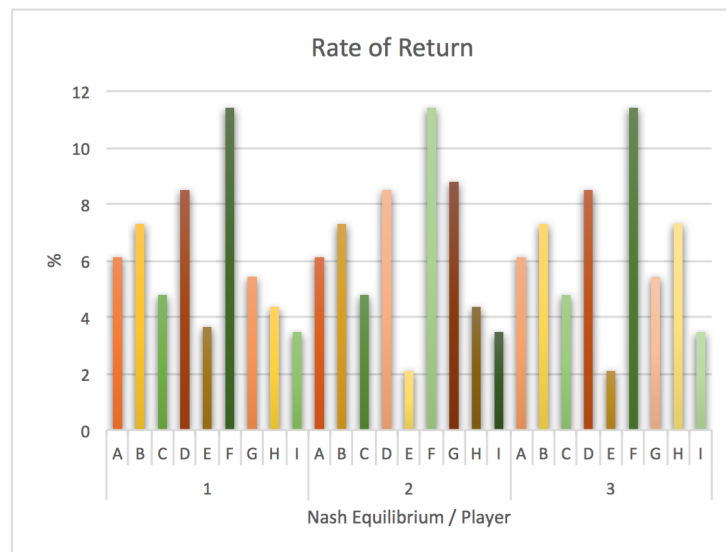


Figure 6.11: Development of Rate of return for each player

Figure 6.12 - 6.14 show the recommendations for the government. It can be also seen that for each Nash equilibrium a government should choose the subvention scenario. For a period over 25 years the decision could be different.

In general, for all simulation rounds of this model the subvention strategy is more advantageous for both, the government and the producers. This could change if on the one side the amount of energy on the market is not limited or the investment costs of the generators are higher.

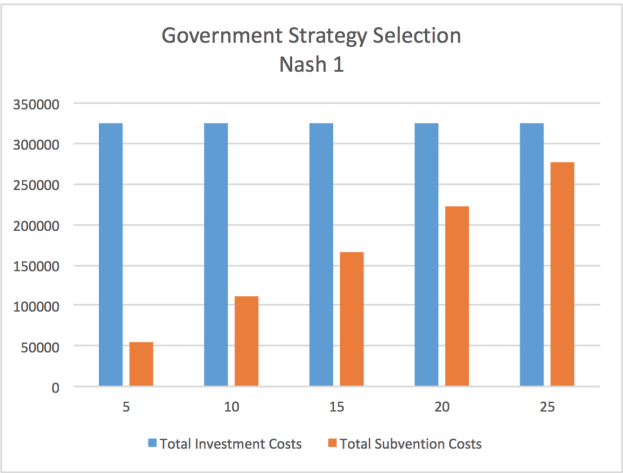


Figure 6.12: Comparison Investment vs. Subvention Strategy 1

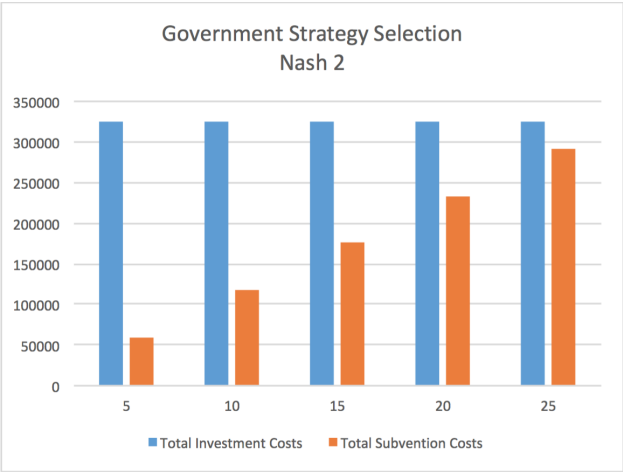


Figure 6.13: Comparison Investment vs. Subvention Strategy 2

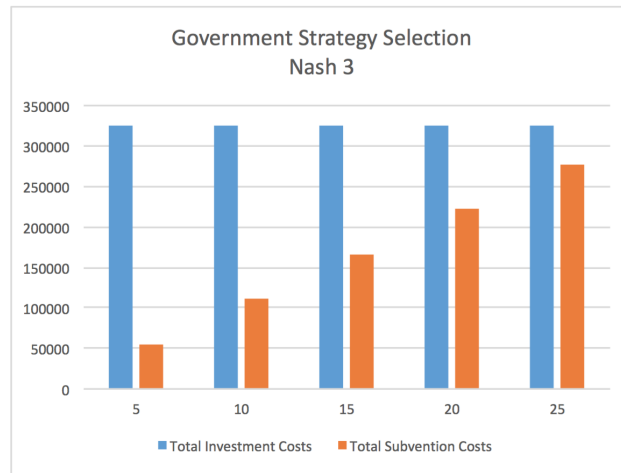
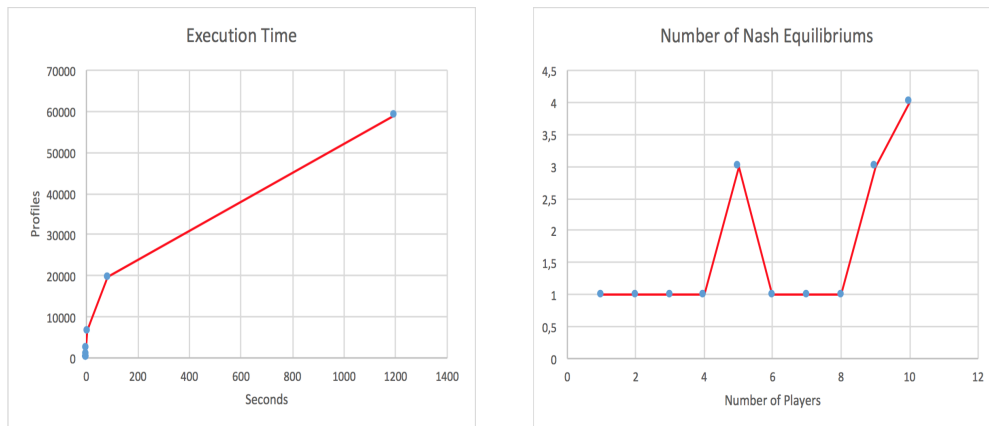


Figure 6.14: Comparison Investment vs. Subvention Strategy 3

Figure 6.15a demonstrates the development of the execution time with an increasing number of strategy profiles or in other words with an increasing number of players. It makes sense that a higher number of players leads to a higher execution time. Figure 6.15b analyses the number of Nash equilibrium's with increasing number of players. The number of equilibrium's is relative static with two exceptions. In both exceptions more than one equilibrium was found.



(a) Execution Time

(b) Number of Nash equilibrium's

Figure 6.15: Simulator Analysis

Chapter 7

Conclusion & Future work

This master thesis deals with the game theoretical analysis of a smart grid system. The following sections present a short summary of the design of the thesis, the implementation and simulation results and should suggest at the end some future improvements.

7.1 Design

The design of the thesis is characterized by two main parts. The first part concerns with the theoretical research which is divided into three chapters. At the beginning, the main idea of game theory was introduced. Therefore, the basic concepts were discussed and explained with numeric examples. In the following chapter the focus was set on the functionality of a smart grid and on its economic benefits. The game theoretical aspect in the topic of smart grids was then presented in chapter four. Here, present research topics of game theory in combination with smart grids were studied and described. At the end of the thesis a game theory simulator was build.

7.2 Implementation and Results

The implementation of the simulator was done in Java. The focus of the implementation was to be able to create different non cooperative games. In this thesis, a fictive local energy market was used to study the impacts of an increasing number of private producers as well as to make recommendations for a government which has the role of the financial supporter. The results showed that if more players are on the market the competition is stronger, the market price is lower and the amount of energy on the market increases. A lower market price leads to less profits of the producers and therefore a higher demand of financial support. For a government it is always interesting to know if they should focus on a yearly subvention or just on a one time financial support. The results of the game simulation showed that in most of time the subvention scenario was better for the government. With an increasing time of the generator durability the choice of the government could be different.

In general, the proposed model was a fictive example of an own local energy market game which tried to find a state where all participating players benefit from investing in renewable energy sources and supporting the concept of a smart grid.

7.3 Future work

This master thesis presents a good and structured overview of game theoretic models in the context of smart grids. The results of the thesis provide a solid starting point for a more detailed research work of the boundaries of techno-economic models in combination with intelligent grid systems.

Due to limitations of the scope of the thesis, I decided to concentrate the simulation part on a competition between different rational thinking local players, which try to increase their financial input stream by selling surplus energy to other locals, which is shown in Figure 7.1.

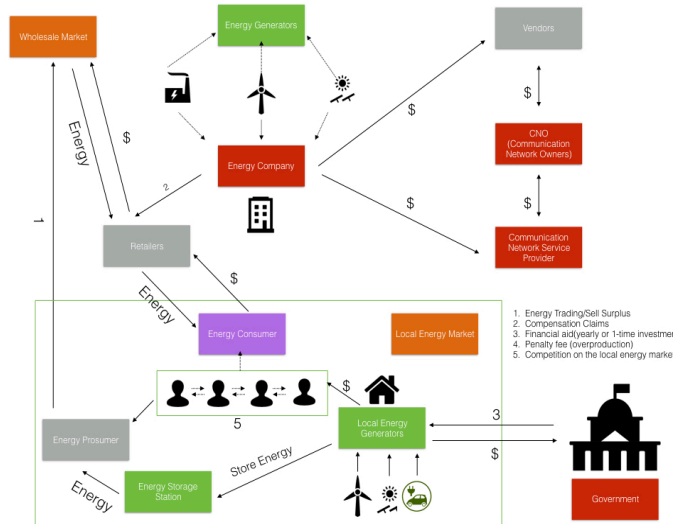


Figure 7.1: Local energy market model (green)

In the future, it will be of high interest to expand the presented model by integrating other rational thinking players, like energy companies (oligopols), retailers or communication network owners. As it can be seen in Figure 7.2, a more detailed and sophisticated scenario includes compensation payments for energy companies, payments for communication network owner/provider or changing weather situations for energy generation through renewable energy sources. The outcome of

a more detailed simulation can be used to analyze the economic effects of smart grids worldwide.

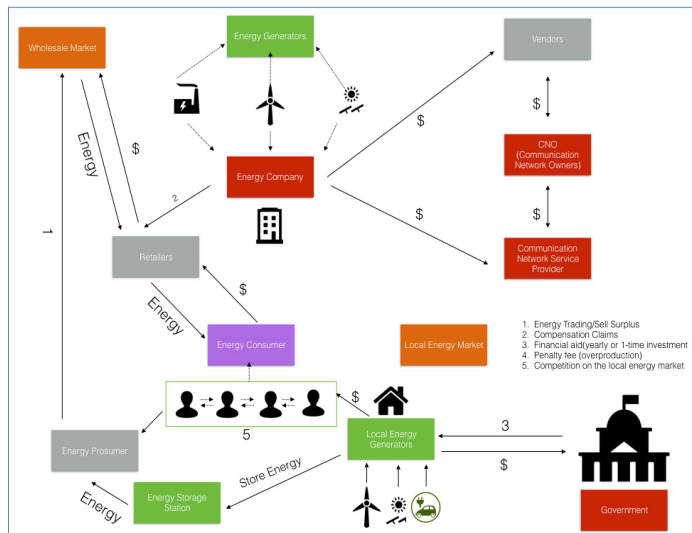


Figure 7.2: Future market model (blue)

At the end, it must be stated that the input data of the simulation are based on statistics and random assumptions. To make reliable predictions in the future it is necessary to concentrate on data collection from reliable sources because of the fuzziness and uncertainty of the included data.

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