Identifying the challenges for a grid operator in the low-voltage grid and the required need for flexibility

An analysis of a low-voltage grid in three scenarios and a challenge solved with two reinforcement approaches: traditional and storage implementation

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Ter nagedachtenis aan József Csik
'Kennis is macht'

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Summary

The energy system is in transition. The structure of the system becomes more complex due to decentralized generation and required flexibility. The demand load increases by the introduction of new technologies such as heat pumps and electrical vehicles. In the western society the electricity grid is maintained by grid operators. The circumstances in the grid changes and the grid operators are obliged to intervene in time. The main question in this research is: Under what circumstances will the grid operator implement energy storage in the local low-voltage grid to create more flexibility in the grid of residential neighborhoods?

The energy system becomes more sustainable. More technologies use electricity instead of fossil fuel combusting. This worldwide sustainable shift may be slower than expected; however, the Dutch government has greater ambitions: more renewables and energy neutrality in 2050. The stakeholders in the energy system conform themselves to the new goals of the energy agreement. The grid operator is responsible for an important part in the energy system: the medium and low-voltage grid. Important company values are: safety, supply certainty, financial return, and service. Endinet B.V. is the grid operator of Eindhoven. Their mission is: *also tomorrow the energetic connection with society in our area*. The future scenarios for their grid are reported in their strategic asset management plan. Insights in developments of the future are useful to make social responsible investment decisions. This research is completed from the perspective of a western grid operator.

The capacity challenges in low-voltage electrical grids are described in the literature review part of this research. The demand loads in the LV-grid increase due to higher penetrations of (new) technologies such as electrical vehicles and heat pumps. The domestic demand load is little compared to the possible loads of those new technologies. Furthermore, decentralized generation on a large scale in an existing LV-grid is new. These higher demand loads could easily be handled due to traditional reinforcements of the LV-grid. However, developments in the LV-grid make it possible to use flexible solutions. These flexible solutions are other approaches to handle the higher loads in the grid. Flexibility in the energy system is divided in three categories: supply, demand and capacity flexibility. Demand management tries to shape the loads in the benefit of the system. Supply flexibility is responsible for an accurate supply certainty. Furthermore, the capacity upgrades of the grid can be smarter and more flexible than with the present assets in the grid. Energy storage can support all three flexibility categories. Lithium-ion batteries are superior compared with other battery technologies. The main disadvantage is still the high price of this technology. However, Tesla introduced a new lithium-ion battery system which is less expensive than before. Therefore, the business case of one challenge of the research model – which is described up next – is solved with two capacity upgrade approaches: battery energy storage and the traditional reinforcement.

This research tries to model the present and future situation in an existing low-voltage grid. The demand and supply loads are obtained from actual measurements in the low-voltage grid. Average profiles are not used because these profiles differ with profiles at the low-voltage scale. The average profiles are applicable at higher scales in the grid. The loads are determined for three scenarios: summer – 2015, winter – 2040, and summer – 2040. On the supply side the PV-solar loads are modeled on an existing low-voltage grid. The demand

loads on this modeled grid are: electrical vehicle, heat pump, and domestic loads. Capacity problems occur in multiple assets in the summer – 2015 scenario. The decentralized generation of solar panels creates high simultaneous loads which lead to capacity problems. Power quality challenges occur in the scenario: winter – 2040. The loads also create capacity problems for an older transformer station in the meshed grid. A combination of both problems is visible in the final scenario of summer – 2040. The challenges are caused by the high loads of electrical vehicles and heat pumps and the simultaneous PV-generation. The challenges decrease after lower penetrations of for example PV-systems. The charging method of EV is not making a very large difference caused by the low factor of simultaneity.

The capacity problem in the first scenario 'summer – 2015' is resolved with two reinforcements approaches. The first approach is the traditional approach for solving these capacity problems. The LV-grid is reinforced with thicker cables and heavier transformer station nowadays. The second approach reinforces the grid with energy storage in the form of batteries. The costs of both approaches are calculated with the total cost of ownership method. The present costs of energy storage are almost a factor eight too high. Therefore, the reinforcement of assets in the grid is still the best approach. The grid operator has to invest social responsibility and an important factor is then the lowest possible cost.

To conclude, the grid operator needs to monitor the developments carefully. Accurate data is crucial for the right decisions. Furthermore, the grid operator needs to inform other related parties more accurate in their new role as network operator. The present governance of the grid operators conforms to these ambitions and their new role in the energy transitions. However, these kinds of researches are crucial to maintain their role and social responsibility. The grid operators monitor these developments carefully and share their findings with NetbeheerNederland; because, shared knowledge is the power of the future.

1. Introduction

In this chapter the general problem is described. The research questions have been formulated. The design of this research is depicted in a flow chart (Figure 1) and is the structure for this research. The goals are described in paragraph 1.3. This chapter finishes with the expected results.

1.1. Problem definition

The energy system is in transition and becomes more complex due to a changing structure and new technologies. The energy system has to deal with different loads and the grid should have enough capacity to bear this burden. The electricity loads result from supply or demand in the grid. In these two categories different developments are in progress.

Firstly, the electricity supply of the future is different; because, renewables are responsible for a larger part of the energy supply. These developments result in higher energy supply loads and load profiles with more spikes in the low-voltage (LV) grid. The peaks could be responsible for problems due to insufficient grid capacity. The supply in a low-voltage grid is higher than before. Days with much wind and sunshine demand much more capacity from the low-voltage grid. The grid should be capable to accept such high loads or energy will be wasted and defects will occur. Different situations occur during a daytime: energy surplus and shortage of energy. The shortage could be solved with extra supply from the centralized generation or flexible management inside a low-voltage grid. If there is more supply than demand in a low-voltage grid then this net load could be distributed to the medium-voltage grid. This surplus energy could be used in grids where there is a shortage of energy; nevertheless, this solution is an extra distribution action. Therefore, it could be interesting to store energy during a surplus in the low-voltage grid. The storage could be used during energy shortage in the low voltage grid or could decrease the supply peaks due to charging the storage with this supply. The overproduction and the shortage of energy could be balanced locally. The low-voltage grid can be a smarter grid and more flexible.

Secondly, the supply loads are not the only problem for a low-voltage grid; moreover, the increased demand loads should be distributed as well in the present grid and in those of the future. More and more electrical appliances are implemented in the western society and these developments could lead to more domestic demand. Furthermore, the introduction of more electrical vehicles has an impact on these demand loads. The implementation of more heat pumps creates also a higher demand in a low-voltage grid. These heat pumps are powered by electricity and replace the central heating systems which operate on natural gas. If consumer demand rises in the future, the grid capacity should be able to handle these developments. The required demand should be distributed in the grids, thus these grids require enough capacity. This extra grid capacity could be in the form of electrical energy storage. Thereby, the extra required demand could be discharged from these storage points in the low-voltage grid.

Thirdly, Endinet – grid operator of Eindhoven – has developed several energy scenarios wherein they try to predict the developments of energy supply and demand. These scenarios describe and quantify the trends of the mentioned developments on the supply and demand side. However, Endinet does not select one scenario above another and thus this research should use relevant scenarios.

Finally, future energy surplus may be managed with storage as well as energy shortage in the low-voltage grid. Therefore, a grid operator should implement energy storage if the investment costs are lower than the present approach. The developments in the energy system affect the low-voltage grid. The present grid capacity is probably insufficient and upgrades are unavoidable. The investigation of this problem is threefold;

1. Determine the impact of new developments on the demand and supply side in a low-voltage grid.
2. Research into a possible flexibility solution and investment: electrical energy storage.
3. Solving the capacity problems with the best business case due to two approaches: traditional investments versus a flexibility investment in the form of energy storage.

Scoped research questions could help to solve this investigation. Therefore, the research questions are described in the next paragraph from a grid operator perspective.

1.2. Research questions

This chapter introduces the research approach and the thoughts in advance. The presented questions show the goal for the research and corresponding methods are depicted in bold. The research questions find their origin in paragraph 1.1. Problem definition.

Main-question

1. Under what circumstances will the grid operator implement storage points in the local low-voltage grid to create more flexibility in the grid of residential neighborhoods?

Sub-questions:

2. What are the energy loads in 2040 in a low-voltage grid in a residential neighborhood? And what are the present loads? **(literature review /expert’s views)**
3. What determines the capacity of a low-voltage grid in a residential neighborhood? **(literature review /expert’s views)**
4. Which capacity challenges do occur in the present grid? And which problems will occur in 2040? **(capacity analysis)**
5. Which flexibility options could solve capacity problems in a residential neighborhood now? And in 2040? **(literature review / expert’s view)**
6. Which actions should be considered to create flexibility in the low voltage grid in a residential neighborhood now? And in 2040? **(literature review /expert’s view)**
7. Is the implementation of electrical storages systems a serious option now for a grid operator? **(literature review /experts view)**
8. What are the costs and benefits involved by implementation of electrical storage systems in the low-voltage grid? Compared with the traditional approach. **(TCO-approach)**

In the light of these questions this study is designed. This research design is described in the next paragraph and is more focused on the three different parts of the research.

1.3. Research design and research goals

In Figure 1 the research design is depicted. The research consists of three parts. These three components are input for one another and will eventually answer the main question.

The first research goal is to indicate different capacity problems in the low-voltage grid. This first goal investigates two scenarios. The first scenario is a present scenario whereby all households purchase a PV system in an existing neighborhood. This scenario determines the loads during a present energy surplus. The second scenario contains the predicted penetrations of electrical vehicles and heat pumps in 2040 within different Endinet scenarios. The second scenario investigates the problems due to an increase of demand. Both scenarios are analyzed in the Aireywijk – a neighborhood in Eindhoven. If those analyses show capacity problems then the grid operator must upgrade the grid to maintain the operation of the grid.

The second research goal is more knowledge on new flexibility solutions due to a literature review. Electrical energy storage is a flexibility solution and could solve multiple problems at once. A more thorough analysis of this solution is done in the literature review. Both investment approaches could solve the challenges in the grid. However, the right approach for these investments should be social beneficial. This requirement results in research goal number three.

The third research goal is establishing a business case for both approaches: traditional and flexible. The business case determines the costs for a traditional upgrade: reinforcement of the present assets. The other part of this business case investigates the costs for a new flexibility option: energy storage in the LV-grid. The input for this business cases is obtained from the first part of the research. The Aireywijk represents many other low-voltage neighborhoods and could therefore be an indication of the challenges of the future. The possible solutions are investigated with in mind the lowest possible costs for the grid operator and thereby the society.

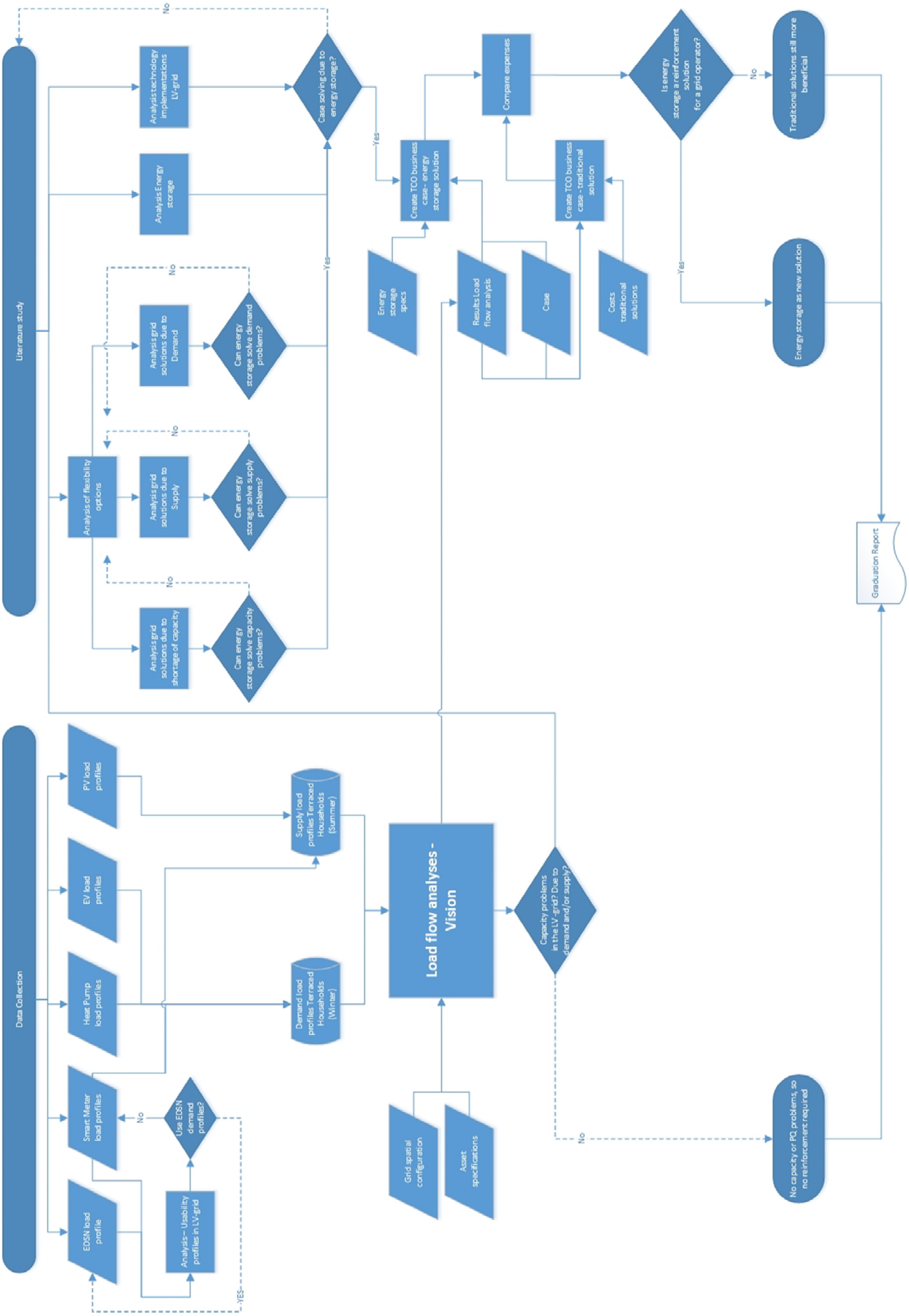

Figure 1: Research design

1.4. Expected results

The expected results due to this research are in twofold. The first research goal will determine the possible need for extra capacity in the low-voltage grid. Furthermore, this analysis shows possible power quality issues. The results of this analysis are used as input for the costs estimations.

Secondly, the cost of implementing an energy storage system in low-voltage grid is estimated. Thereby, a comparison is made with the cost of a traditional reinforcement of the low-voltage grid in the same situation. Both of these estimations are done with the results of the previous analysis in the Aireywijk. The grid operator should invest social responsible. Therefore, the least expensive solution is applied in the grid. The alternatives are compared and thus the grid operator could make a deliberate choice in the future.

In conclusion, the results hopefully show capacity problems in the low-voltage grid. Unusual data is used for these analyses. The data are actual measurements in the low-voltage grid and applicable for low-voltage grids. This approach will slightly differ with the already completed research which mainly uses average data. Furthermore, the alternative of energy storage is explored with the case study. The difference between both solution costs will determine if energy storage is already an actual alternative.

2. Background

This second chapter provides a broad overview of the energy sector. The most relevant developments are described. Furthermore, different stakeholders are introduced. The different scenarios of Endinet B.V – Dutch Grid operator – will lead to the actual research. In between this chapter and the model description a literature review searches deeper in the matter of a low-voltage grid and the possible flexibility options in the grid. The state of science on this subject is mainly discussed in this literature review. Nevertheless, first a broader point of view on the energy sector is described.

2.1. The energy system

In this paragraph a brief overview is given about the developments in the energy system. First, the present fundaments of the system are discussed. Secondly, the shift to more sustainability is discussed. Finally, the future grid is described with new technologies.

2.1.1. Until now – 2015

Since the industrial revolution the need for energy – in any form whatsoever – is drastically increased. The increased demand created a system which could contain and deliver this energy. This system contains every aspect from generation to consumption. The present system generates energy in the top part of the system. The production of energy is mainly decentralized in large generation facilities. Energy is distributed in the electricity grid to the consumer from these generation sides. This grid contains different levels with different ranges of voltages. The voltage levels in the system are high, medium and low. The high voltage grid has a range from 380 kV till 50 kV in the Netherlands. This high voltage grid is managed by TenneT (TSO) in the Netherlands. This transmission system operator (TSO) is also active in Germany and serves with their grid 41 million consumers. This grid contains 21.000 km of high voltage connections and connects thereby the lower levels of total grid (TenneT, 2014).

Several different grid operators manage the medium and low-voltage grid. NetbeheerNederland represents these grid operators as their industry association. The grid operator is a distribution network operator (DSO) and becomes more and more a system operator. A distribution network operator distributes electricity and in many cases also natural gas. The DSO receives input from the high voltage grid and distributes this on their grid. First, the medium voltage grid (10 kV) distributes the electricity nearer to the consumer. Secondly, the medium voltage electricity is transformed to the low-voltage grid for the consumption of the end-user. Electricity is then used and completed the distribution from top till bottom. This system – from production in high-voltage to end-use of low-voltage electricity – is the present system and thus the situation in many developed countries, sometimes with slightly different voltage ranges. The present electricity system is depicted schematically in Figure 2.

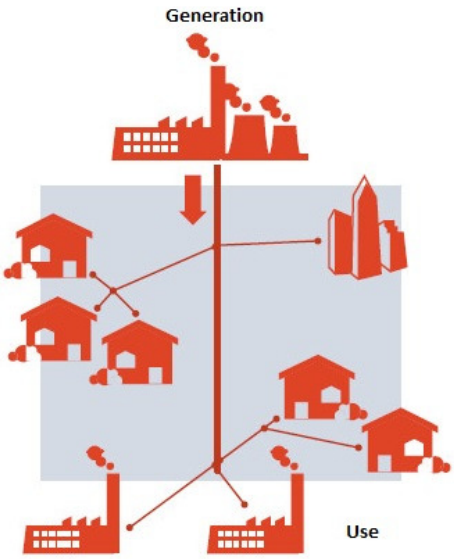

Figure 2: the present electricity system

2.1.2. A shift to more sustainability

The United States of America were the largest energy consumers of the world until 2011. Since then China uses more energy than the US. The energy problem is a worldwide problem and this problem is also relevant for developing and third world countries. Most of the well-being of these countries depends on a decent energy provision. The fossil fuel market created this rapid growth and welfare. The energy supply due to fossil fuels was cheap and highly efficient. This efficiency became the base for the present system in which generation is mainly based on these fossil fuels. The positive points of the rapid industrialization of these countries have also a downside; namely, the combustion of fossil fuels results in carbonization and pollution of the environment. This downside has a negative impact on the climate and therefore many people favor a shift to a sustainable future and energy supply. This shift – to reduce the emission of greenhouse gasses – is defined in the Kyoto protocol. The Kyoto protocol describes the ambition of the industrial countries to reduce their emission by 2012 and this agreement is extended until 2020.

The Kyoto protocol could be seen as the first step towards an energy transition. This transition tries to reduce the use of fossil fuels and stimulates growth of renewables. Nevertheless, this shift is not as drastically as might be hoped by some authorities. Developing countries and upcoming economies still depend on fossil fuels and their quick benefits. The energy demand of mainly China and India still rise and will until 2035 (BP, 2015). Moreover, the developed economies also still prefer cheap and efficient fossil fuels above the unreliable and pricy renewables. Therefore, the prediction of each share of the energy production by fuel is not much different than the current share ratio, see Figure 3.

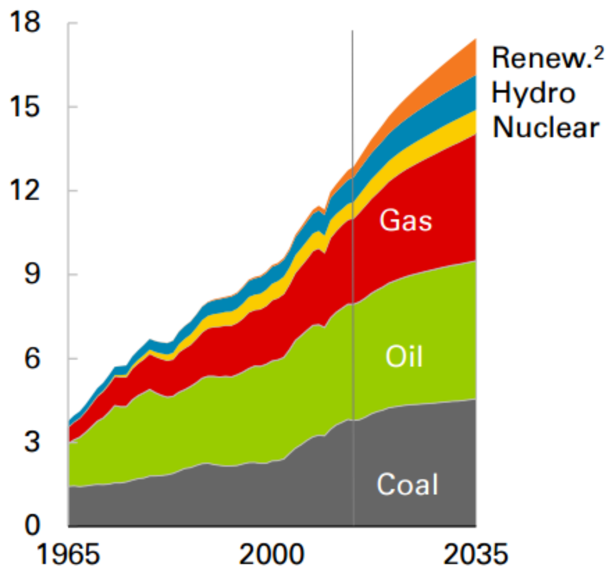

Figure 3: Consumption by fuel in billon tons – worldwide

The share of renewables will increase the upcoming years with six percent every year and this will result in a share of eight percent of the total generation in 2035 (BP, 2015). Thereby the present grid structure will probably be sufficient. However, several local energy markets transform faster to a more sustainable system. The ambition of the European Union is to reduce the long-term greenhouse emission by 80 till 95 percent in 2050 compared to levels in 1990 (Europese Commissie, 2011). Hence, the European distribution system needs to adapt to this energy transition with more renewable generation. This future energy system is discussed in the next section.

2.1.3. The future energy system

The energy system is shifting towards another structure. The present energy system is no longer sufficient due to this shift of more sustainability and decentralized production. The energy system of the future cannot be predicted in perfect detail; nevertheless, a schematic system is depicted in Figure 4. The future energy grids are smarter with more potential for flexibility. The core of the grid depicted in Figure 4 matches with the grid in Figure 2. The additions to the present grid are forced by new consumer products and new supply and demand techniques. The energy supply is derived from two sources: fossil (including nuclear generation) and renewable generation. The centralized production is still fossil based; however, fields of renewable' production are implemented. These renewable production fields are 'wind farms' and fields with solar panels. Furthermore, renewable generation plants use hydrogenation, biomass, biofuels or geothermal energy.

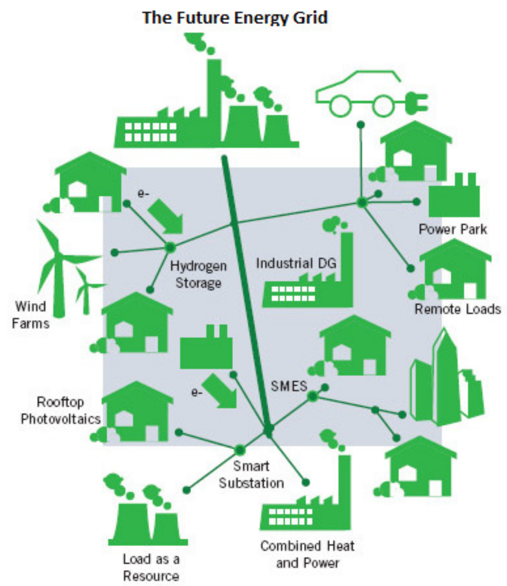

Figure 4: The future structure of the electricity system

The renewables sources such as biomass, biofuel, wind, and solar are applicable in the Netherlands. Furthermore, the impact of decentralized renewables is visible in Figure 4. The photovoltaic panels will be more common on rooftops. The attendance of electrical vehicles and heat pumps has consequences on the low-voltage grid. All these shifts and new introductions demand more from the energy system, the system needs to become smarter.

Many stakeholders have to cooperate for developing the structure of the new energy system. Some stakeholders are already mentioned above; others will be introduced in the next section.

2.2. Stakeholders

Different stakeholders should reorganize the present electricity grid for the future. In this chapter important stakeholders are introduced and their role is discussed.

2.2.1. Conventional electricity generators & the transmission system operator (TSO)

A centralized power plant and his project leader generated electricity already in the 19th century. This project leader was Thomas Edison. The size and efficiency were inadequate, if you compare them to the present system (Coned, 2015). Although, the first power plants were used mainly for lighting, the first step in the power generating operations was taken.

The high-voltage grid consist of several grids with voltages of 110 kV or higher. The minister appoints a grid operator for this grid for 10 years. The authority of consumer and market will monitor the high-voltage operator then and could correct this operator. (Dutch Government, 1998) Large power plants generate electricity for the energy market. These plants supply electricity to the high-voltage grid. TenneT is operator of this high-voltage grid in the Netherlands. TenneT is a transmission system operator (TSO) in the north-west part of

Europe. The TSO has three duties: provide power transmission service, offer system services, and facilitating smoothly functioning, liquid and stable electricity market (TenneT, 2015) The TSO purchase electricity from the energy producers and distribute this electricity to grid operators or direct consumers. The energy producers generate electricity due to combustion of coal and natural gas in the Netherlands. Other renewable producers act on a smaller scale. The most important renewable producing facilities work on biomass and ambient heat (TenneT, 2014). The role of the TSO is defined by the European Union in their code. The electricity transmission system operators are called ENTSO-E and are interconnected in a European grid. TenneT is one of the 41 connected TSO's in the grid (Figure 5). In this European grid different energy producer are active, which obtain their energy from sources such as renewables, coal, natural gas, oil and nuclear power. Cooperation could be necessary in this grid. Occasionally, assistance between these ENTSO- E's occurs: TenneT helped Elia (Belgium) with export insurance if required in the winter of 2014. Elia had some troubles due to a stop of two nuclear generation plants (ANP, 2014).

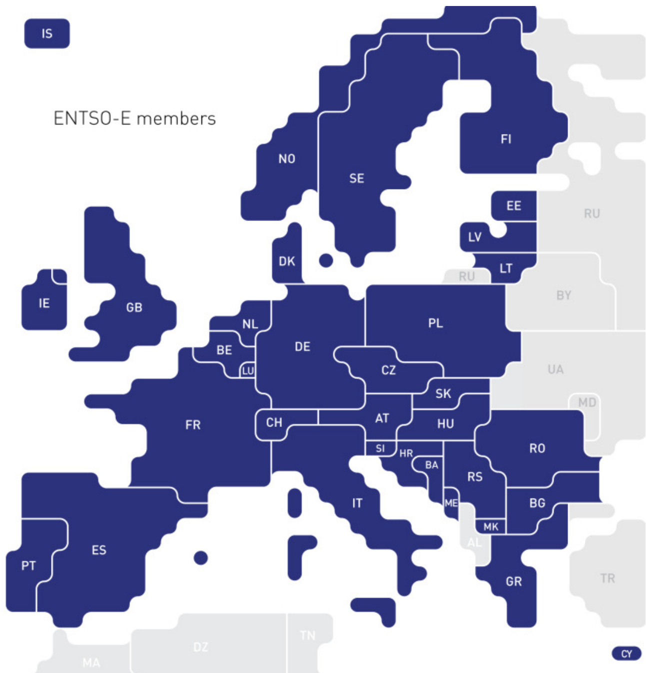

Figure 5: ENTSO-E members in Europe and their catchment

2.2.2. Grid operator

The grid operator manages a sub-grid of an ENTSO-E's grid. The Dutch grid operators have the responsibility of the (natural) gas and the electricity grid. The grid operators distribute electricity with medium-voltage to low-voltage electrical energy and are responsible until the meter of the consumer. Furthermore, the grid operator is mainly a facilitator for their (new) customers. In 2030, the grid operator aims for more transparency and should be more approachable. They should be an open source which mainly facilitate. (Netbeheer Nederland, 2013) NetbeheerNederland expects that information supply will be a part of the integrated energy transport. The grid of these operators is linked to each other and the gas grid to the electricity grid. These grids are updated to new standards for the energy transition. The new grid contains an extra grid for just heat which functions in the same way as the electricity and gas grid. These developments should be realized in 2030. The grid operator needs to deal with new requirements. The competence of managing big data and using this data for justified analyses is required in the future. (Netbeheer Nederland, 2013)

The grid operators can try new concepts in pilot projects. These projects will help designing the new grid and provide insights for the (new) role of the grid operator. Already, these investments have started. Enexis – a Dutch grid operator with 2.7 million connections - has as goal to implement ICT to deliver more control possibilities for the customer in 2016. The role of new engineers is crucial for the total transition (Enexis, 2015).

Even after the implementation of the electricity and gas law of 1998 the grid operators still have a monopoly. Their behavior is monitored by the authority of consumer and market (ACM). The grid operator is held accountable for their capacity and quality investments and should report this every uneven year in a quality and capacity report to the ACM. The grid operators have a monopoly due to the high investment cost for more grids thus one grid is the logical solution. Meanwhile, the electricity utility companies could freely access this grid since 2004. Since then, the energy market is a free market for energy companies. These utility stakeholders are discussed in the next paragraph.

2.2.3. Energy companies

In 2004 the Dutch energy market was privatized. The impetus was given in 1998; since then, the market has developed itself to a mature energy market in 2014. The consumer only has a contract with their energy company. Since august 2013 consumers pay indirect fee to the grid operators. The consumer only has a direct financial relation with their energy company. The authority Consumer and Market monitors the energy market. (ECN; Energie-nederland; Netbeheer nederland, 2014)

Presently, thirty energy utilities are active in the Netherlands. These utilities sometimes produce energy themselves. However, most of them only buy energy and sell it to the consumers. The energy is bought at the wholesale energy market by the energy company and distributed with the help of the grid operators to the consumer. The utility can also buy from the consumer which can be a producer as well these days. (ECN; Energie-nederland; Netbeheer nederland, 2014)

Furthermore, the utility is responsible for the direct contact with the customer. This contact concerns charging the cost of the consumer’ energy use. Further, the utility delivers customer services and response to their question and complains. The meter reading withdrawal is also a responsibility of energy companies (ECN; Energie-nederland; Netbeheer nederland, 2014). Recently, the implementation of smart meters is ongoing in the Netherlands. As result, the utility can read the electricity and natural gas use of the customer with ICT.

2.2.4. Consumer

The end-user in the energy market is the consumer. A consumer can have different forms such as a resident, commercial party, and industrial producer. The delivered energy is finally used and no longer distributed. The consumer is free to choose their supplier in the Netherlands due to the privatization of 2004. The consumer can choose his own utility and is free to change whenever he needs; furthermore, the consumer can also produce energy itself (ECN; Energie-nederland; Netbeheer nederland, 2014). Their produced energy is distributed in grid and this production is settled with the consumer consumption.

The consumer should report their malfunctions to the national error number. This malfunctioning is handled by the responsible grid operator. Furthermore, if the consumer wants a different connection this should be requested by the grid operator (ECN; Energie-nederland; Netbeheer nederland, 2014). The grid operator will then facilitate such a connection within a certain time period.

The consumer has several appliances which require energy during a year. In the report Energietrends 2014 a top tend is presented with the appliances which consumes the most electricity in the Netherlands. The top three consist of the central heating system, the car and lighting in and around the house. The list is completed by these appliances: TV, refrigerator, ventilation, heating devices, dryer, ICT, and audio/video equipment (ECN; Energie-nederland; Netbeheer nederland, 2014). The energy transition influence the consumer as well

The consumer is an increasingly important producer. The heat demand is approached with different technologies these days. The implementation of heat pumps is the most important transition. The fossil fuel car is slowly replaced by hybrid or electrical cars. Furthermore, the lights in households are slowly replaced with more sustainable lights such as compact fluorescent lamps (CFL). Further, most household appliances are more energy efficient by the incentive of energy labels. These kinds of incentives are mainly caused by governmental influences. The European Union and national governments implement laws and policies to create new standards for consumers. In the next paragraph these agencies are discussed.

2.2.5. Government

The governmental agencies set the standard for the market. The government has regulated the standards by law. In the Netherlands, the Electricity and Gas law of 1998 is still applicable for the energy market. However, these laws are outdated and should be updated soon. The Dutch government had privatized the energy market in 2004 and thereby showed their intentions: as little interference as possible.

Also the European Union (EU) has impact on 'local' markets. The European countries try to create a joint approach to reduce the CO_2 emissions. The European Union has a commission of energy and their strategy is driven by three main goals:

1. The EU should have a secure and reliable provision of energy.
2. The energy providers should be competitors for the purpose of affordable prices for consumers.
3. The energy consumption should be sustainable. The decrease of polluting sources is crucial.

(European Commission , 2015)

These incentives of the European Union stimulate the independent countries to create their own policies towards these joint goals. In different reports the vision of the European Union is given. These EU- reports have a timeframe of five, fifteen and thirty-five years (2020, 2030 and 2050). The European Union cooperates with other major parties such as the United States, China, Russia and Norway. Furthermore, they have many partnerships with countries such as India, Brazil, Japan and South Africa. In this way the global challenges are addressed with a more global approach. Nonetheless, the changes on lower levels will have an impact on the global level.

In the next chapter, the grid operator is clarified in a more complete way than before. The grid operator is discussed by the following subjects: mission and vision, company values and their scenarios for the future.

2.3. Grid operator – Endinet B.V.

In the previous section the grid operator is mentioned as stakeholder in the western energy system. The main target for the grid operator is facilitating a grid in a secure and liable way. In this chapter the role of the grid operator is discussed more thorough. The Dutch grid operators justify their policies to the authority of consumer and market. The grid operator' goals are discussed by the different company values. Furthermore, the determined scenarios by the grid operator are discussed. This chapter uses Endinet B.V. as example for more western grid operators.

2.3.1. Mission & Vision

The mission of Endinet is engaged with the future. Their mission is: *Also tomorrow the energetic connection with society in our area.* Endinet makes a clear statement which reveals two important values: future and social. They want to prepare themselves with a long term perspective and their governance is social responsible. The Endinet vision states a more complete picture of their ambition. The following statements are part of their vision:

1. The customer will experience us as competent, energetic and efficient
2. We are a modern and attractive company in which we continuously improve and work with pleasure and ambition.
3. We do this in a safe environment with responsible work, openly, and with mutual trust.
4. We are a predictable and reliable partner.

The long term vision and core business of a grid operator are described with this mission and vision. In the next paragraph the values of a grid operator are elaborated.

2.3.2. Company values of the grid operator

Endinet B.V. works with eight company values which are very similar to the values of other Western grid operators. The eight company values are:

1. Safety
2. Supply certainty
3. Laws and regulations
4. Financial return
5. Service
6. Partnership
7. Image
8. Quality organization

Safety for employees and consumers of the grid is of great importance. The safety issues are primarily issues for the natural gas distribution; however, the electricity grid should safety should also be guaranteed. The associated risks with managing a grid are mitigated and analyzed thoroughly by the grid operator. The second company value is supply certainty. This value is defined as: degree of where uninterrupted transport services can be achieved for the supply of gas and electricity, both in the short term and the longer term. If this degree is low – which is the goal – then the consumers could use their services generally. Laws and regulations – the third value – should be complied. Legislators, regulators and supervisory requirements are respected. These guidelines are starting principles for each task. Grid operation tasks are delivered with this as standard. Furthermore, the grid operator has an active attitude with respect to new or changing regulations. The fourth company value is financial return which indicates careful monitoring of expenses. The investments are checked by the Authority of Consumer and Market. The grid operator needs to justify their expenses carefully and defend their behavior. The grid operators facilitate a connection to each willing consumer. The consumer expects service if something is wrong. The grade of delivering services in time, complete and correct is important. Endinet B.V. has this as fifth company value. The sixth company value is partnership. The grid operator aims for a good connection with other parties in their region. The relationship with local authorities is important and could lead to an increase of business value. The seventh company value is image. A positive image is crucial for the state of the company. Safety incidents and consumer problems leads to negative publicity which could damage the operations of the company. Endinet wants to be a social responsible partner to all stakeholders and their employees thus a positive image contributes to this goal. The last company value is related to a part of the seventh value. They want to be a quality organization which creates a positive image to their employees. The quality of the employees needs to be high and the equipment for each employee is excellent. Endinet employees need to be content with their jobs.

These values represent some important principles for a western grid operator. The consumer is very important as well as safety in the work related environment. Technical knowledge is crucial and the consumer is treated with care. The role of the grid operator is changing in the upcoming years because the grids are more and more a complete system.

In the upcoming decades the grid operator becomes a system operator. In this new role the side-activities are clarified. The system contains an infrastructure for electricity, natural gas, heat and water. The data of these grids should be actively shared with other parties in the market. The market could use this data for their purposes due to these new measures. Thereby, the market gets more competitive and this competition leads to faster developments and higher standards. The new system is the result of multiple possible scenarios. The Endinet' scenarios are described in the next paragraph.

2.3.3. Energy scenarios created by Endinet B.V.

The asset management team of Endinet describes four possible energy scenarios in one of their studies. This asset management team creates a view of the energy system in 2045 for the region of Eindhoven. The trends and developments are carefully analyzed to create four scenarios which find their origin in two axes, see Figure 6. A decrease of customer demand is displayed on the left side of the horizontal axe. The right side of the axe stands for an increase or equal demand of the customers. The prediction of Endinet is that these two possibilities are important for the future scenarios. The second axe depicts another crucial variable: decentralized generation and the share of this generation. Due to these two axes the four scenarios are created. Each scenario describes trends of different consumers and implementations of technologies.

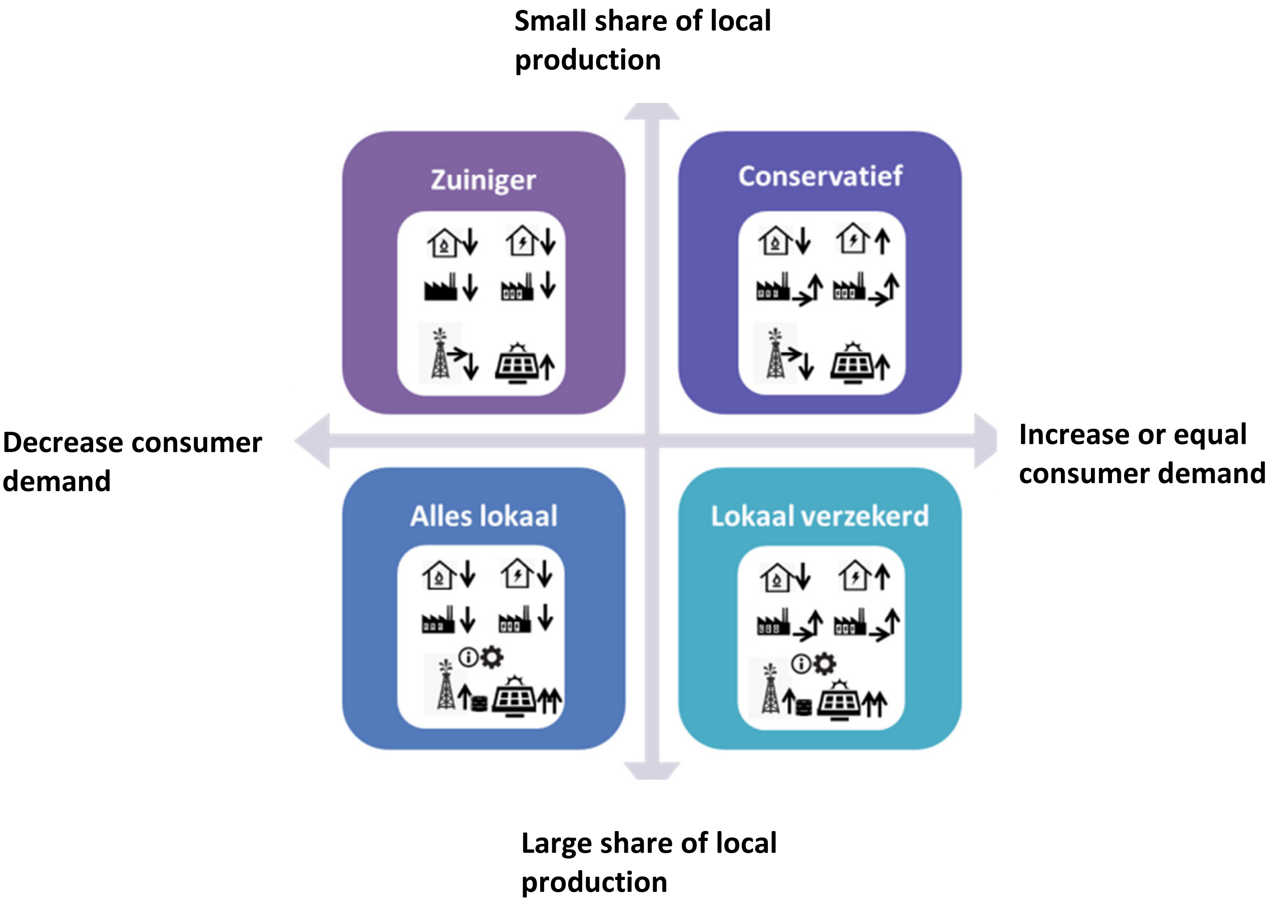

Figure 6 : Energy scenarios until 2045 by Endinet

Scenario 1 – Economical

In this scenario the natural gas and electricity demand of the households decrease. The same applies for the industry in the catchment of Endinet B.V. The implementation of PV-systems increase; however, with lower percentages than in other scenarios. The impact of green gas or shale gas stays equal or decreases. The heat demand decreases and electrical appliances become more efficient. Electrical vehicles and heat pumps have an impact; however, this impact is small.

Scenario 2 – Conservative

The heat demand decrease due to extra isolation. The appliances become more efficient, nevertheless the number of appliances will increase and thus the total demand. The number of electrical vehicles and heat pumps increase. The system becomes more efficient due to policies. Shale gas and green gas decrease their share. The implementation of PV increase, nevertheless, centralized facilities are still required.

Scenario 3 – All locally

In this scenario, the heat demand also decreases due to extra isolation. The appliances become more efficient and the demand decreases. The number of electrical vehicles increases slightly. The number of heat pumps increases with much larger numbers. The industrial demand decreases for both sources: natural gas and electricity. The part of green gas increases due to subsidies and new production techniques. Shale gas has a share and thrives due to economic considerations. The implementation of more decentralized generation continues. Furthermore, smart technologies are required such as peak shaving and demand response.

Scenario 4 – Locally secured

In the last scenario the heat demand still decreases. The domestic demand increases due to more appliances. Electrical vehicles and heat pumps take a serious share in the demand load. The implementation of PV-systems continues. The heat demand of the industry increases due to new economic developments. Green gas takes a large share and further shale gas increase. The implementation of smart technologies is also required in this scenario.

To conclude, the actual situation is one of these scenarios or a mix of these scenarios in 2045. Nonetheless, all the scenarios involve new challenges for a grid operator. These challenges are monitored and analyzed in time.

In the next chapter the academic and scientific world is reviewed on this subject. The scope is more focused on the actual research goal. This chapter showed a brief introduction in the developments. The next chapter introduces a more complete research to the subject in the academic field. The research is described in chapter four and this report concludes with a final conclusion.

3. Literature Review

Capacity challenges in low-voltage electricity grids of residential neighborhoods due to implementation of (new) technologies

Analyses of present governance, research and possible flexibility solutions for a grid operator. Energy storage analyzed as flexibility solution. A Business cases solved with the total cost of ownership.

KEYWORDS: FLEXIBILITY, DEMAND & SUPPLY, GRID OPERATOR, ENERGY STORAGE, CAPACITY, TOTAL COST OF OWNERSHIP, LOAD PROFILES.

3.1. Introduction

The renewable energy transition has a great impact for the upcoming decades in the energy sector. The energy sector should anticipate for this transition in time. The energy demand rises worldwide with 56 percent by 2040 (U.S. energy information administration, 2014). The transition of the old fossil fuel system towards a sustainable renewable system is the main challenge. The investments in the energy infrastructure are modest and the renewable energy sources get too little attention (Committee on America's Energy Future, 2009). The uncertainties about the required support and investments are still present (Dóci, Vasileiadou, & Petersen, 2015). Energy is the fuel for our society and influences our well-being tremendously. This energy should be delivered to the consumer safe, secure, sustainable and affordable (European Commission, 2011). The capacity of renewables in the electricity grids grow rapidly and take a significant part of the generation (Wang, Yin, & Li, 2009). The shift towards a more sustainable energy system is deployed due to the reduction of carbonization in the Netherlands. The government created a policy for a sustainable energy transition by 2050. Several commercial and non-commercial parties have agreed for a comprehensive approach in the national 'Energieakkoord' of the Netherlands. (SER, 2013)

The presence of renewables in the energy system is not unfamiliar; however, the introduction of renewables on this scale has a different impact. The generation of renewable sources is more unpredictable and depends upon natural influences. This results in periods with energy surplus and energy shortages which should be managed in a suitable way. The renewable generation is still a small part of the total generation. In the future this part will grow and the energy of these renewables is clean without a major impact on the environment. However, sometimes – if there is an energy surplus – the renewable production is shut down to balance the system. Germany – where there is a significant part of renewable energy – has several policies to turn off photovoltaics panels to reduce the input of these sources (Molengraaf, 2014). The extra generation is shut down and possible energy production is going to waste. The halted generation is a shortcoming in the German system; especially, if there are times with energy shortages. Therefore, the operators of this system must find an answer. A more flexible system could be the answer to this shortcoming. Flexibility could be created in many ways and will be discussed later in this literature review. Energy storage is discussed as the main flexibility option.

An energy network of the future should still be safe and reliable. The key value of grid operator 'Endinet' is safety (Endinet, 2014). The future network should be handled with care and risks should be mitigated. Other values are mentioned in 2.3.2. Company values of the grid operator. Challenges occur due to implementation of new systems and technologies. The implementation of energy storage or other systems bring other or even unknown costs. These costs should be handled with the same care as grid operators handle their finance now.

The energy transition affects the grid operator and therefore the grid operator should monitor and act in time to be effective. The challenges and possible solutions for a grid operator will be discussed in this review; subsequently, the research is described in chapter four. This literature review tries to explore and investigate the impact of the energy transition on the low-voltage grid and the impact for a grid operator from a neutral point of view. In the conclusion of this review the impetus for the actual research is given. The findings provide the framework for the research in the Aireywijk.

The transition towards a sustainable energy system is the key motivation for this review. Moreover, the process is not linear and should be managed carefully. Due to research this transition could be managed in an optimal way. The developments in the system are treated by many grid operators. NetbeheerNederland tries to monitor these developments and create a platform for information exchange. Therefore, the local grid operator does not have to reinvent the wheel over and over again. The results of this research are thus shared with other grid operators. The energy transition should be managed within a safe and reliable system. Research to parts of this greater puzzle should help to solve the puzzle. This research contributes to a piece of the puzzle.

The scope of this research is crucial for the use of this report. The focus is on the energy transition in Western Europe. The main focus on the grid operator in the Netherlands and their flexibility challenges. However, some findings are of universal use or could be adapted to local circumstances. The key concepts and variables are discussed in the next sections of this review.

3.2. Electricity supply and demand in the low-voltage grid

In the upcoming section, the energy supply and demand is discussed briefly and challenges in the low-voltage grid in neighborhoods due to supply and demand are discussed. Knowledge of loads and generation in the distribution grid are crucial for a grid operator. Neighborhoods consist mainly of households and therefore this is the perspective.

3.2.1. Electricity supply in the low-voltage grid of residential neighborhoods

In the present energy system the supply of electricity is mainly decentralized. Furthermore, this supply is based on the combustion of fossil fuels. The system of energy supply is changing into a renewable energy system (RES) in many western countries. In the Netherlands the RES production was 9.5 percent of the total energy production in 2009. Nonetheless, countries such as Austria and Sweden had rates above the 50 percent of their total production. The chance that the main European countries generate at least 30 percent of their supply with RES in 2020 is 78 percent (Meade & Islam, 2015).

The energy transition creates new problems in the electricity grids. The renewable energy systems are driven mainly by wind and solar in the low-voltage. The Dutch electricity works with alternating current (AC). The input from solar panels and wind turbines supply is in direct current (DC). The renewable generation can be distributed into the local grid due to an inverter. These grids dealt with distribution from top to bottom before this energy transition. However, the renewables are implemented directly in the low-voltage grid and these grids are not designed for this purpose. The capacity of these grids can be insufficient due to decentralized supply. The results of simulation show capacity problems in the low-voltage grid, because of large scale photovoltaic generation (Bhattacharyya & Karremans, 2015).

The climate change concerns resulted in many supporting policies from governments for more implementation of RES. These policies gave extra incentives to adopt RES in many European countries. The adoption of RES such as PV is mainly driven by the standard of the innovation, which should have a high compatibility, high trialability, high observability, high relative advantage, and low complexity. Furthermore the adoption of these systems are driven by the need to be self-sufficient and independent (Karakaya a, Hidalgo, & Nuur, 2015). The renewable energy systems respond increasingly better to these needs. Therefore, the adoption of more renewable energy systems in the low-voltage grid is plausible. Furthermore, the social housing associations are obliged to change their housing stock to a sustainable stock due to the energy agreement. These changes could result in investments such as implementation of PV-panels in a whole neighborhood at once. Hence, the grid operator have unforeseen capacity problems in the low-voltage grid (Bhattacharyya & Karremans, 2015).

3.2.2. Electricity demand in the low-voltage grid of residential neighborhoods

The energy demand in in residential neighborhood is mainly determined by the sum of energy consumption of households. A common used method to categorize the different loads is (EnergieNed, 1996):

1. Small business usage
2. Small household consumption
    a. Detached houses
    b. Family homes
    c. Flats
3. Small mixed usage

The components of residential consumption are more uniform and predictable than the other categories. The loads show annual growth on the low-voltage grids. The grids are designed by the grid operator based on the maximum demand that occurs on the end of the grid's economic lifetime (Oirsouw, 2012).

Grid operators need to predict the behavior of consumers and the increase of number of households in the grid. The behavior of consumption is unpredictable; therefore, grid operators design with extra save margins (Oirsouw, 2012). However, these extreme margins come with extra societal costs and those costs are undesirable.

As mentioned before the demand of a household is hard to predict due to the behavior of the consumers. However, the household demand depends on several components such as number of appliances, number of residents, and the size of the building. Consumption trends – due to the energy transition – predict more electrical vehicles and heat pumps in the low-voltage grid. Heat pumps replace the domestic boiler for heat production and reduce CO_2 emission (Jeremy & Kelly, 2006). These pumps function on electricity instead of natural gas. Furthermore, these heat pumps require more from the physical state of the building. Therefore, the heat pumps cannot be implemented in every household; nevertheless, an increase of heat pumps is visible in the past few years. The number of heat pumps increased with 52.000 in 2010. The heat pumps still cover only 1 percent of all the heating devices; however, they grow every year with 20 percent (ECN; Energie-nederland; Netbeheer nederland, 2014). In 2012 the total number of installed heat pumps in households was 88.331 and increased in 2013 to 101.066 *(+ 14 percent)*. The total number of heat pumps increased with 15 percent (CBS, 2014).

Slowly, electrical vehicles are replacing the conventional vehicles which use fossil fuels. These vehicles have little CO_2 impact and presently these vehicles are more attractive due to policies. To sum up, the most important trends on the demand side are heat pumps, electrical vehicles, and smarter domestic appliances (Veldman, 2013).

These developments are important for actions of a grid operator. If these developments create higher loads than expected by the grid operator – simply because it was unlikely to be foreseen – the designed grid fails.

3.2.3. Capacity of the low-voltage residential grid

Capacity problems may occur due to these developments of the electricity demand and supply in a low-voltage grid. However, which elements determine the capacity of a low-voltage grid?

The grid capacity is especially determined by the capacity of the cables and distribution transformers in the low-voltage grid. Furthermore, the present grids have fixed grid capacity based upon these cables and transformers in the grid. The developments in these low-voltage grids are incentives for more capacity and more flexibility. The general solution for extra capacity is the reinforcement of the existing elements in these low-voltage grids. However, capacity problems can also be solved with other solutions which are more flexible.

Capacity problems – due to developments on the demand and supply side – are likely to occur. The capacity of the grid could be upgraded by the conventional method which implies thicker cables and heavier distribution transformers. Furthermore, these solutions are fixed and not very flexible; therefore, flexibility solutions in the electricity grids become more and more interesting. In 3.3. Flexibility options in a low-voltage residential grid these flexibility options are explained. The loads on the grid

3.2.4. Demand and supply profiles

The new developments create extra loads in the low-voltage grid. These loads have certain profiles over time. These profiles are predicted or modified in the scientific literature and used for capacity analysis. Load profiles of different technologies are described in this paragraph and the method behind the creation of those profiles.

The loads could be segmented to technology or type of consumer. The summation of domestic appliances is monitored by different agencies. EDSN (energy data services Netherlands) is responsible for public information in the Dutch energy market. This agency publishes electricity usages of an average household in the Netherlands. The electricity demand of one average household is provided in fractions each quarter. A daily load profile in Watt is depicted in Figure 7.

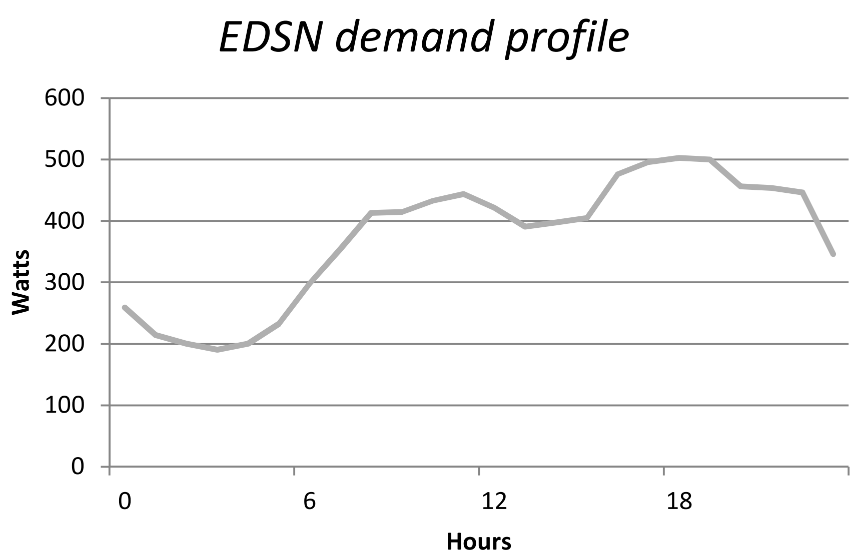

Figure 7: Demand load (W) of an average household in the Netherlands

The depicted profile is not segmented and general due to top-bottom approach. This approach means that the sum of all profiles is divided by the number of profiles. The EDSN profile is smoother than one measured profile. The EDSN profile is used by many Dutch grid operators and related organizations due to public access. An actual measurement of a randomly picked domestic load is much more accurate. In Figure 8 the profile of a house built before 1940 is depicted. A couple without children lives in this house; furthermore, the type of building is a semidetached dwelling. The difference between both profiles is clear. To conclude, segmented domestic profiles differ with average profiles and therefore loads could differ in the lower grids. If the measurements are completed on a higher level then the load profile will become more and more a plurality of the average profile.

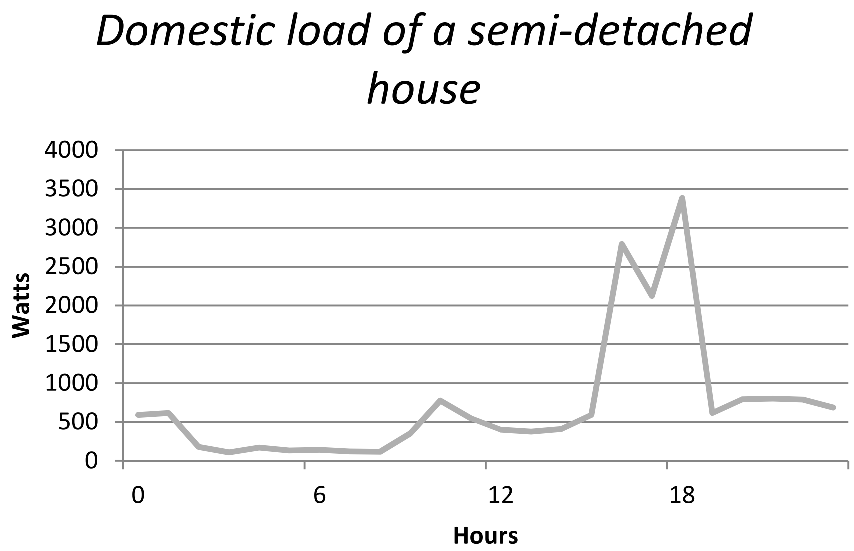

Figure 8: Demand load (W) of a semidetached dwelling built before 1940 in the Netherlands on 01-01-2013

A load profile applicable for capacity analysis in the low-voltage grid should be determined by the research goals. In the depicted profiles of Figure 7 and Figure 8 the electricity demand of general household appliances are combined. New demands and supply techniques are not included in these profiles. Those required demand loads must be added to the basic household profiles. First, the supply profile of PV is discussed. Then, the demand profiles of heat pumps and electrical vehicles are described. The supply load must be deducted from the demand load to create the net load.

The PV loads are most of the time simultaneous because the systems start and produce at the same time. A profile of a PV system is depicted in Figure 9. The PV-systems start in the morning and stops with sundown. The generation intensifies due to heavier sunshine during the day. In the winter months the generation is little to none compared with the summer situation. The peaks on a sunny day are just 60 percent of a summer peak. The PV-systems do not generate at all during some days in the winter. The generation in the summer could create capacity problems because the system was not designed for bottom-up generation.

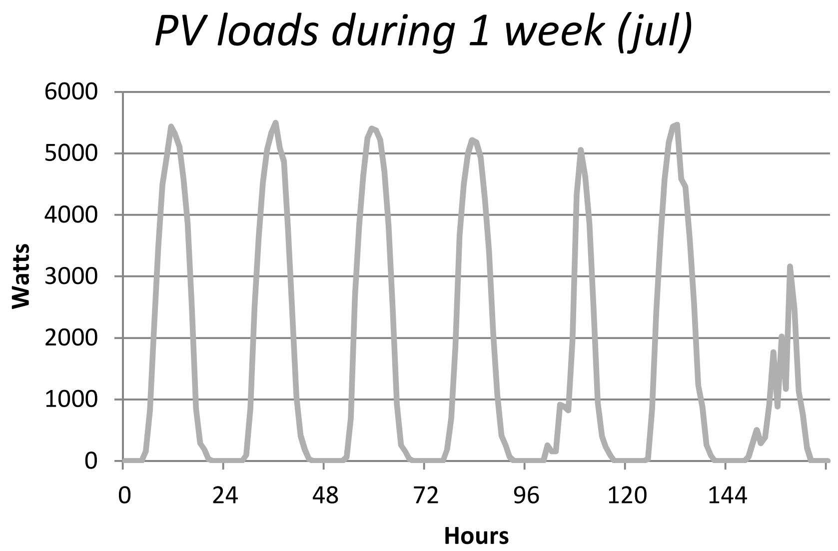

Figure 9: Supply load (W) of a PV-system

A heat pump demand profile differs during a daytime. Sometimes the heat pump is active, and then the heat pump could deliver hot water or heat the dwelling. These two different active states create spiky profiles. A load profile of a measured heat pump in July is depicted in Figure 10. The heating state of the heat pump is not visible in this figure.

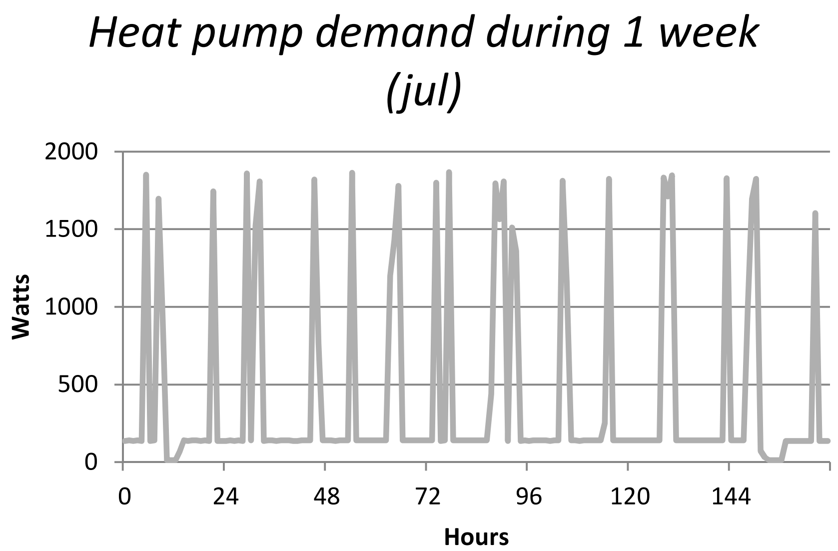

Figure 10: Demand load (W) of a Heat Pump in July during 1 week.

The demand loads of a heat pump are at least the present domestic load. The demand load is doubled due to one single appliance. The simultaneity of these loads could mean a double load on the grid. Electrical vehicles expect also high loads distributed in the low-voltage grid.

An electrical vehicle is charged with at least a 3.7 kW peak load. The electrical vehicles charge – without intervention – since the consumer connects the car till the battery is full. The load profiles of EV on low-voltage grid are scares. The penetration of electrical vehicles in these grids is minimal. Nevertheless, some approaches modelled these demand profiles with the use of passenger movements in the Netherlands. Veldman created an average profile due to the arrival time of resident at home. The period of charging is determined with the distance traveled that specific day (average of 30 km). In this database 44000 respondents are used to determine a final average charging profile which is depicted in Figure 11. The work of Veldman is useful and with the scarcity of data necessary. However, the charge profile of one single charging station is very different, see Figure 12. The most valid use of these profiles should be elaborated. The use of the right data could differ per case. Simultaneity of all these loads could be crucial on the low-voltage grid. In this grid the loads are not summed and combined to average loads. The loads on higher levels are better predictable and smoother. The simultaneity of these loads could be managed with different approaches. The peaks of the loads are then not simultaneous. The management and flexible approaches for an improved load share in the grid are discussed in the next paragraph.

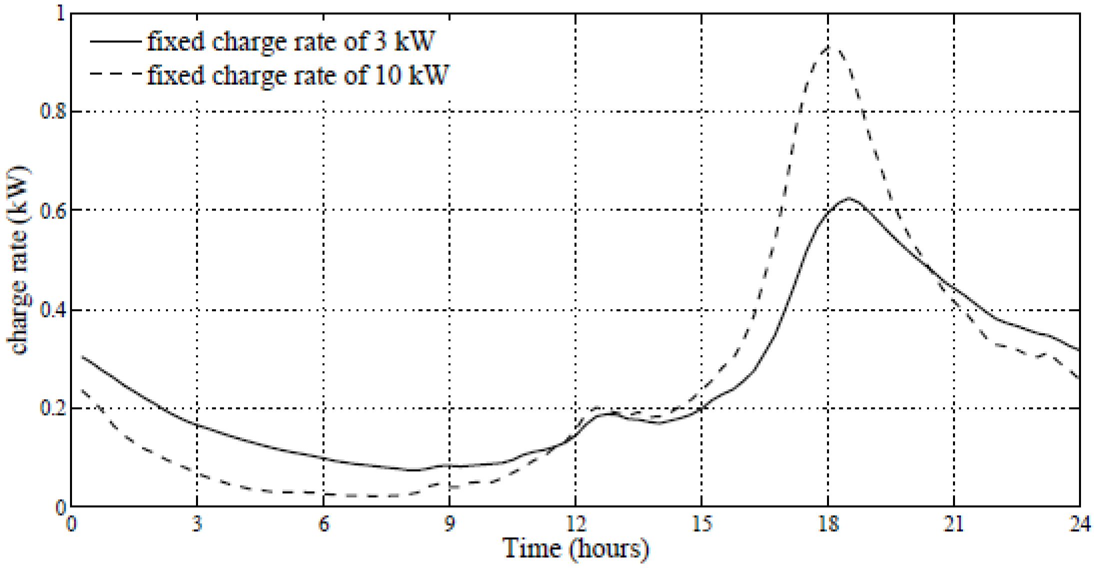

Figure 11: aggregated load profile of EV – fixed charge rate.

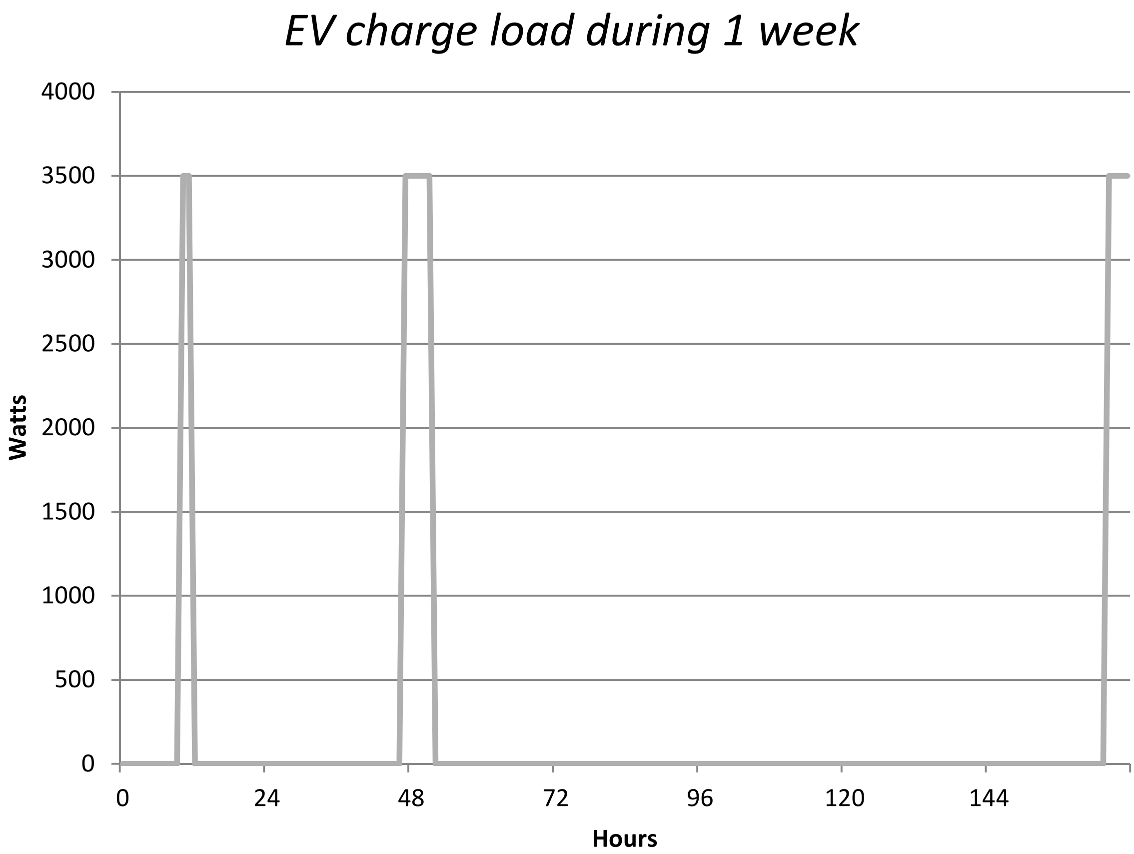

Figure 12: Demand profile of a charging station in Pilot case of Liander

3.3. Flexibility options in a low-voltage residential grid

The conventional governance of grid operators is no longer the only solution for grid capacity problems. In this section different flexibility options are discussed. Some will have their influence on demand, others on supply or extra capacity. However, all these solutions create more flexibility in the present low-voltage grid.

3.3.1. Defining the term flexibility in an energy system

The system between supply and demand need to be balanced. This balancing means that the supply and demand need to match on each time. Furthermore, the system creates extra capability to deal with unpredictable events on the demand and supply side (Lund, Lindgren, Mikkola, & Salpakari, 2015). Flexibility could manage these unpredictable events in a better way. What is meant by the term flexibility in the electricity grid? Ma et al. define flexibility in their paper:

The term flexibility describes the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons. (Ma, Silva, Belhomme, Kirschen, & Ochoa, 2013)

Ma et al. also mention the costs in relationship with flexibility which is crucial in grid operator perspective. For example, the investments in flexibility should always be reasonable. The authority of consumer and market asses the reasonableness. Another definition is given by Olsen et al. This definition is based on more flexibility due to several options. Their definition is:

Improved system flexibility from generation units, energy storage, or demand response; renewable resource diversity, enabled by expansion of transmission infrastructure; and mechanisms to ensure adequate planning and operating reserves for system reliability. (Olsen, Jones, Hart, & Hargreaves, 2014)

The additions of Olsen et al. are the diversity of RES and mechanism to ensure adequate planning. The reliability as mentioned in both definitions is a key-value for a grid operator. Their grid should facilitate in a safe, secure and reliable way as stated in their company values in paragraph 2.3.2.

The energy system can become more flexible due to flexible powers plants, storage, demand side management and coupling the heat system (Hedegaard, Mathiesen, Lund, & Heiselberg, 2012). These energy system solutions are discussed in the upcoming paragraphs.

3.3.2. Demand side management (DSM)

Demand side management is categorized by different shape patterns. Gellings and Smith describe in their paper six different load shapes which are depicted in Figure 13. Demand side management requires a form of intermediate storage and the utilization of electricity could not be a fully 100 percent (Lund, Lindgren, Mikkola, & Salpakari, 2015).

In these six categories, a couple of interventions decrease their load profiles: peak shaving and conservation. Peak shaving reduces the maximum peaks of a load profile. These peaks determine the minimum required capacity. The consumer is assisted to decrease their demand in both interventions. The guidance can be performed in different ways such as smarter appliances or more consumption awareness. If these maximum peaks decrease the grid will have more unused capacity and thus the ability to react on unanticipated events. This last observation is a clear example of more flexibility as mentioned in 3.3.1. Defining the term flexibility in an energy system.

Valley filling and load growth are both categories which focus on increasing the profile. The increased demand could mean more revenue for the energy sector. Furthermore, valley filling could create better prices for the customer because the lower demand in the total market. Valley filling is often combined with load shifting.

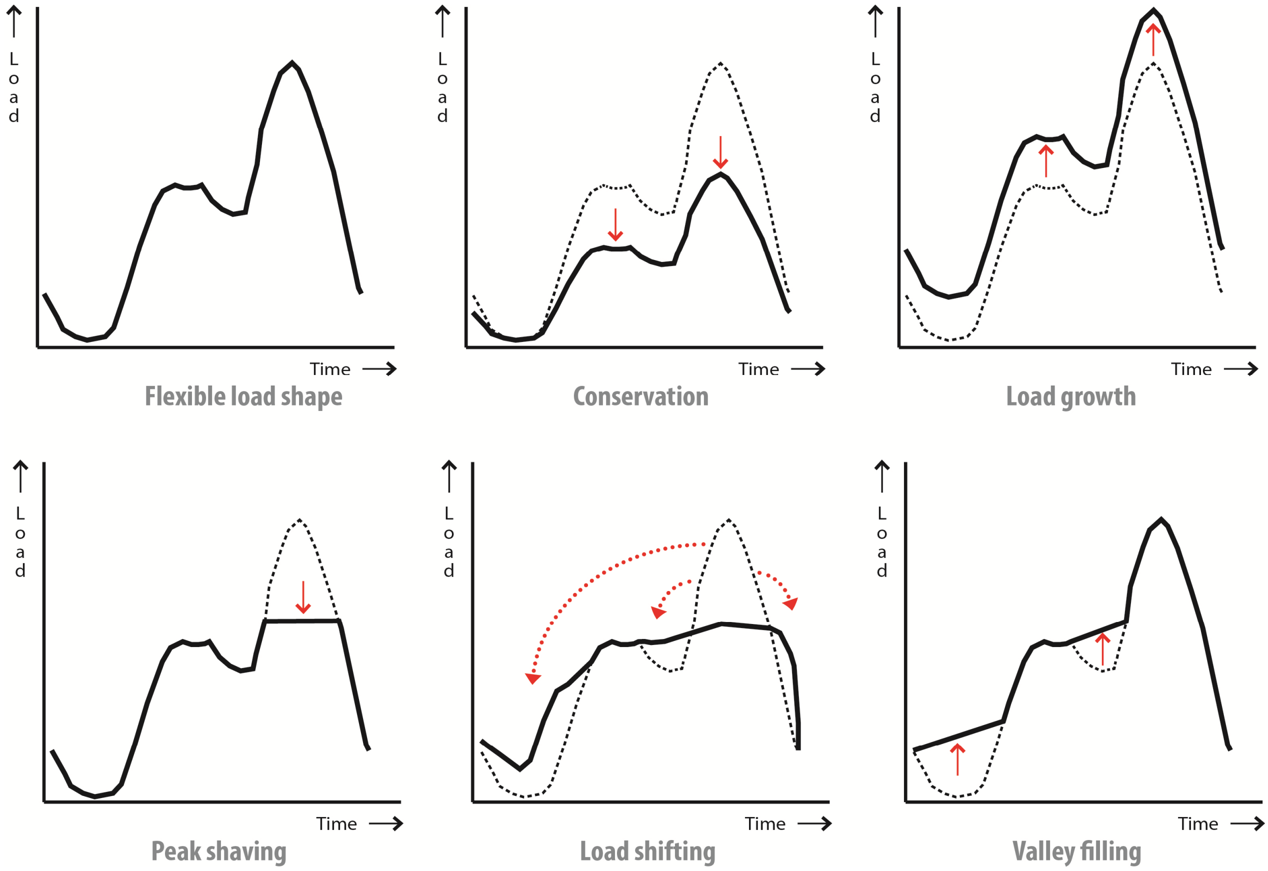

Figure 13: Load-shaping

Load shifting has as purpose to reduce the load peaks. These peaks are shifted to periods with lower loads. Such a situation could be created by incentives to use appliances – which are normally used during such a peak – when there is little or no consumption. These DSM measures are used for goals which could create more flexibility in the grid. These goals are balancing energy and capacity, flattened profiles, and efficiency measures (Lund, Lindgren, Mikkola, & Salpakari, 2015). The measures on the supply side are described in the next paragraph.

3.3.3. Supply side flexibility

The energy system can be divided in supply and demand. Those two categories require different flexibility solutions. Flexibility in supply could be reached with diversity of renewable energy sources. Furthermore, the flexible power plants create extra flexibility because they can be activated to cope with energy shortage.

Supply side flexibility is defined by Lund et al.: *With supply-side flexibility, we mean measures or technologies through which the output of power generation units can be modified to attain the power balance in the grid, e.g. when large amounts of variable renewable energy power are in use.* (Lund, Lindgren, Mikkola, & Salpakari, 2015)

The grid balance should be guaranteed by three types of power plants: base load, peaking, and load following power plants. The base load power plants are mainly nuclear and coal in the present system. These plants run a constant power level. These plants cannot be shut off due to economic reasons or technical aspects. Peaking power plants do not generate constantly; however, these plants generate on high demanding moments. The third category – load-following plants – are the balancing plants in the grid. Load-following plants produce on different sources such as gas and hydropower. The load-following plants have a short response time and thereby these plants are suitable for balancing measures. (Kilmstra & Hotakainen, 2002)

The mentioned power plants are more predictable then renewable energy sources in their behavior. The diversity of renewable energy generation is an important new flexibility aspect. After the energy transition, the energy supply is 100 percent sustainable and thus renewable. The power plants which are fossil based will no longer be in use. A 100 percent renewable energy system is physically possible as concluded by Lund & Mathiesen for fellow European country Denmark. Biomass power plants will have an important role in such a system. The process for creating a 100 percent renewable system in 2050 is very complex and need much attention (Lund & Mathiesen, 2009). The unpredictability of renewable generation by wind and solar makes this system more complex than the present system. The way of operating a renewable energy system requires a radical change. The system will use electricity and the combustion of natural gas will decrease. The heating part of the system will change due to implementation of heat pumps. The transport sector will use more and more electrical vehicles or synthetic fuels. (Connoly & Mathiesen, 2014) The present system and the new system are depicted in Figure 14 and Figure 15. These figures are schematic and will provide an impression of the increasing complexity. This complexity is for the whole system and thus for the supply side. The demand part of the systems remains the same; however, higher penetrations have their impact.

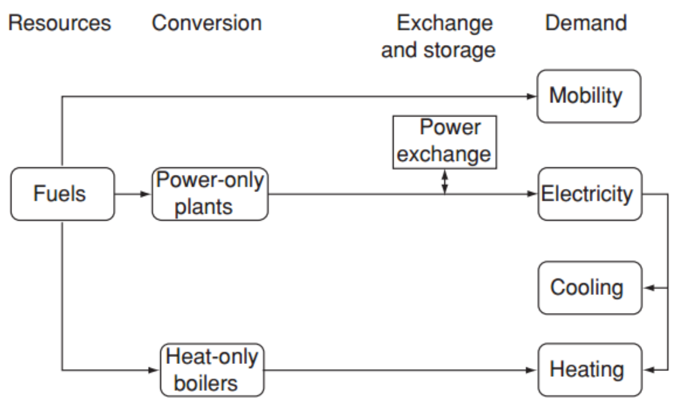

Figure 14: Interconnected sectors and technologies in the traditional energy system (Connoly & Mathiesen, 2014)

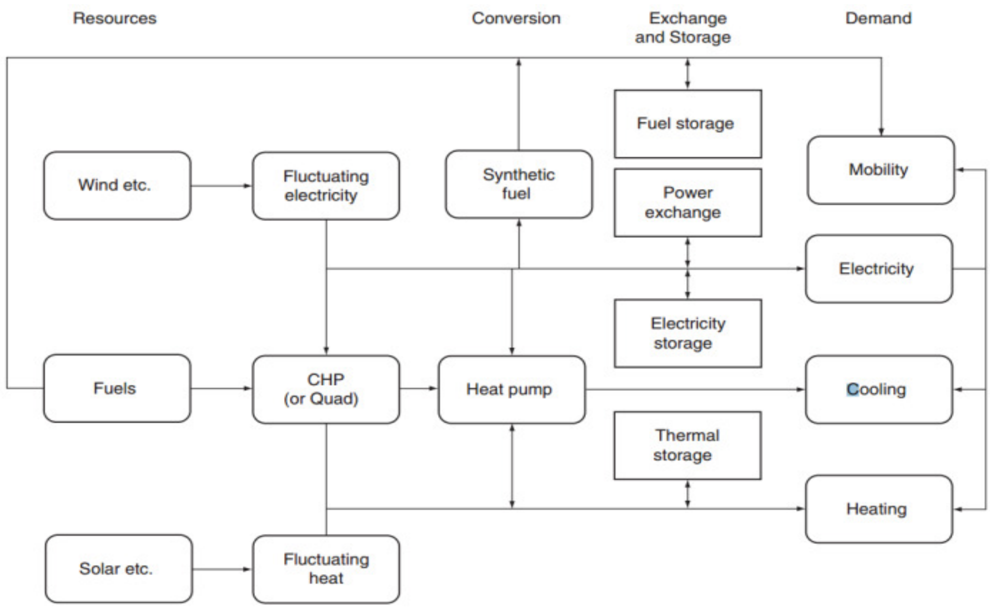

Figure 15: Interaction between sectors and technologies in a future smart energy system (Connoly & Mathiesen, 2014)

3.3.4. Capacity side flexibility

Extra capacity is reached in the (smart) grid due to implementation of new assets. These assets could be new substations, cables or distribution boxes. These assets are the core of a low-voltage grid; however, the addition of these assets is not always desirable or optimal. Furthermore, the grid could increase the capacity with other means. The implementation of storage is thereby a very interesting option. Storage could tackle many problems at once. Storage could help the integration of renewables in the grid. Furthermore, the energy storage increases the flexibility, security and reliability of the grid (Das, Krishnan, & McCalley, 2015). There are several different types of energy storage. These are discussed more thorough in 3.4. Energy storage.

More capacity could be reached with flexible storage in the grid. The storage inside a grid could be increased for a short time due to dynamic adjustments in the storage unit (Kim, et al., 2014). The introduction of more electrical vehicles creates a naturally distributed storage unit. The technology of vehicle to grid (V2G) could create a bi-directional energy transfer (Wanger, Brandt, & Neumann, 2015). Furthermore, the integration of other heating systems gives long term seasonable energy storage options. Those storage options are part of heating systems such as heat pumps (Hesaraki, Holmberg, & Haghighat, 2014). These flexible storage units could create extra capacity. In fact, some of these storage units are available without extra investments.

3.3.5. Flexibility and the grid operator

The grid operator is responsible for a reliable and secure grid. The investments should be social responsible thus the grid operator is interested in flexibility solutions which are less expensive. If the flexibility investments can outweigh the conservative measures than a more social responsible solution is found. The importance of flexibility is reinforced by a workgroup of NetbeheerNederland, ECN, GasTerra and Energie-Nederland. The energy system and the addition of more flexibility is discussed and evaluated. The workgroup creates a research report which could lead to a more integral approach. The grid operator manages their own part of the system; however, their flexibility measures influence the whole system. Therefore, their role could be a crucial one and therefore they anticipate.

3.4. Energy storage

One of the solutions for a more flexible system is the implementation of energy storage. The implementation of energy storage could solve multiple problems in the electricity grid and therefore could be very interesting for grid operators.

In the upcoming chapter several systems are discussed – which may be relevant – for the low-voltage grid. Some systems are not applicable on a lower scale and thus are mentioned for future developments and a complete overview. The energy storage technologies which are discussed are: the flywheel, pumped hydro energy storage, compressed air energy storage, hydrogen energy storage, superconducting magnetic energy storage, supercapacitors, and batteries.

3.4.1. The flywheel

The flywheel is a mature energy storage principle. A flywheel is used for Uninterrupted Power Supply storage (UPS) for over more than five decades. The research on magnetic flywheels created a base for more industrial applications. The final achievement is a mechanical battery which can withdraw electrical power during an energy surplus and discharge during energy shortage. (Owusu-Ansah, Yefa, Ruhao, & Huachun, 2014)

The flywheel got several benefits such as quick response time and high reliability. A flywheel could easily switch between storing and supply energy. The short response time could also help with sudden changes in the grid (Koohi-Kamali, Tyagi, Rahim, Panwar, & Mokhlis, 2013). However, the flywheel technology also got some downsides. A flywheel energy storage system got a relatively short duration. The system got a high frictional loss due to windage. Moreover, the system got a low energy density. (Chen, et al., 2009)

The application of a flywheel energy storage system in a low-voltage residential grid is depending on the requirements for such a system. This system got some advantages and shortcomings.

3.4.2. Pumped hydro energy storage (PHES)

A PHES system acts on a total different scale than the flywheel. The PHES system is the largest used energy storage system in the world. This system is responsible for 99 percent of the world’s total storage capacity (Tuohy, Kaun, & Entriken, 2014). A PHES system is commercially proven with a scale of at least 100MW. Three-hundred PHES plants are installed worldwide and the number is increasing due to interest from Japan and Europe. (Deane, Ó Gallachóir, & McKeogh, 2010)

The benefit of pumped hydro energy storage is not only based upon the maturity of the principle. Moreover, the technology could be applied in large scale project in combination with renewable projects (Lund, Lindgren, Mikkola, & Salpakari, 2015). The development for a more flexible system which is applied on more locations is ongoing.

The clear disadvantages are the physical requirements for a PHES system. The location of a PHES plant requires an elevation difference and water. Furthermore, the connection with an electricity transmission network is crucial. The elevation does not have to be naturel as long as there is a possibility to dig an elevation (Lund, Lindgren, Mikkola, & Salpakari, 2015). Although there is a possibility of custom made elevations these systems require much space and investing.

3.4.3. Compressed air energy storage (CAES)

The principle of compressed air energy storage is a relatively mature and operating. The system uses large caverns for compressed air storage such as ancient salt mines and natural gas caves (Ibrahim, Ilinca, & Perron, 2008). The technology compresses air to a higher pressure. The stored air is mixed with a fuel which is combusted and expanded through turbines. CAES is a variation of a gas turbine with an addition of compressed air. The CAES system could be well integrated with renewable sources such as wind farms. (Lund, Lindgren, Mikkola, & Salpakari, 2015)

One of the benefits of CAES plant is the potential for more related renewables. Furthermore, the system has the same benefits as PHES systems because of the many similarities in the principle of the technology. The cons of this technology show similarities with PHES system as well. In this case, the need for a large storage space is problematic. Furthermore, this system seems more suitable for a connection on a higher grid level.

3.4.4. Hydrogen energy storage

Hydrogen energy storage consists of four steps. The first step is from electricity to an electrolyser. Secondly, the electrolyser creates hydrogen in a stored form. Thirdly, the hydrogen is brought to a fuel cell when electricity is required again. Finally, this fuel cell transforms the hydrogen to electricity. The energy is temporally stored in hydrogen due to an electrolyser. The hydrogen is then an energy source in combination with a fuel cell to create electricity. (Dell & Rand, 2001)

This energy storage principle is more sustainable than other alternatives. Although hydrogen and fuel cells are not strictly renewable the availability of these sources is abundant. The hydrogen system got a high storage capacity. The psychical aspects are favorable caused by the size of a storage system: a shipping container. A disadvantage is hydrogen storage. The hydrogen is hard to contain in some sort of storage due to his structure.

3.4.5. Superconducting magnetic energy storage (SMES)

A SMES system stores electricity in a direct current. This direct current generates a magnetic field in a large superconducting coil. The SMES system works on a very low temperature: cryogenic. The superconductive technology is only feasible and applicable on electrical utilities. The principle was introduced at large power plants; however, nowadays these SMES systems can be installed in a truck trailer. (Buckles & Hassenzahl, 2000) The system may be used for power quality, small-sized applications and energy storage.

A benefit of this system is minimal energy loss during operation. The only energy loss occurs during operation is caused by conversion between alternate current and direct current (Lund, Lindgren, Mikkola, & Salpakari, 2015). The SMES is capable to handle very low temperatures due to his cryogenic functioning. A SMES system has high durability and efficiently. Furthermore, the responds time is very fast and the system has little maintenance. (Ferreira, Garde, Fulli, Kling, & Lopes, 2013)

The downsides on the other hand are the cost of a SMES system. A SMES system is expensive. The magnetic field could cause issues. Moreover, the constant low required temperature is a disadvantage. (Ferreira, Garde, Fulli, Kling, & Lopes, 2013)

3.4.6. Supercapacitors

The supercapacitor was formerly known as ultracapacitor. At the moment, the system is mostly used in electrical vehicles. Supercapacitors are suitable for electrical energy storage.

A supercapacitor has several benefits relatively to other energy storage systems. A supercapacitor has a rapid charge/recharge capability. The power density is high. A supercapacitor degrades very slow even after 100,000 cycles. A supercapacitor has little to no maintenance and a high reliability. The temperature for system operation is wider than other systems. Furthermore the system has lower impact on the environment. (Bullard, Sierra-Alcazar, Lee, & Morris, 1989)

The downsides of supercapacitors are the low energy density and the high price of a system. The recent developments in nanotechnology will deduce these negative aspects. (Liu, Mao, Lu, & Wang, 2009)

3.4.7. Batteries

The batteries which can be seen as energy storage systems are those who are rechargeable. A secondary battery or rechargeable battery is based on two electrodes. These electrodes have affection to different electrons and the stream of electrodes determines charging or discharging. (Lund, Lindgren, Mikkola, & Salpakari, 2015)

The battery systems do differ in their chemical composition and therefore there arise various advantages and disadvantages. The battery systems are described by invention year chronologically. The argued systems are based on the following chemical composition:

- Lead-Acid;
- Nickel-Cadmium;
- Nickel-Metal hydride;
- Sodium-Sulphur;
- Sodium Nickel-Chlorine;
- Lithium-Ion.

3.4.7.1. Lead-Acid batteries

Lead-Acid batteries have matured over time. The first Lead-Acid battery was charged in 1859 and was invented by Gaston Planté. Since then the design and configuration changed; however, no real change in reactions occurred. The modifications were mostly material or design-based. A Lead-Acid battery got a coulombic efficiency around 85 percent. The energy efficiency is approximately 70 percent. (Rand & Moseley, 2015) The implementation of these Lead-Acid batteries occurs and several pilots have been done.

Benefits of Lead-Acid batteries are the low cost per unit energy capacity (Lund, Lindgren, Mikkola, & Salpakari, 2015). The system could easily be adjusted to the grid requirements. Capacity can be added just by increasing the electrolyte storage tanks. Further, the high energy density compared to other systems is a benefit. (Bates, Mukerjee, Lee, Lee, & Park, 2014)

The process of deposition of Lead-Acid batteries is crucial for the degrading of the battery. This reduces the lifetime of a battery and thereby the suitability. The services needed for maintenance or replacing these batteries is pricey for a grid operator. Furthermore, the functionality of these batteries is influenced by temperature fluctuations (Bates, Mukerjee, Lee, Lee, & Park, 2014).

3.4.7.2. Nickel-Cadmium batteries

A Nickel-Cadmium battery is an alkaline battery which has the properties of an alkali or contains an alkali. These kinds of batteries were discovered by Dr. Ernst Waldemar Jungner in 1899. During the 20th century some developments occurred for these batteries. The main improvement is done by Dr. P. Bernhard due to a new plastic bonded positive electrode. This development reduces the cost and improves the high electromechanically performances.

The Nickel-Cadmium batteries have several advantages:

- High discharge rate;
- Long cycling life;
- Low initial cost;
- Can support a certain amount of overcharge;
- Robustness and reliability.

(Bernard & Lippert, 2015)

A downside from Nickel-Cadmium batteries is that these batteries are highly toxic. The batteries have to deal with the memory effect. The batteries slowly lose their maximum energy capacity if they are repeatedly charged, this phenomena is called memory effect. The battery seems to remember the smaller capacity. Furthermore, the cell operates low voltages. (Lund, Lindgren, Mikkola, & Salpakari, 2015)

In the next paragraph a variant battery is discussed. This battery is an also Nickel based.

3.4.7.3. Nickel-Metal Hydride batteries

This battery type is a variation on the Nickel-Cadmium battery. Almost simultaneously and besides Jungner, Thomas Edison discovered and patented Nickel-Metal batteries around 1901. After a conflict between both inventors, Edison focused on the development of Nickel-metal hydride batteries and Jungner developed the Nickel-Cadmium batteries (Bernard & Lippert, 2015). The batteries are common used in consumer electronics and electrical vehicles.

A benefit of these batteries is the replacement of cadmium by metal. Thereby the highly toxic part of the batteries is replaced. The other benefits match with the benefits discussed in 3.4.7.2. Nickel-Cadmium batteries.

Negative aspect of this technology is the high self-discharge rate and the rare minerals required for creating this battery. (Ferreira, Garde, Fulli, Kling, & Lopes, 2013) Furthermore, most of the downsides of Nickel-Cadmium are applicable, except the high toxic levels.

3.4.7.4. Sodium-Sulfur Batteries

The Sodium-Sulfur battery is developed in the second part of the 20th century. In 1960 N. Weber and J.T. Kummer described the battery system at Ford Motor Company (Weber & Kummer, 1967). The manufacturing of these batteries were highly demanding of the producer. A malfunction was easily created. The batteries must be sealed hermetically. However, due to developments these problems have been overcome in the past 40 years. (Mosely & Rand, 2015)

Sodium-Sulfur batteries are deployed in several countries such as Japan, Germany, USA, and France. They function for four purposes, namely:

- Load-leveling;
- Power quality;
- Peak-shaving;
- Integration and management of renewables. (Mosely & Rand, 2015)

The Sodium-Sulfur batteries do have a long life cycle. They are produced with use of less expensive sources. The specific energy is significant higher than other battery systems (Mosely & Rand, 2015). The batteries have low maintenance and can be used for pulse power. Furthermore, these batteries can easily switch between charging and discharging (Lund, Lindgren, Mikkola, & Salpakari, 2015).

This battery system only functions at temperatures between 300 °C and 350 °C. These temperatures are required even when the system is idle. Safety issues are also greater due to the high operating temperatures.

In the next paragraph a related high temperature battery is discussed.

3.4.7.5. Sodium-Nickel-Chlorine (Zebra) batteries

This 'Zebra' battery system is relatively new and patented in 1978. This battery system operates also at high temperatures, namely from 270 °C till 350 °C. The reaction inside the battery does not have a side reaction and therefore the charge efficiency is 100 percent. The Zebra battery system is designed for electrical vehicles (Dustmann, 2004).

The benefits & disadvantages do not differentiate much from the other high temperature battery system. However, the Zebra batteries are more robust against overcharge and over-discharge. Moreover, the safety issues are lower than those of a sulfur system; although, there are still risks caused by the high temperatures (Dell & Rand, 2001).

3.4.7.6. Lithium batteries

The latest invention in the battery branch is the Lithium battery. This battery technology is state-of-the-art due to their superior performance. In 1971 M. S. Whittingham proposed the idea of lithium batteries; however, the first commercial battery ($LiMoO_2$) was produced by Moli in the late 1980s. This battery system did not thrive due to safety issues. In 1991 the Lithium-Cobalt-Oxide battery was introduced by Sony. This system overcame the safety issues of their competitor Moli. Nowadays, the Lithium batteries are applied in small mobile devices, electric vehicles, and grid stabilization systems. (Kurzweil, 2015)

The lithium-ion battery has several variations in composition. The battery compositions used for grid stabilization are given in order of market share:

- $LiMn_2O_4$ spinel (LCO);
- $LiNi_{0,8}Co_{0,15}Al_{0,05}O_2$ (NCA);
- $LiNi_{0,33}Mn_{0,33}Co_{0,33}O_2$ (NMC, MNC);
- $LiFePO_4$ (LFP).

(Kurzweil, 2015)

The Lithium-Ion batteries do have many advantages. They score excellent in specific energy, energy density, and specific power. Lithium-ion batteries almost outweigh every other system on these criteria. However, the lithium batteries do have disadvantages. The technology is not much used for high power solution because of the high prices. The cost of this technology is more expensive than competing systems. Furthermore, safety issues could occur due to high temperatures. A Lithium battery should be stored ideally below ambient temperatures and should not be stored under minus 40 °C. If the system is exposed to high temperatures several events could occur: explosion, short circuits, and thermal runaway. The batteries should not be operated above 70 °C. The resources of Lithium are sufficient available for us in the 21th century. The lifecycles of lithium-ion batteries are not totally clear. Degrading factors are charging, temperature and number of cycles.

The main disadvantage is the high cost. A mid-term Lithium-ion battery costs 500 -600 € kW/h. The high power systems have multiplied these prices with a factor three till five. Nevertheless, these high costs will decrease price until 2020: 200 € kW/h. (Kurzweil, 2015)

Tesla showed enormous progress in April 2015 with the introduction of the Powerwall and Powerpack. The prices of Tesla are 250 $ kW/h and 350 $ kW/h.

3.4.8. Applicable storage systems in a low-voltage residential grid

Some of the mentioned energy storage systems are not applicable in low-voltage residential neighborhoods. Although PHES systems are responsible for 99 percent of the total world's energy storage they are not applicable in a common residential neighborhood in the Netherlands or even Europe. These systems require enormous spaces and therefore they are mostly deployed near the higher ends of the grid. The requirement of much or specific space is also the reason why a CAES system will not work in a residential neighborhood.

The other systems – such as SMESs, Flywheels, Batteries, and supercapacitors – could not be ruled out immediately. These systems got all disadvantages; however, none of these reasons is decisive. The specific benefits do not prefer a system either. The purpose and need for the system will determine which technology is more suitable. The chosen system will bring in different kind of costs and side effects which should be managed by the grid operator or the owner. The Lithium-Ion battery is superior several aspects such as power-density, energy density. In Figure 16: Key parameters of selected secondary battery chemistries this superiority is compared with other systems.

Chemistry	Efficiency (%)	Specific energy (W h/kg)	Energy density (W h/l)	Specific power (W/kg)	Cycle life (cycles @ DOD), NR=DOD not reported
Lead-acid (PbA)	75–85	20–40	55–90	75–415	250–2000 @ 60% 200–800 @ 80% 300–1000 @ NR
Nickel–cadmium (NiCd)	60–75	40–65	60–150	100–175	5000 @ 60% 1000–2000 @ 80% 2000–2500 @ NR
Nickel–metal hydride (NiMH)	64–66	45–80	140–300	200–1500	300–1200 @ 80% 200–1500 @ NR
Sodium–sulphur (NaS)	75–85	100–200	150–250	150–250	1000–5000 @ 80% 1000–5000 @ NR
Sodium nickel–chlorine (Zebra)	90–100	85–140	150–175	150–250	1500–3500 @ 80% 1000-3000 @ NR
Lithium-ion (Li-ion)	90–100	90–190	250–500	500–2000	500-7000 @ 80%

Figure 16: Key parameters of selected secondary battery chemistries (Lund, Lindgren, Mikkola, & Salpakari, 2015)

The developments at Tesla decreased the purchase price drastically. Therefore, a Lithium-Ion system is chosen as alternative solution for the research of chapter four. The EES is suitable for grid operations and could be used as flexibility option.

In the next paragraph the total cost of ownership is discussed. This concept tries to give a total overview of the cost made during a lifetime of the product.

3.5. Total cost of ownership (TCO) of grid investments

Recently, the method of total cost of ownership is more used due to it added value. Total cost of ownership does not have one universal formula. The total cost of ownership does not only take in account purchase price. This is only a small part of the total cost estimation. The TCO-method takes the during a lifetime expenses in consideration. TCO is defined by Hockel and Hamilton as: *TCO is a five-step methodology used for comprehensive lifecycle planning to ensure that all associated costs over a given time period are considered when acquiring an asset.* In their report they describe the importance of TCO and mention the benefits and limitations of this method. The variables used in this report are modified to match them with the investments of grid operator. These variables are described in the next paragraph.

3.5.1. Variables

The report of Hockel and Hamilton provides three examples of TCO sheets. The variables used in these sheets are:

- Purchase price;
- Installation costs;
- Financing costs
- Energy costs
- Repair costs
- Upgrade costs
- Maintenance costs
- Repair costs
- Downtime costs
- Disposal costs

The variables indicate some of the many possibilities. Additional variables can be added as required. These variables will differ per case. The TCO method is closely related to other methods such as life-cycle costs, zero base pricing/all-in costs and cost-ratio method. The chosen variables are described in 4.3.3. Total Cost of Ownership.

3.5.2. Benefits and limitations of TCO

In multiple papers TCO is described and the benefits and limitations are distracted. The benefits are multiple. The supplier of the product could be consistently be evaluated. Thereby, the performance of a supplier is defined and clarified. The TCO reveals priors in which cost savings are possible. Furthermore, the result of TCO creates data for negations with possible suppliers. Finally, the high initial costs can be justified over a total lifetime. The creation of a long term vision is thereby achievable. (Ellram, 1995) TCO is useful for budgeting two similar projects (Wettemann, 2008). The reinforcement of the low-voltage grid is done with two approaches. The insights of calculating the investment costs with the help of TCO could be beneficiary for the grid operator. The initial high costs could be justified by the grid operator if this solution is cheaper in the long time.

On the other hand TCO has downsides and limitations. The method requires hard numbers as input. These numbers are not always available and thus the method cannot be applied correctly. Furthermore, the method does not have a universal approach and thus hard to compare. Moreover, the TCO calculations are situation specific. The method requires a cultural shift in an enterprise. Hence, if an enterprise wants to use this method it requires determination.

3.6. Conclusion

This literature review has identified some of the challenges due to the energy transition. The energy transition is shaped in the upcoming decades. New technologies occur more regularly in the low-voltage grid. The (new) technologies discussed in this literature review are: heat pumps, electrical vehicles, photovoltaic panels (solar panels). The energy system may be insufficient with higher penetration of these technologies. Therefore, a more flexible energy system could be the answer. The grid operator is responsible for maintaining the low-voltage grid. The purpose of the present study was to determine the flexibility options in the low-voltage grid. One flexibility option is chosen for the creation of a business case. This business case is solved with the Total cost of ownership method.

The loads on a low-voltage grid and the simultaneity of these loads are crucial. The domestic demand loads are obtained from different sources. The use of real measurements is preferred. Otherwise the average profile of EDSN could be used. The load profiles of the new technologies should be matched with the specific case. Different future scenarios show multiple challenges in the grid with different focusses. The load profiles are crucial to determine the right flexibility solution. The flexibility options in a low voltage grid are categorized into: demand side management, supply side flexibility, and capacity side flexibility. Energy storage is a flexibility solution which includes all these flexibility categories. Energy storage increases the grid capacity. Furthermore, this storage could be charged at energy surplus times and discharged in times with an energy shortage. Therefore, this solution could be applied on a low-voltage grid which is suffering with overloads and requires demand and supply side flexibility. Eventually, the grid operator chooses the social most preferable solution. A traditional or flexible solution is picked based upon the less expensive investment.

Energy storage systems come in many different forms. Some energy storage systems are not applicable on the low voltage grid such as CAES and PHES. However, a superior battery technology – Lithium-Ion – could be applied in a low-voltage grid. The decrease of price and the present developments on battery technology by Tesla are grounds to review this flexibility solution. If these batteries are cheaper than traditional grid reinforcement then this flexibility solution is preferred by the grid operator.

The next chapter describes a research in the low-voltage grid. The low-voltage grid is modeled in a load-flow analysis tool. The demand and supply loads are modeled upon several nodes which represent a number of households. The (new) technologies and their loads are also included. The research approach determines the use of case specific load data in the low-voltage grid, thus no average profiles. The capacity challenges in low-voltage grid are solved with two approaches: energy storage and the traditional reinforcement. The business case of these two upgrades is completed with total cost of ownership. The insights of this literature review contribute to the Aireywijk research case. In the first place, this case indicates the capacity and power quality problems in a low-voltage residential grid. Finally, the required reinforcement of the low-voltage grid is input for solving a business case with total cost of ownership. This business case contributes to social responsible governance of the grid operator.

Analysis of a Low-voltage residential grid in two scenarios and the costs of two upgrade approaches: traditional and with energy storage

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Abstract

The energy transition affects the low-voltage grid. More demanding technologies enter the low-voltage grid. The grid operator needs to maintain this grid. The low-voltage grids are designed for the present situation. The new energy system is much more complex. The present grid is unable to cope with these new demands & supply loads. The capacity of the low-voltage grids may be insufficient. The under capacity is examined in a low-voltage grid with help of Vision. Different scenarios are modified for new insights in an existing residential neighborhood. The case reveals capacity problems for assets such as transformer stations. These problems are solved with two reinforcement approaches. Energy storage is applied as flexible solution and the traditional solution includes heavier assets. Both solutions are input for a business case. Presently, the traditional approach of grid reinforcement is more profitable. Nevertheless, the grid operator has (new) insights in the present situation and the problems which may occur due to higher penetrations of technologies. The most important findings are: the relevance of segmented data, monitoring and measuring new demand & supply loads is crucial, and the costs of energy storage do not outweigh the traditional upgrade costs.

Keywords: *Low-voltage grid, Mean average percentage error, Capacity analysis, Power quality, Total cost of ownership, Business case, Flexibility*

4.1. Introduction

In the fourth chapter of this report the required (future) flexibility in the low-voltage grid is described. Basically, this research consists of three parts:

- Data sampling and adjustments;
- Capacity & power quality analyses;
- Total cost of ownership calculation.

This section starts with a small introduction which sketches the boundaries of this research and the applied solutions. The method of this research is discussed in the second section. The results of completed analyses are described in section three. Finally, Chapter four ends with a conclusion and discussion.

In the upcoming years new technologies have effect on the low-voltage grid such as PV-generation and electrical vehicles. The stakeholders should cooperate to keep the grid operational as discussed in chapter 2 & 3. The renewable transition and possible scenarios are also discussed in those chapters. This research focusses on a specific case which could be an illustration for future challenges and research.

The research case is a small neighborhood in Eindhoven. The neighborhood is called Aireywijk referring to the designer of these small houses, Sir Edwin Airey (1879-1955). These buildings can be recognized due to the design with prefab concrete. A building block is depicted in Figure 17.

Figure 17: Impression of types of buildings in the Aireywijk

The social housing associations need to sustain their housing stock due to the incentives of the national government. A potential transformation of all rooftops in a neighborhood is thus very realistic. The Aireywijk has this potential and therefore this scenario is investigated for this low voltage grid.

The 232 households are distributed on multiple building blocks which all have the same design. The family composition of these households is relevant; however, this composition is left out the scope of this research. The Airey neighborhood is sixty years old and the buildings are ready for a renovation. Woonbedrijf and Morgen Groene Energie are planning this intervention. This upgrade is funded in two ways:

- a major maintenance fund of Woonbedrijf;
- A lease contribution of the residents.

The present planning reveals the implementation of new rooftops with solar panels as main upgrade for these houses. This improvement will be tendered in the summer 2015 and the execution will probably start in September 2015. Furthermore, the renovation includes additional elements such as extra isolation. The Aireywijk is depicted schematically in Figure 18. The layout of this neighborhood is common to many Dutch neighborhoods.

Figure 18: Schematic overview of the Aireywijk - Eindhoven

The Aireywijk has to deal with the impact of new technologies demand more of the low-voltage grid. The first and actual technology which will introduce itself is photovoltaic generation. The new roofs will contain 40 square meters of solar panels per house which are implemented on at least 50 percent of the houses. However, the ambition of Morgen Groene Energie reaches further than just that 50 percent. They expect that a 100 percent is feasible and then each rooftop will contain 40 square meters of solar panels. The implemented PV-systems produce a Watt peak of 5.5 kW per household. The neighborhood has a low-voltage grid which is meshed. The medium-voltage grid has a ring structure with transformer stations. Between two transformer stations a meshed low-voltage grid feeds the customers. The ring structure of the transformer stations is depicted schematically in Figure 19.

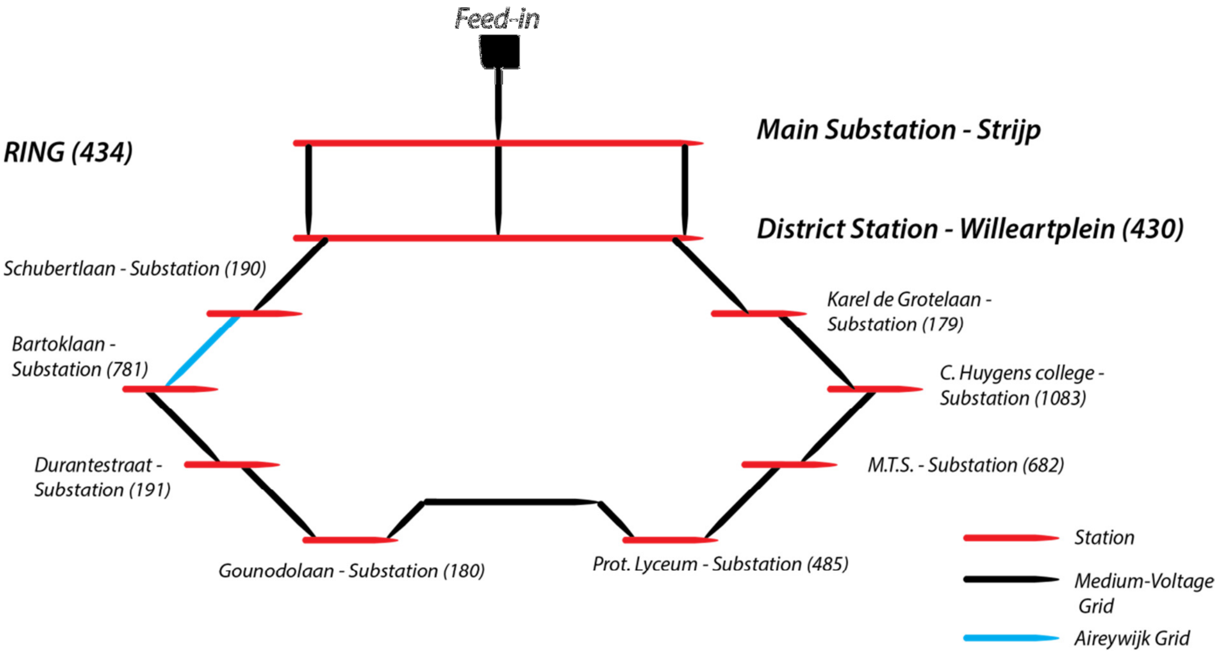

Figure 19: Ring structure (medium voltage) of transformer stations

The two transformer stations in the Aireywijk are: Bartoklaan – 781 and Schubertlaan – 190. The Bartoklaan station is a distribution station of 315 kVA. The Schubertlaan has more capacity: 500 kVA. In the Aireywijk grid different types of cables are used with diameters of 70 and 95 mm. Furthermore, the meshed grid contains six distribution boxes. This low-voltage grid has to deal with the implementation of solar panels and in the future with electrical vehicles and heat pumps.

The case of the Aireywijk is a start to discover a protocol for future similar situations for the grid operator Endinet. Many questions need to be answered and should be secured in the enterprise. This research will show the challenges for the future and could be a start for further research with more data or more suitable data. Monitoring of the new developments is crucial.

4.1.1. Importance of this research

This research investigates the importance of the segmented data. Furthermore, the analysis of capacity and power quality will indicate present challenges and future challenges. These challenges are known by grid operators; nevertheless, the analysis on a modeled grid delivers new information for the grid operator. Endinet B.V. defined this Aireywijk case as starting point for a universal process approach. The Aireywijk could be the first neighborhood in Eindhoven with many PV-systems in an existing neighborhood. Therefore, this case is a perfect learning experience. This research is shared with other grid operators and is input for the Flexnet project of NetbeheerNederland and ECN. External parties such as the heat pump association are also curious. Therefore, this research is not only relevant for the grid operators; moreover, interesting for many parties in the related sector. This research indicates new challenges and investigates possible solutions.

4.1.2. The research design

This research requires data of different technologies which are mentioned earlier. The demand profiles are required for preforming these capacity & power quality analyses. First, this required data is described and the adjustments are justified. The capacity & power quality analyses are done with a tool – Vision. Secondly, the analyses which are preformed will be described. Finally, the results are given in the next chapter. This research is divided in three scenarios. These three scenarios are:

1. Summer 2015;
2. Winter 2040;
3. Summer 2040.

Scenario – Summer 2015 – has much generation without much demand and thus this generation could cause capacity problems. The required data for this scenario is depicted in Figure 20.

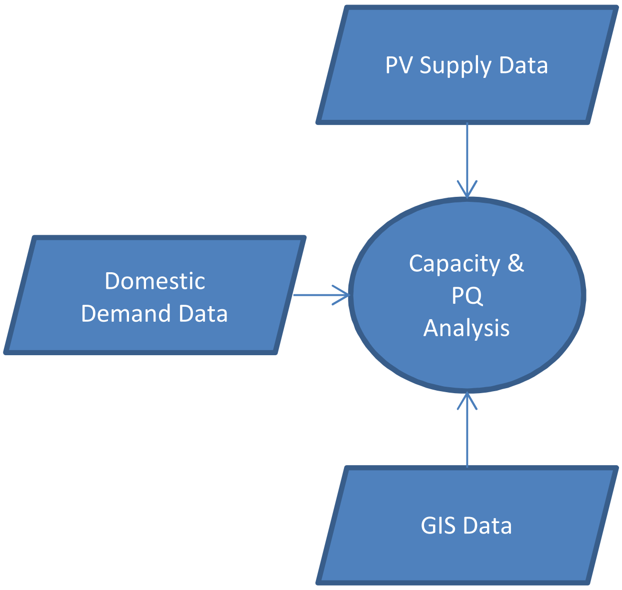

Figure 20: Required data for capacity analysis – Summer 2015

The second and third scenarios are analyses of future scenarios. In these scenarios the demand increase drastically and thus the grid capacity might be insufficient. The capacity & power quality analyses require different input as depicted in Figure 21.

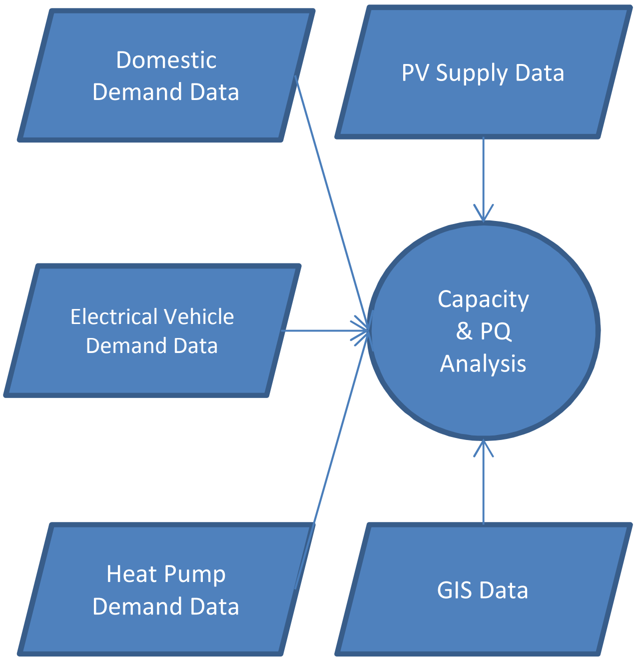

Figure 21: Required data for capacity analyses – Summer & Winter 2040

The different data is collected and adjusted by the following vision:

1. The data should be as raw as possible;
2. The data is suitable for a low-voltage grid;
3. The data is not aggregated.

These three analyses investigate multiple challenges. Scenario – Summer 2015 – could be very urgent and could have immediate impact on the grid. The bottom-up generation may provide grid capacity problems in this scenario. Secondly, the additional demand could create problems in the Winter situation of 2040. In the summer the renewable supply due to solar panels is high and the demand is low. In contrast, the second situation has little to none supply due to solar panels in the winter. Nonetheless, the demand is traditionally on the highest level. The heat and domestic demand will rise further in the future with the addition of heat pumps and electrical vehicles. The third scenario – Summer 2040 – combines both extremes. The supply and the demand are both higher. This situation may result in a combination of both problems or solve itself due to a net positive result. Variables change in these three scenarios due to other values of PV-systems penetration and home or public charging of electrical vehicles.

The Aireywijk is the starting point for this research. Furthermore, the data required for this analysis is collected through different sources and sometimes merged together to forecast future profiles. More information on the data modifications could be read in the next paragraph.

4.1.3. Data sampling

The data preparation for several researches is described in this paragraph. The data is obtained from different sources and sometimes require additional information. The data modifications are described in the following order: Domestic, PV, GIS, HP, and EV.

4.1.3.1. Domestic demand data

Domestic demand during a time period could be obtained in many ways. A few of the possibilities are:

- EDSN average household profile;
- Demand data after a measurement;
- The sum of all the demanding appliances;
- Etc.

The EDSN profiles are common used by grid operators. The demand data of an actual grid measurement is scarce. The system is measured mainly at the top levels due to the structure of the system – top-bottom. The EDSN demand data is an example of a measurement with a top-bottom structure. The total demand of all the households is scaled backwards to the demand of one single household. An EDSN profile is depicted in Figure 22.

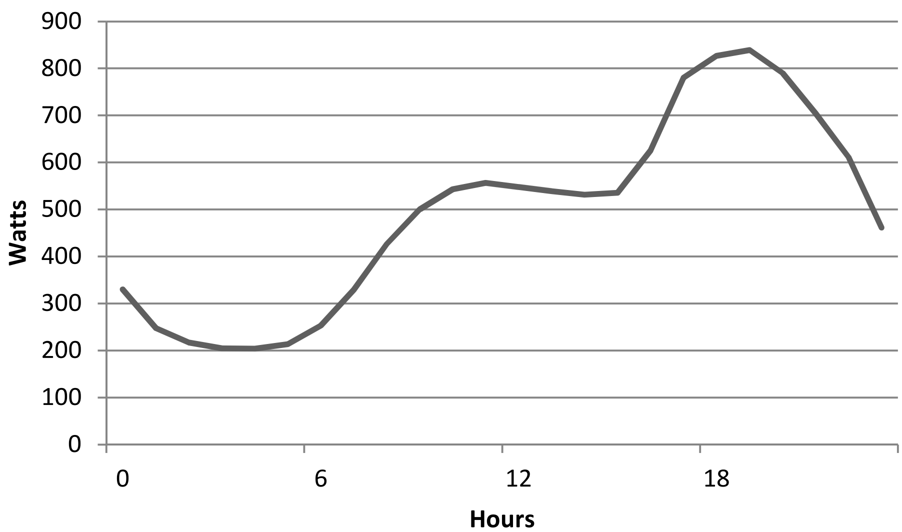

Figure 22: EDSN load profile in Watt during a day

Another option is the use of data measured in the lower parts of the grids. The grid operators measure loads in their assets occasionally. The data of these measurements is not always suitable or unattainable. However, Liander – another Dutch grid operator – has measured in the low-voltage grid with the help of smart meters. This data is published on their website and is free accessible. The description of this data contains a more detailed list of customer specs. Furthermore, the data is corrected or removed if there were very unrealistic results. However, these actions happened occasionally and are rather an exception than common. Some of the demand profiles contain additional information such as type of building; build year, and or household composition. The Liander data is used because this data is more accurate for this research than the EDSN profile in the low-voltage grid. In chapter Results this assumption is examined with MAPE. The choice for segmented data is thereby crucial.

The neighborhood consists of terraced houses (Row houses) as described in the introduction. The number of profiles – only ten after the filter – is minimal and will not contain the full diversity of demand profiles. Therefore, this filtered data could not be applied without adjustments. The domestic demand data contains 80 demand profiles of households. The 80 demand profiles are filtered on:

1. Year of build;
2. Type of household.

When this filter is applied there are only ten profiles useful for this research. The ten profiles are terraced households (row houses) and built in the time period 1940-1979. The compositions of the residents differ and are not filtered. Segmentation of different clients is crucial; however, for this research outside the scope. The filter on the data is only the first adjustment which is applied. Secondly, the 232 households in the Aireywijk should all have a demand load which will be analyzed with Vison. These profiles are not available and this data could not be obtained easily due to the necessary permission of the residents and the extra measurement operation. New data may become available due to the implementation of the smart meter in the upcoming years. Nevertheless, the Liander data is available at the present and thus used for this research. The data is adjusted with the following approach:

1. The data should be as random as possible without specific preferences.
2. The ten filtered Liander domestic profiles are the base for creating 36 sum profiles of building blocks.
3. The 36 sum profiles represent the 232 households in the neighborhood - Aireywijk.
4. The Vision model contains 36 nodes which each represent a total building block.
5. Each load of a housing block has their load profile for a period of a week.

The next two points refer to the modification of the data. The week data of Liander has 672 values because this data is measured for each quarter. The data is modified because the analysis in Vision is done with profiles in hours. The data is modified to create the worst case scenario with the following approach:

6. The summer profile will use the lowest fraction of the 4 fractions in an hour because this will create more net load.
7. The winter situation uses the maximum load fraction of the 4 fractions in an hour because this will create the maximum demand load.

The load profiles are created for two weeks of the year 2013. The first week is from July 1st to July 7th. In general this week has much generation and little demand. In the second week it will be reversed; high demand and little generation. This second week is from December 25th to December 31th. Both weeks will be input for the three different analyses as mentioned before. The week in July will be used for a Summer analysis. The Winter analyses use the December week.

Furthermore, an extra analysis is done to verify the input of the Liander data with an actual measurement in the Aireywijk. Endinet has done a measurement in September and thus this could be compared with the smart meter data of Liander during the same period of the year with the applied adjustments. This analysis shows how representable the Liander data is. The results of this analysis are described in appendix 2.

4.1.3.2. Photovoltaic supply data

Solar panels are very common in low-voltage grids. The implementation persists and the panels increase efficiencies. These systems got a particular power profile which is the same for most systems on the market. These profiles are determined mainly by sun rise and fall. The present most efficient and beneficial systems have more or less the same profile during a sunny day. The profile – depicted in Figure 23– shows the generation in Watts in December during the last seven days of that month. The generation is little or none during some days with one exception which represent a sunny day in December. The peak load lies around 3300 W which is 60 percent of the summer peak.

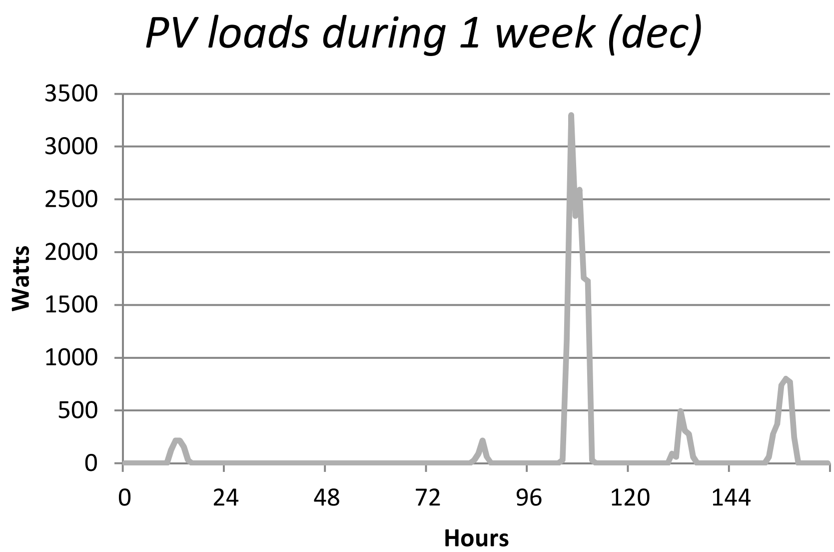

Figure 23: PV generation profile – December – 25th to 31th.

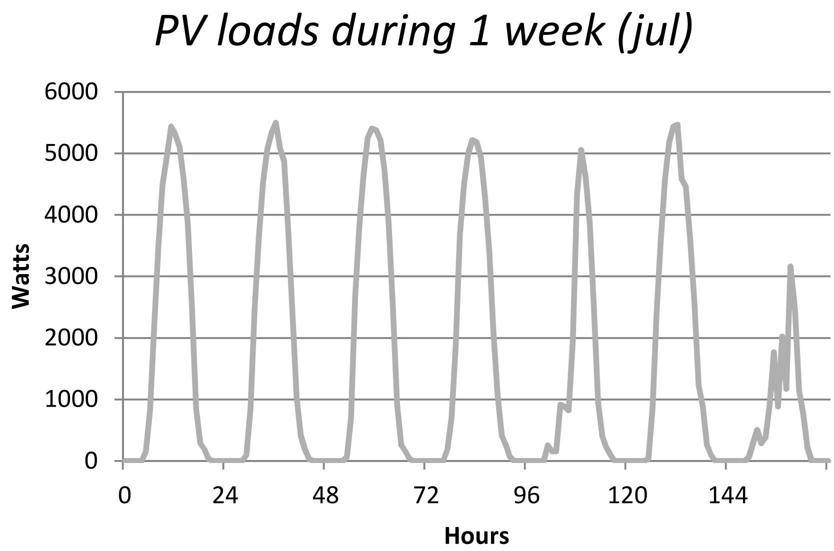

Figure 24: PV generation profile – July – 1st to 7th.

A generation profile of a sunny period such as the chosen week in July is depicted in Figure 24. This profile of July has a repeating character. One or two days differ due to less sunshine; however, these days still generate the same or more than the December situation. The data used for the capacity & power quality analyses is based upon these profiles. The peak production is determined by the maximum generation of a specific system.

The third and last common part in all the scenarios is GIS data. The next paragraph describes this data and possible adjustments.

4.1.3.3. Geographical information system (GIS) data

The analysis in Vision also requires grid specific data. The data retrieved from GIS data is:

- Types of assets;
- Length of assets;
- Specifications of assets;
- Connections;
- Spatial information/orientation.

The assets in this analysis are: transformer stations, distribution boxes and cables. This data depends on each individual case. Endinet - grid operator – has a GIS system. They use Mapinfo and GIS-SIAS (smallworld internet application server). The basic input for the model is extracted from this database. The most crucial information for creating a Vision model is retrieved from these data bases. The assets could be created with their specifications such as capacity. Nonetheless, a model is always a simpler version of reality. The model only represents the main features which are notable in Figure 25 and Figure 26.

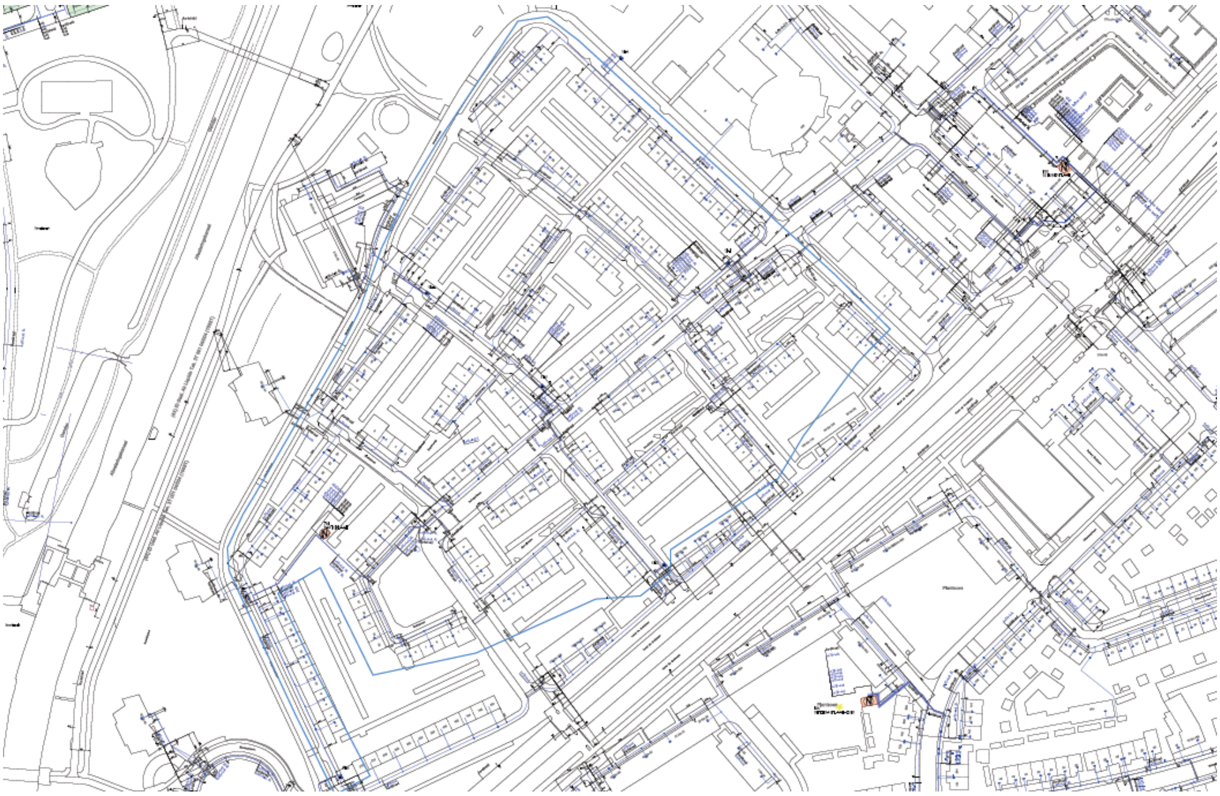

Figure 25: Aireywijk grid in GIS

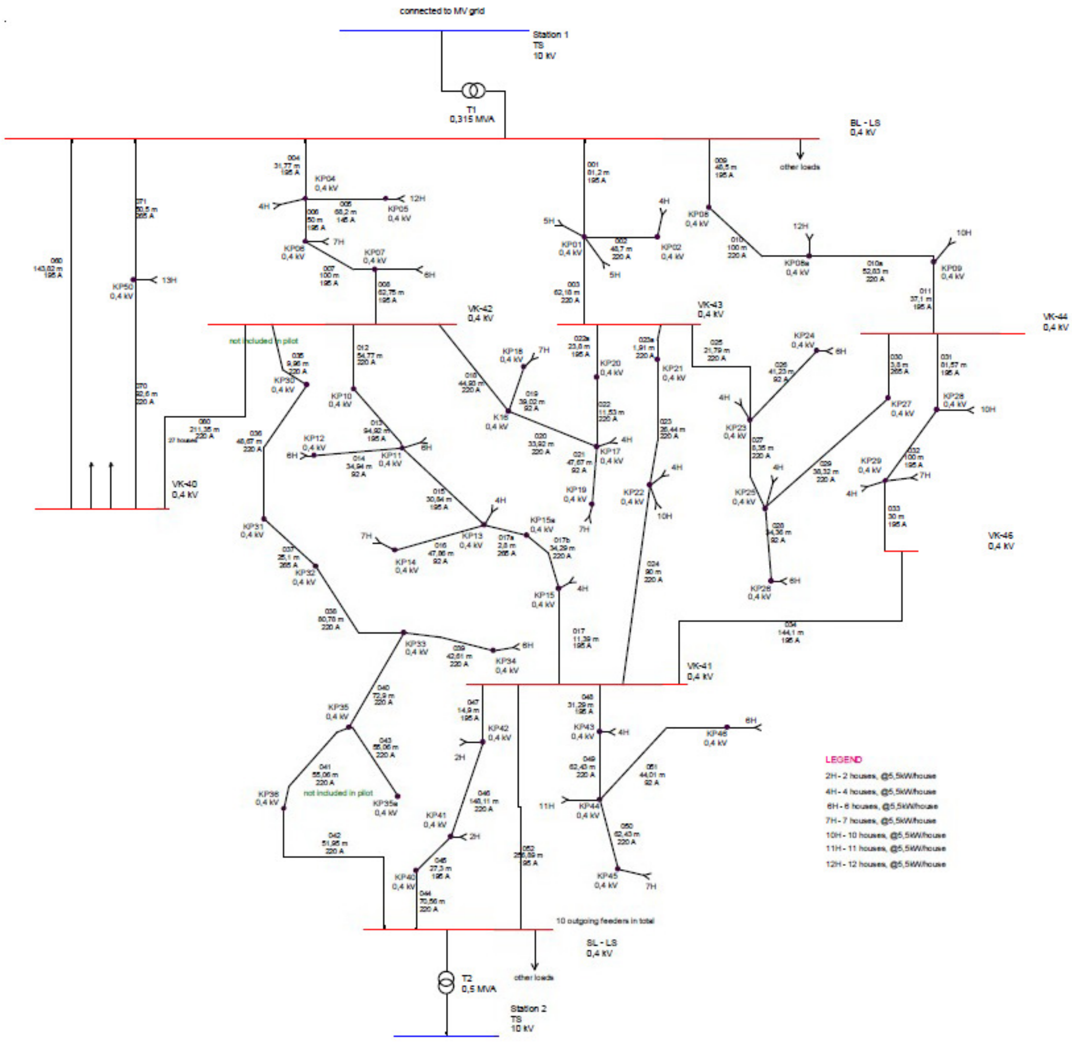

Figure 26: Aireywijk simulation grid model

The model is an abstracted grid and fewer complexes than the actual grid. The model consists of 2 transformer stations and many nodes which represent the building blocks. Furthermore, the grid contains six distribution boxes which create a meshed grid. The nodes, distribution boxes and transformer stations are connected by cables. The simplifications are especially applied on the cables and actual connections. The nodes are a summation of households and thereby the cables which lead to each household are left out. Furthermore, the connections in each household are simplified by one node for each building block. Despite all simplifications the research is still effective because the model represent the crucial part of the grid.

Two (new) technologies – heat pumps and electrical vehicles – are described in the upcoming paragraphs. The demand profiles are discussed. Furthermore, the adjustments to the data are described and finally the penetration considerations of these technologies are explained.

4.1.3.4. Heat pump demand data

The use of heat pumps for the heat demand is more common. The use of this other technology has an impact on the low-voltage grid. Data of this new technology is crucial to see the impact on the low-voltage grid. The demand data of heat pumps is obtained from another Dutch grid operator Enexis. The data shows many similarities with data of Liander. The demand data is measured for each quarter in an hour and available for both months December and July. The delivered data contains multiple measurements on different heat pumps. This data is obtained due to measurements at participants of the pilot project 'Jouw Energie Moment'. This data is the result of 10 different random heat pumps in the residential neighborhood Meulenspie in Breda. The heat pumps are ground-source heat pumps and used in well isolated semi-detached houses.

The heat pumps require space and in some cases need an intervention, namely an intervention in the ground underneath the dwelling to create the closed water system. The expectation is that the heat pumps will penetrate mainly in new developed neighborhoods. Thus the implementation of heat pumps in existing neighborhoods will be very low. The number of heat pumps implemented in the model is based upon the scenarios determined by Endinet. The intensity of heat pumps will differ per scenario as can be seen in the following table:

Table 1: future scenarios with penetration of heat pumps

Scenario	Penetration of heat pumps in %
Conservative	7%
Economical	12%
Locally insured	22%
All locally	31%

The highest penetration percentage is 31 percent and the lowest is just 7 percent. Two scenarios were examined namely 'Economical' and 'all local'. The highest percentage is used to create a worst case scenario and belongs to the scenario 'all locally'. Economical is chosen because this scenario has a midrange percentage. These scenarios result in 29 or 72 dwellings with a heat pump in the year 2040. This research only describes the scenarios with 72 heat pumps because this results in the worst case.

A remark should be made due to the fact that these heat pumps mainly are implemented in new neighborhoods. The assumption will be that at least some of these building blocks will be completely renovated in the year 2040. Thereby the implementation of these heat pumps is a fact. The Vision model includes nodes which represent these blocks and the heat pumps are modeled randomly in the grid on these nodes with eventually the total number of household covered. A separate sum profile is made for each building block. A single profile of a heat pump differs in the winter and the summer. The summer heat pump demand of one single pump is depicted in Figure 27. The spikes in this profile represent the demand for warm tap water. The constant demand of 100 W is for water cooling inside the pump in July.

The consumer demand in the winter differs with the Summer situation. The heat demand is an extra addition and visible in Figure 28. The peaks still represent the demand of warm tap water. Furthermore, a constant demand of 1100W represents the heat demand in the winter. The sum profiles for each node are created by the same standards as mentioned at domestic loads.

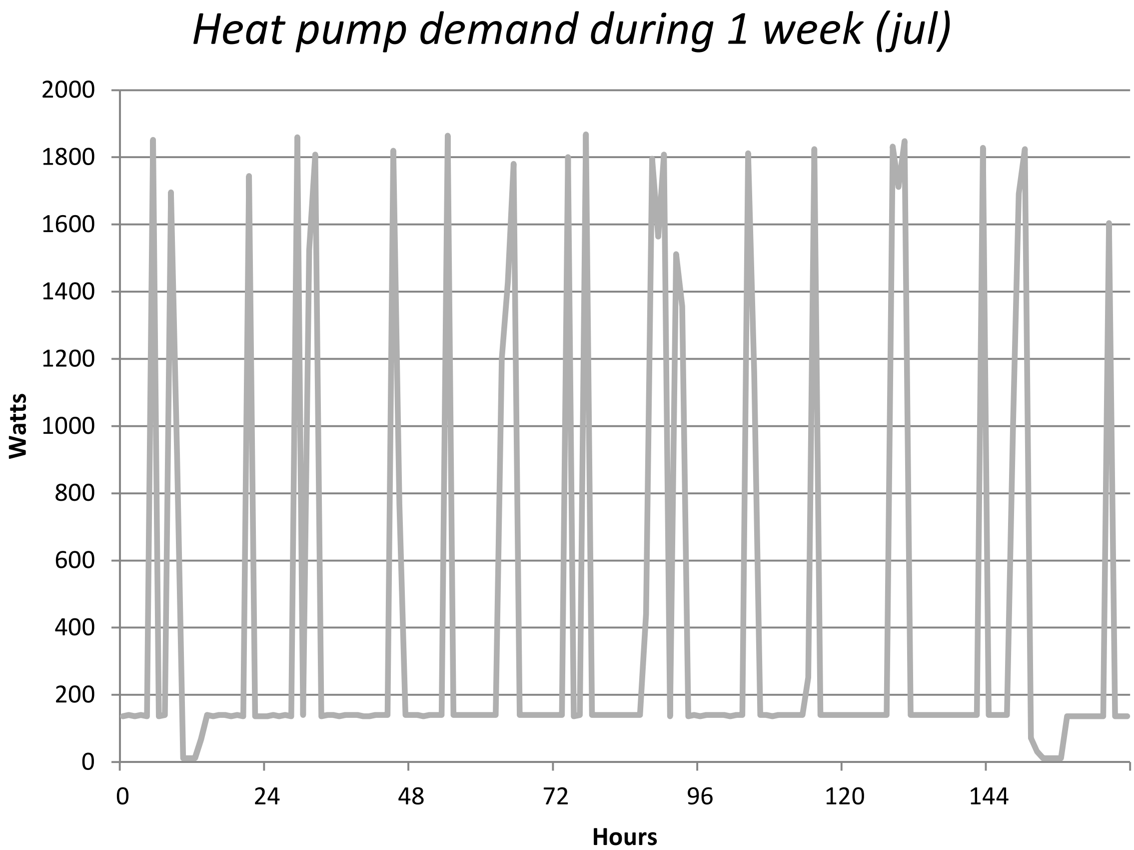

Figure 27: Heat pump demand – July – 1st till 7th

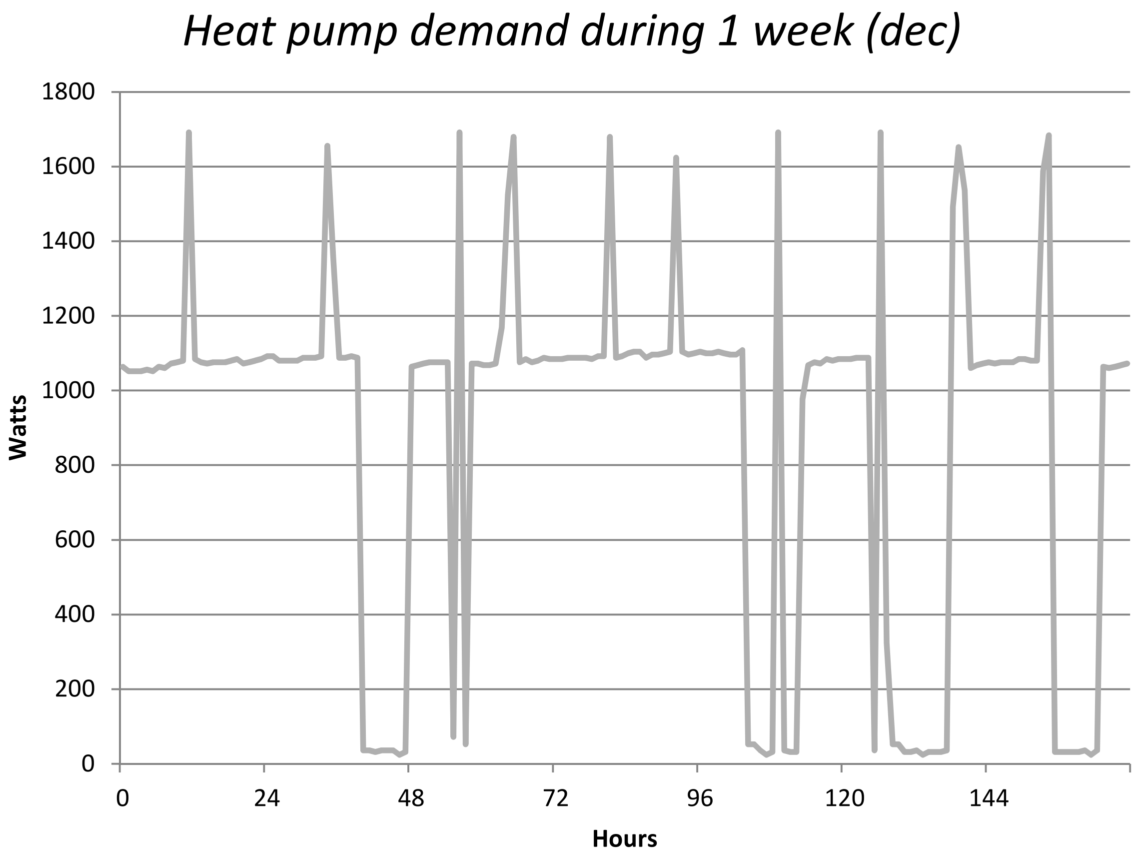

Figure 28: heat pump demand – December – 25th till 31th

4.1.3.5. Electrical vehicle demand data

The electrical vehicle data is not widely available today. The number of electrical vehicles is still limited and thus is data scarce. Movares & NetbeheerNederland has determined scenarios in an earlier report. Movares and NetbeheerNederland wrote that report on charge strategies of electrical road traffic in January 2013. The different charging scenarios and the load peaks are provided in Table 2.

Table 2: Charging scenarios with load peaks by Movares & NetbeheerNederland

Scenario of charging	Load peak in kW per EV
Home charging	3.7 kW
Public charging	11 kW
Fast charging	100 kW

The two scenarios which are applicable for the Aireywijk are home charging and public charging.

Furthermore, load data is obtained from Liander. The data which is retrieved from Liander was part of a pilot project. The load data is based upon three public chargers. This data is input for the load profiles.

Another important factor will be the number of electrical vehicles in the Aireywijk. In the report of NetbeheerNederland and Moveres three categories are distinguished in which adoption of electrical vehicles could occur: high, medium, and low. In this research the medium curve is used. A simple, however crucial, arithmetic determines the number of cars in the neighborhood of the Aireywijk. The vehicle fleet has a total number of 10.312.500 vehicles in the Netherlands in 2040. The total number of electrical vehicles will be around the 3.3 million. Presently, every household owns 1.06 vehicles. If in 2040 and every household still consists of 2.2 person per household then the number of vehicles per household will be 1.27. With the assumption that the number of households in the Aireywijk stays the same then the total number of cars will be 295. The medium adoption curve determines that 32 percent of those cars are electrical vehicles and thus generate extra load on the low-voltage grid. The assumption will be that 94 electrical vehicles will be owned by residents of the Aireywijk. The final numbers are shown in Table 3.

Table 3: Car fleet in 2040 in Aireywijk

Number of cars in the Aireywijk	Number of electrical vehicles in the Aireywijk
295	94

The next step is finding the right load profiles for the different scenarios. Charging of electrical vehicles – without interventions – is all or nothing. The charger connects with the car and in a few minutes the charger fully charges. The start and end times of charge stations in Lochem are measured by Liander. The data from Liander is modified to create profiles. An example of a created profile is depicted in Figure 29. Furthermore, sixty-one week profiles are created out of the measured data from Liander. The peak load differs per situation. Home charging uses a peak load of 3.7 kW and public charging uses a peak load of 11 kW. The creation of the sum profiles is done in the same way as mentioned in the domestic paragraph. A final remark, the same profiles are used for the public charging situation. However, this is slightly incorrect because the charging times will be shorter caused by the higher charging rate. These home charging profiles are adjusted with a third of the charging time to create the public charging profiles.

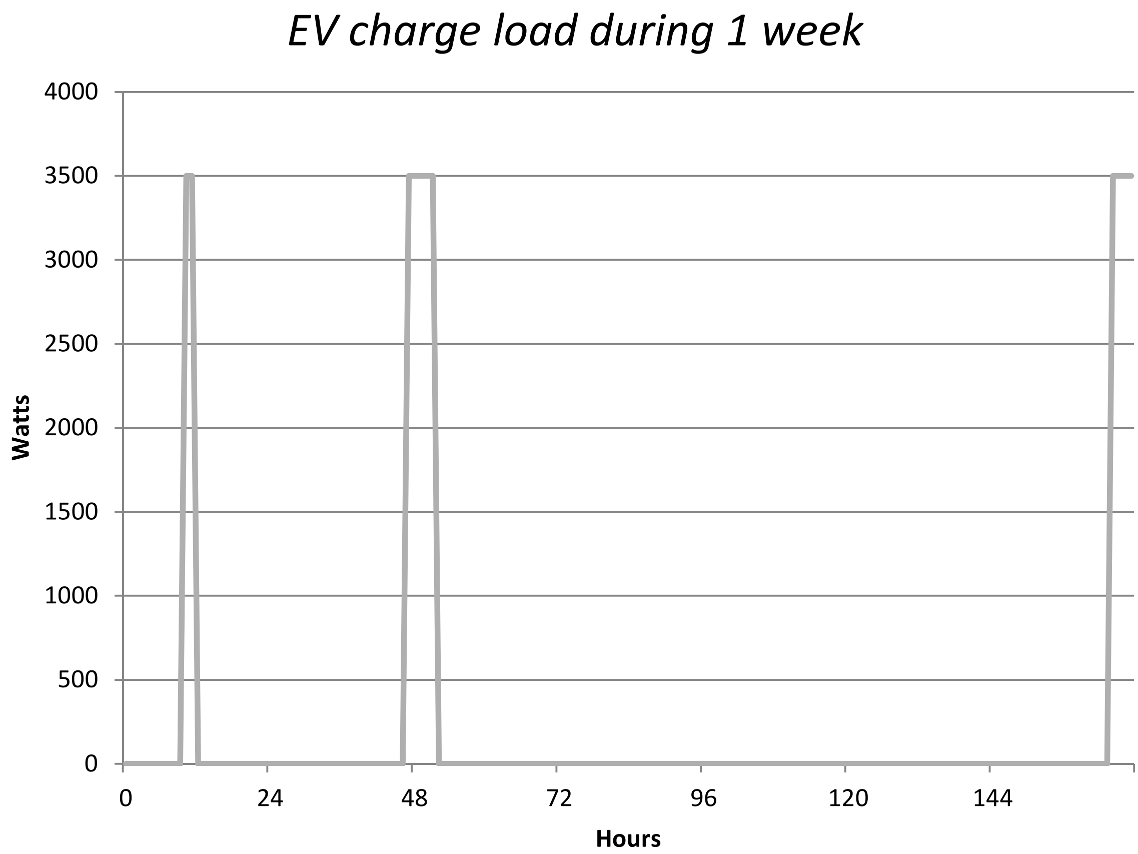

Figure 29: EV charge load during 1 week

All the required data is discussed and is used for the analyses. These analyses are:

- Segmented (domestic) data analysis with help of MAPE;
- Capacity analysis in the grid;
- Power quality analysis in the grid;
- Total cost of ownership calculation expansion of the grid.

The methods for these analyses are described in the next section. In combination with the data the analyses could be completed.

4.2. Method

In this section the used methods and research approaches are explained. The most important goal for this chapter is a clear overview and a justification of the completed research. A research design & goals are described in chapter 1 and is leading for the chosen methods. The used methods are mean absolute percentage error, literature study, and total cost of ownership. Furthermore, an electrical engineering analysis tool (Vision) is used for the capacity and power quality analysis. The data of 4.1.3. Data sampling is required for the analysis with this tool. The research stages are described in the upcoming paragraphs and could be a base for further research or a repetition of this research.

The first analysis is done to pick the most suitable data of domestic demand in a low voltage grid and find out the importance of segmented data. If this analysis is done then the capacity and power quality analyses are executed with the help of Vision. The math behind vision is given in 4.2.2. The problems which will arise from those analyses could be solved with different approaches. The costs of these approaches are analyzed and this results in a business case.

4.2.1. Domestic data analysis with help of Mean absolute percentage error (MAPE)

The first analysis is done to find the most suitable data set for a capacity analysis in a low-voltage grid. This analysis is done with the use of the mean absolute percentage error. In this analysis data of EDSN and Liander is compared to each other with the use of MAPE.

The EDSN data is the forecast variable. Despite that EDSN data is based upon real measurements and thus actual data. Nevertheless, this profile is scaled backwards towards the level of one individual household based upon the total demand of all household divided by the number of households. The absolute mean percentage error will be eventually zero if all measured data is available. The data from EDSN is measured on a high level and thus could be very different compared to data from a specific segment of domestic demand. This suspicion could be proofed with use of MAPE. The mean absolute percentage error is mainly used for trend estimations. This research method can determine the accuracy of estimation due to a deviation rate. This method shows error approximations of the actual situation relatively to the forecast. The mean absolute percentage error is a statistical analysis and is described by Oxford – A dictionary of Statistics due to this formula:

$$\frac{100}{n}\sum_{j=1}^{n}\frac{|y_j - \hat{y}_j|}{|y_j|},$$

MAPE is one of the statistics which describe the agreement between the observed and the predicted values. Other statistical analyses are mean absolute error, mean squared error, and root mean squared error (Upton & Cook, 2008). In Table 4 the domestic data of 4.1.3.1. Domestic demand data is divided in forecast and observed data.

Table 4: Forecast variable and observed variable

Forecast (y_j)	Observed ($\hat{y}_j$)
EDSN domestic demand profile	Liander smart meter measurement

The results are shown in section 3. The results of this analysis will determine whether EDSN or open data is used for the capacity & power quality analysis. In the next paragraph, the tool Vision is explained and how it could help with a capacity and power quality analysis.

4.3.2. Capacity and PQ-analysis with the help of Vision

Vision is a high-end tool for analysis on electricity grids. The tool is in use since 1991 and applied by many Dutch grid operators and other related industries. This tool is used for different analyses such as load flow, short circuit and failing behavior. The load flow analysis generates results such as loads and power quality. The grid operator uses Vision for designing, planning and maintaining the grid. (Phase to Phase BV, 2014)

The structure of Vision determines the required input. The basic structure of Vision is depicted in the Figure 30.

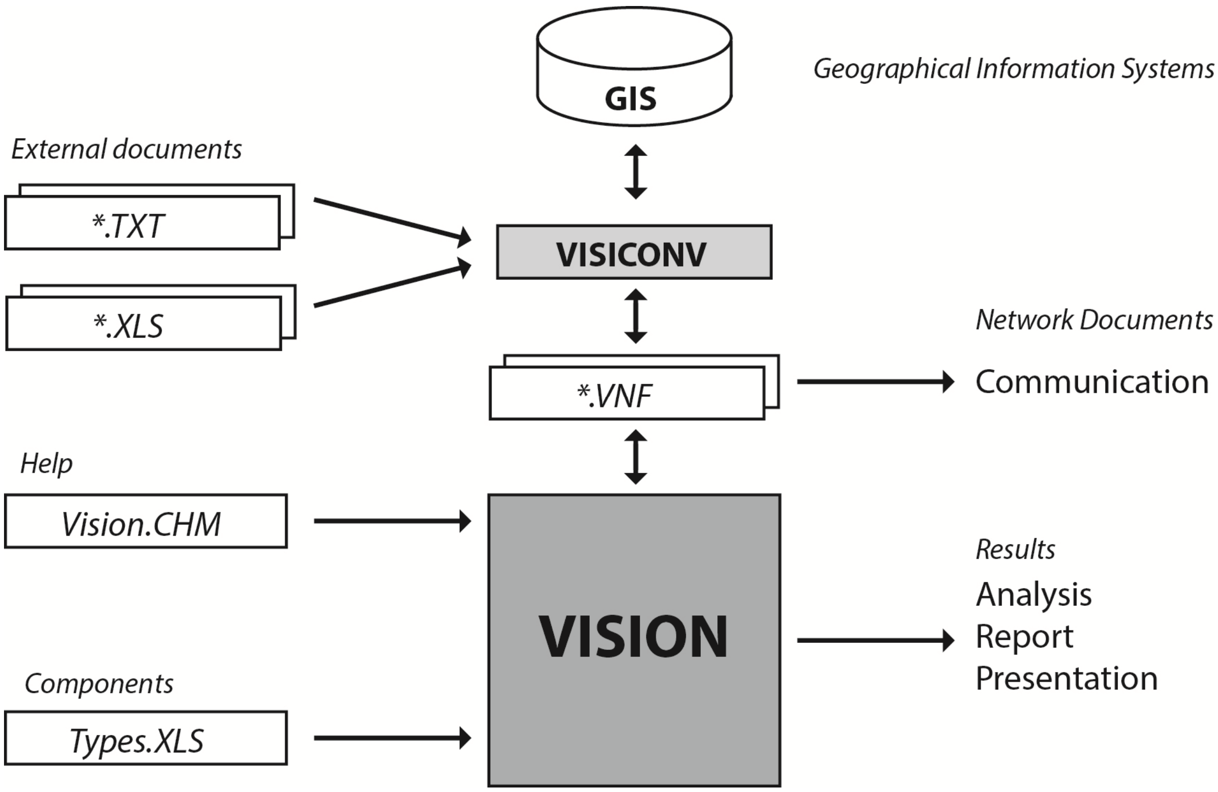

Figure 30: The structure of the tool Vision

The external documents are important and most of the input for these documents is discussed in the data part. The analyses are based upon many variables which could be implemented with these external documents. These documents provide data input for the model such as load profiles. The load flow analysis generates results with consideration of load profiles, asset specifications, and simultaneity. The capacity & power quality analyses are done with help of this load flow analyses. The demand and supply is modeled for each capacity analysis.

First the Summer situation is explained. The capacity of the grid should handle supply and demand. The net load should be handled by the assets and their capacity. The summer combination of supply and demand is as followed:

'Summer' load profile = generation of PV panels – domestic demand

PV generation and the demand of the households is modeled separately, see Figure 31. However, the analysis tool Vision is capable to handle all these variables at once. Node 32 is used as an example and is representable for all the other nodes.

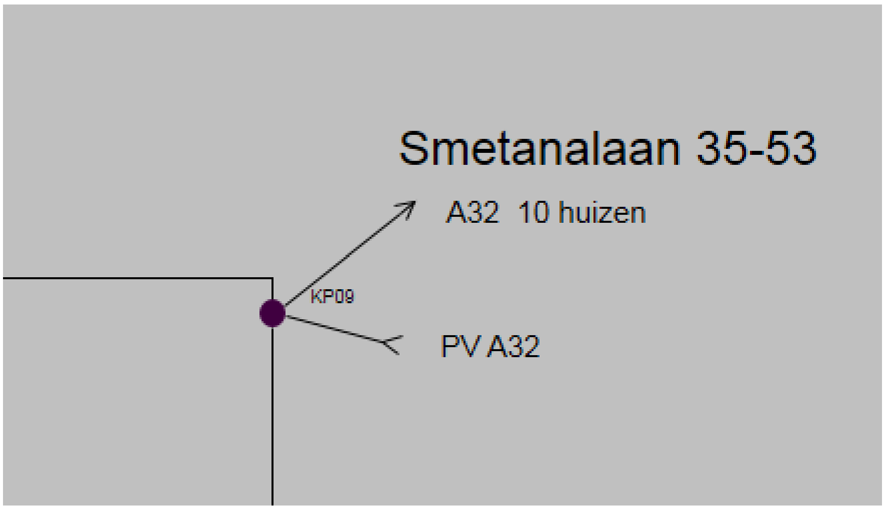

Figure 31: Housing block Smetanalaan 35-53 modeled with domestic demand (A32) and supply (PV A32)

The 2040 scenarios are slightly different. These scenarios have the following structure:

'2040' load profile = Domestic demand + Heat pump demand + Electrical vehicle demand – Generation of PV panels

Not every household has a heat pump or electrical vehicle. However, again node 32 is used to give an example of a node with all these loads. In Figure 32, node 32 is depicted.

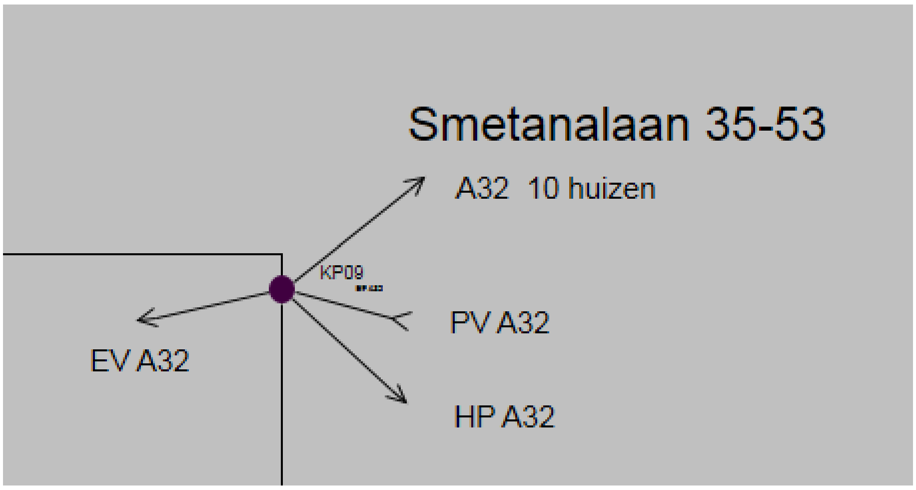

Figure 32: Housing block Smetanalaan 35-53 modeled with domestic demand (A32), PV supply (PV A32), heat pump demand (HP A32) and EV demand (EV A32)

The capacity and load flow analysis is done by the Tool Vision. The math behind this analysis is crucial for understanding the outcomes of the analyses. Furthermore, other grid tools could be compared in this way.

4.3.2.1. Capacity analysis & Power Quality analysis

The method used for these analyses in Vision is Newton-Raphson. This method is a load flow method which is described for the first time in 1961 and 1967. This method converges to a quick solution. The Newton-Raphson method is matured and accepted worldwide. The math behind this analysis is given in appendix 12. The description in the appendix is unfortunately in Dutch. However, the power quality and asset load mathematics are represented in this appendix. The load flow analysis makes use of profiles. The loads differ over time due to these profiles.

The capacity analysis could now be done and results could reveal new challenges. Those results are discussed in the next chapter. The new challenges could be solved with different approaches. Which approach is the best fit for a grid operator is determined with the help of a business case? The total cost of ownership for both solutions should be calculated. The method of total cost of ownership is discussed next and this is the final and last analysis.

4.3.3. Total Cost of Ownership

The concept of total cost of ownership cannot be summarized in one formula. However, the basic principle is clear and is disclosed in chapter 3. For this research several variables are determined:

1. Purchase price;
2. Physical costs;
3. Installation cost;
4. Financing costs;
5. Upgrade costs;
6. Maintenance costs;
7. Repair costs;
8. Downtime costs;
9. Removal costs.

The sum of all these variables determines the total cost of ownership over a period of a lifetime. The first three are initial purchase costs. The other costs occur during the lifetime of the product. The use of these variables is described and where they were obtained is given in this paragraph. First, the variables are described for the battery storage systems and after that the traditional upgrade is discussed.

4.3.3.1. Purchase price

The purchase price is determined by the number of kWh of energy storage needed times the price of kWh energy storage in the market. The determination of the battery capacity is crucial. This ascertaining is completed with the use of the results of the capacity analysis in Vision. Appendix 11 provides the method for this ascertaining of the battery capacity.

The purchase price for a traditional upgrade is based on other variables. The purchase price consists of systems needed such as cables, distribution boxes and transformer stations. The method used for determining the costs of a traditional expansion is done by a costs sheet of

Endinet. This sheet shows costs based on key figures. The price of the cables is established by the length times the type of cable. The transformer station costs consist of: the building and the transformer times the number of purchases. Last, the purchase of additional distribution boxes could bring extra costs. The sum of these parameters determines the actual purchase cost due to a traditional upgrade of the grid.

Some of these new assets require extra space or spatial interventions. These costs are called physical costs and are stated in the next paragraph.

4.3.3.2. Physical costs

The battery system requires space and that space should be obtained by the grid operator. The psychical costs consist of three factors:

- the land on which the system stands;
- the surrounding building of the system;
- The terrain interventions.

The key figures used for this summation are based on the costs made for a similar sized system with almost the same physical requirements: a transformer system. Endinet does have key figures for these parameters of a transformer station. Therefore, these costs are used as physical costs for a battery storage system.

The three factors which determine the costs for a battery system are also applicable to traditional investment behavior. The physical costs are made by the purchase of a transformer station. The other assets do not require space which is property of Endinet. In the case of a transformer station upgrade the land is already acquired by Endinet. Thus the research case will not have any physical costs due to implementation of a transformer building. However, the present cables sometimes need to be removed for an improvement. These removal costs are also part of the physical costs. The removal costs are obtained by the same data sheet of Endinet. These costs are multiplied by a factor of 1.6 – 1.7 due to experience with these interventions. Those interventions often have to deal with soil pollution.

4.3.3.3. Installation costs

The installation costs are made during the actual implementation of the system and the transformation of the physical space. The installation is done by workers which require a payment. The installation cost is therefore determined by: the number of hours needed times the price of a man hour. The price for a man hour is set at 68 euros per hour. This price is the standard man hour price of Endinet B.V. The installation costs are the number of men hours made before and during the actual Implementation of the asset. Other labor can be found in the other variables.

4.3.3.4. Financing costs

The financing costs are paid every year and consist of interest on the outstanding loan. An interest percentage determines these costs and the amount of paid interest normally decrease after years due to repayment of the loan. The first three variables are together the total loan. Endinet pays internal interest to Alliander of 4.1 percent. The investment is repaid by Endinet at the end of the year. Each grid operator will have another policy; however, the structure of financing cost will not differ much.

4.3.3.5. Upgrade costs

The implemented products sometimes need to be upgraded over time. Examples of reasons for an upgrade are capacity losses and software updates. As discussed in a previous paragraph battery systems could lose capacity and in contrast with starting with additional capacity, one can also choose to upgrade the system. To upgrade the system overtime could be beneficial because of reduction of financing costs.

Furthermore, the assets in the traditional grid are sometimes upgraded due to a shorter lifetime than the core product. In the case of the Aireywijk all the assets which are upgraded have at least a lifetime of 30 years.

4.3.3.6. Maintenance cost

Endinet has a maintenance schedule for all their electricity assets. In their quality and capacity document an appendix is included with this schedule. The maintenance is categorized by asset. The maintenance is preventive and applicable on the following assets:

- Main and district substation
- Transformer stations
- Cables
- Distribution boxes
- Other components such as: public lighting.

Their maintenance schedule is described for the upcoming years (2014-2020). The used table is shown in Figure 33:

Preventief onderhoud transformatorstations

Onderhoud transformatorstations	Frequentie	Inhoud werkzaamheden/te onderhouden componenten
Groot onderhoud	Eens per 8 jaar	• MS installatie: Rail stromen / Contacten smeren / Schoonmaken • MS schakelaars: Schakelen / Contacten smeren / Olie monsteren/testen • Transformator: Olie controleren / Temperatuur controleren • Visuele controle alle componenten • Beveiligingen testen (installatie afhankelijk) • MS ruimte schoonmaken • LS rek schoonmaken • OV-rek schoonmaken
Klein onderhoud (niet voor alle stations)	Eens per 4 jaar	• Beveiligingen testen (installatie afhankelijk) • Visuele controle
Accu controle (niet voor alle stations)	Eens per jaar	• Geleiding • Temperatuur • Laadspanning
Terrein en gebouwen	Eens per jaar	• Dak • Muren • Begroeiing • Ventilatieroosters vrij- /schoonmaken

Figure 33 Overview of preventive maintenance of transformer stations (Dutch)

The maintenance is divided in large, small and annual maintenance. The large maintenance costs one working day. A work day is 8 hours of labor. The annual and small maintenance will cost both a halve day of work. The maintenance is done by Endinet employees. The rate for a man hour will again be 68 euros per hour. The maintenance costs for the battery system and the transformer station will be the same. The technologies are probably comparable and therefore the frequencies are matched. Furthermore, cable maintenance is done incidental and if necessary. This maintenance will thereby not be taken into account. The maintenance will not differ by the solution, but by lifetime.

4.3.3.7. Repair costs

The repair costs are a result of unpredicted maintenance during the lifetime of a product. The maintenance occurs after a defect of an asset. These defects are unpredictable and are based upon chance. The curve of failure of a product could determine this chance overtime. However, during the lifetime of these products normally the chances for failure are minimal. Endinet does not have failure curves of specific assets. Nevertheless, the defects in the grid are monitored during the year. The number of defects in the low-voltage grid in the past few years was 90. The damage is in 60 percent of cases caused by excavation damage. However, the number of 90 incidents on 1200 km low-voltage cable is low. The chance that the new cables have to deal with a defect is thereby very small. The grid reinforcement contains less than one kilometer of cable. The chance of a defect in this additional cable length is too small to be considered in the Total cost of ownership. The numbers as a result of this chance times the repair costs are not significant.

4.3.3.8. Downtime costs

The downtime costs are a result of compensation towards customers after a period of downtime. The grid does not operate for a long period of time and therefore the customer is disadvantaged by the grid operator. Endinet got a downtime policy with the following compensations towards the customer:

- Small demand – at least four hours – 35 euro’s.
- high demand – at least four hours – 195 euro’s
- Medium voltage connection – at least four hours – 910 euro’s

This downtime compensation will also be a result of a probability. The downtime is the result of a defect and the time used for repairing the grid. If the defect chances were higher than the present failures by Endinet then these costs could be considered in the TCO. However, the failure chances are not significant as stated in the previous paragraph.

4.3.3.9. Removal costs

The removal cost is based upon the key figures of Endinet B.V. The removal costs consist of the removal and then the rehabilitation of the used grounds. The costs for a transformer station will be the same as of the energy storage system.

4.3.4. Method summary

In this method section the research approach is clarified. The required data is described and the modifications are discussed in the first section. This data is used in analyses and those provide results. The results are shown in the next section. The results of the capacity analyses are used and processed with a total cost of ownership. The literature review (chapter 3) is the result of a literature study. For the completeness of this research the method of this literature review is given in the appendix 1.

4.3. Results

In the previous sections the case and methods are described. The results of this research provide the following insights:

1. The importance of segmented data;
2. The (possible) future challenges in the grid;
3. Insight of the implementation of one flexibility option in the low voltage-grid;
4. Insights in the costs of two approaches for reinforcing the LV-grid and the most important costs variables.

In this section the results of the three analyses are discussed. First the most suitable domestic demand data is determined and the importance of segmented data is proven. Then, the results of the capacity analyses in the low-voltage grid are discussed. This section ends with the development of a business case. Finally, the conclusion and discussion complete this chapter.

4.3.1. Results of the domestic data analysis with MAPE

The domestic data needs to be optimal for the low-voltage grid. The EDSN domestic load profile is smooth without many spikes. The profile spikes represent peak loads which can cause problems in a low voltage grid. The difference between a daily profile of EDSN and a profile of the smart meter measurement of Liander is depicted in Figure 34 and Figure 35.

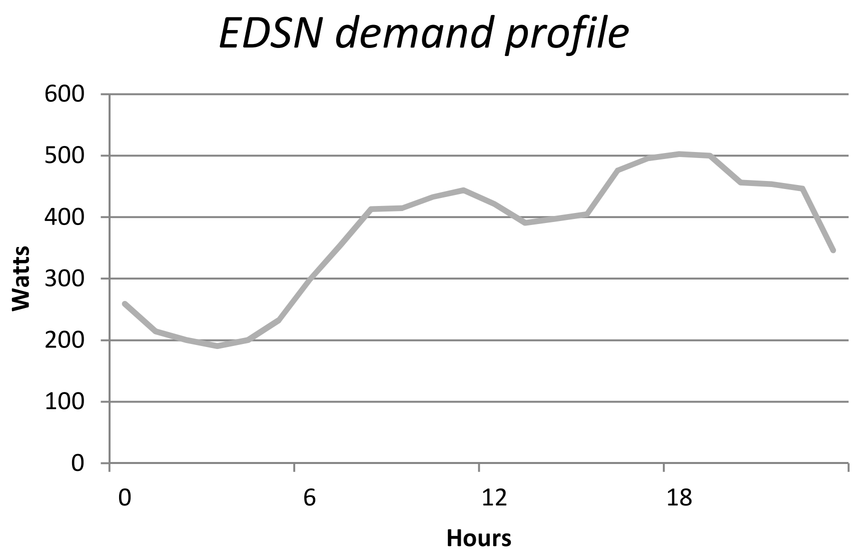

Figure 34: EDSN profile – 1st of July

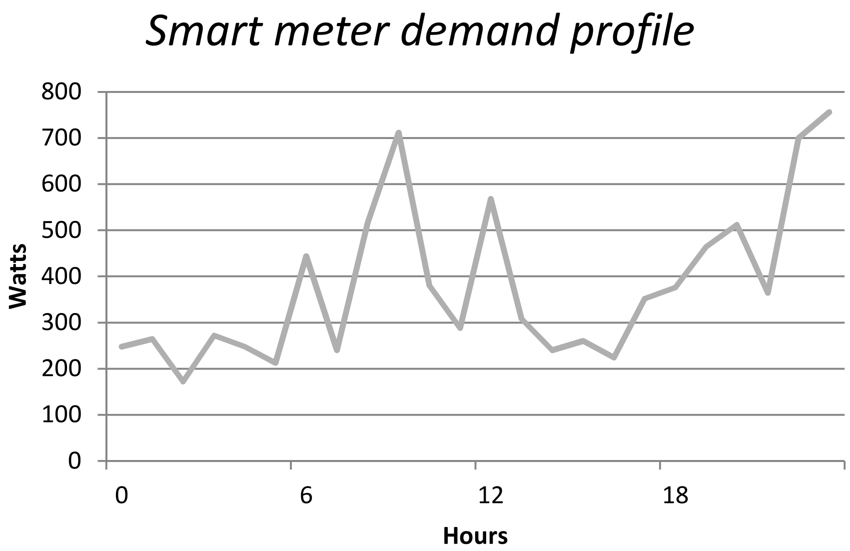

Figure 35: Smart meter profile of a consumer - 1st of July

The EDSN load profile is not segmented by type of user or dwelling. The Liander data could be segmented with use of three variables. The MAPE analysis predicts the difference between the number of Liander domestic load measurement and the forecast domestic load profile of EDSN. More Liander domestic load profiles will approach the EDSN 'average' domestic load profile. The result of the MAPE analysis is visible in Figure 36.

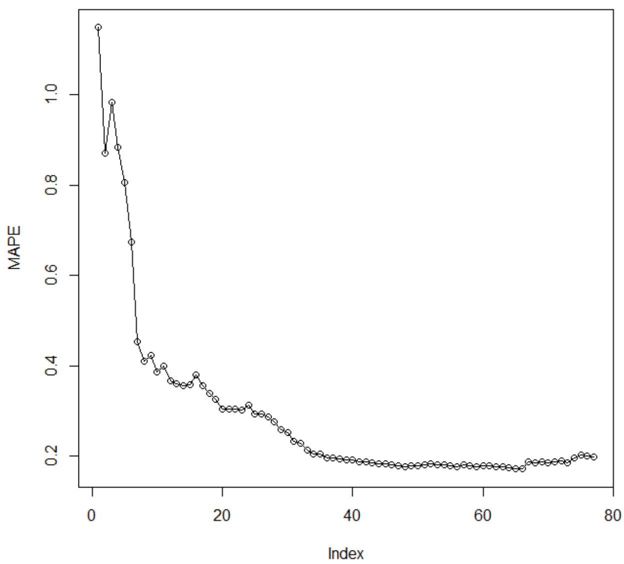

Figure 36: MAPE - EDSN vs the number of profiles of Liander

The conclusion of the MAPE analysis is that a couple of profiles may differ tremendously. The first domestic profile varies more than 100 percent with an EDSN domestic load profile. The sum of 10 Liander household profiles differ less with 10 summed EDSN household profiles; however, the difference is still around 40 percent. The graph shows that around 40 profiles the deviation is steadier and slowly approaches zero. Nonetheless, the assumption that some segments of customers could differ majorly from an EDSN profile is reinforced. This assumption could be proven with the help of segmented Liander smart meter data compared with the EDSN data. In Figure 37 such an experiment is depicted. The Liander data is only filtered by type of dwelling and year of built.

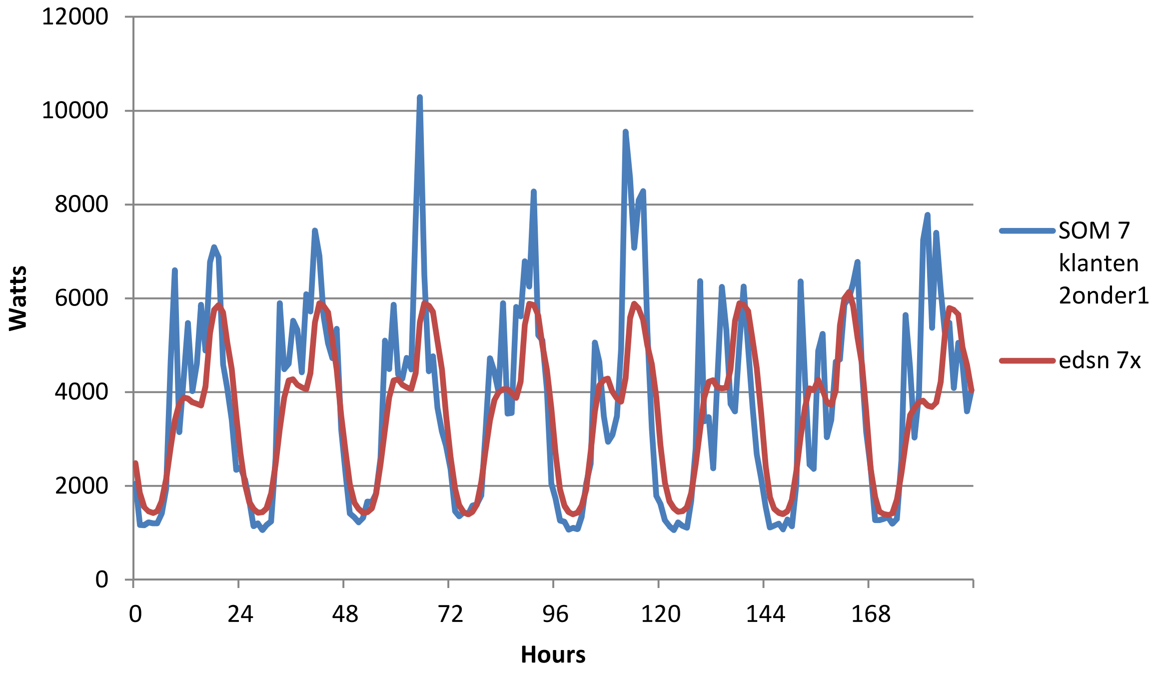

Figure 37: Sum of 7 EDSN profiles vs 7 semi-detached houses of the year 1940-1979

Seven semi-detached buildings (1940-1979) with their domestic demand are analyzed and compared with the sum of 7 EDSN domestic profiles. The third peak of the EDSN profile is half of the measured peak of these segmented customers. Other comparisons show the same conclusions. The implications of this result could be that the designed capacity – based on EDSN profiles – could be insufficient. The load peak could rise even above the safety margin. These extreme load peaks could cause defects which obstruct the delivery to the customer. To conclude, the segmented customer could have more demand than the average EDSN profile indicates.

One clear segment of customers is visible In the case of the Aireywijk: Terraced houses built in the 60s. Therefore, the capacity analyses are done with the input of the Liander data. The preparation of this data is already described in 4.1.3.1. Domestic demand data. Data used in the model is compared with an actual measurement of Endinet. The results of this comparison are described in appendix 2.

4.3.2. Capacity & Power quality analyses in the low-voltage grid

The case is the residential neighborhood Aireywijk in Eindhoven. The model is created in Vision as described in the method part. The capacity analysis is a load-flow analysis which generates results of loads at the assets. Furthermore, the power quality is reviewed. The capacity and PQ-analyses are completed for the three scenarios. The first scenario is the Summer 2015 situation as depicted in Table 5.

Table 5: Scenarios in 2015

Scenario	Time of year	Percentage of PV-implementation in the Aireywijk
Summer 2015 scenario – 100	July	100
Summer 2015 scenario – 50	July	50

4.3.2.1. Summer 2015 - 100

This analysis is done for the first week in July. The analysis is done for every hour in this week based on different load profiles. The loads in this situation are:

- Domestic demand load
- PV supply load

The earlier mentioned node 32 is also used for these results. This node represents other nodes in the model. The domestic & PV loads on this node are depicted in Figure 38.

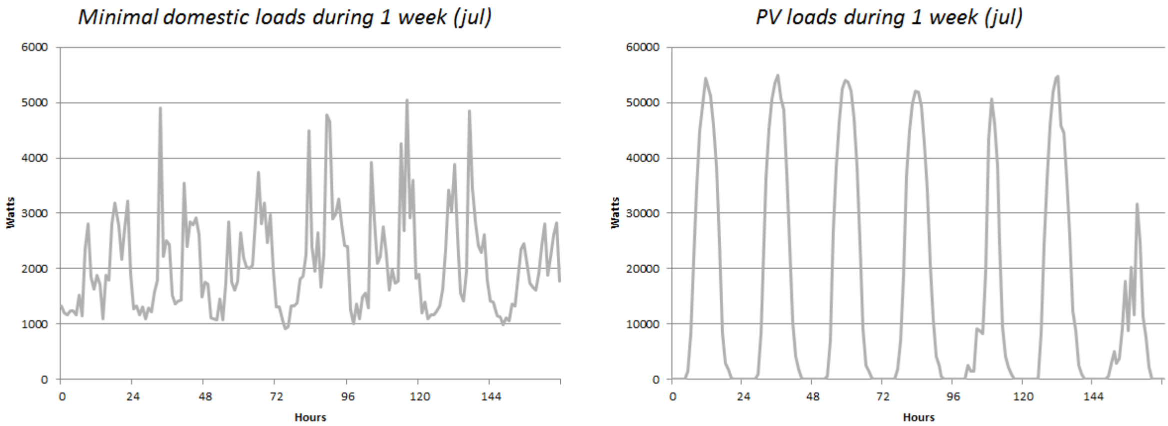

Figure 38: Domestic & PV loads in node 32

The supply of one system has peak load of 5500 Watt. In the first scenario, the penetration of PV is a 100 percent and all the households in the neighborhood have a system with a peak load of 5.5 kW. The result of the load flow analysis in Vision is depicted in Table 6 and appendix 3.

Table 6: Results of capacity & PQ analysis – Summer 2015 - 100

Undershoot & overshoot	Total number of assets
Nodes with (too) little voltage	0
Nodes with (too) much voltage	0
Branches with little load	0
Branches with (too) much load	10
Elements with little load	0
Elements with (too) much load	0

According to the load-flow analysis: 9 cables and one transformer station are overloaded. The overload percentages differ per asset as can be seen in Table 7

Table 7: Asset – maximum overload percentage – Summer 2015 - 100

Asset	Maximum overload percentage
Transformer station	182%
Cable 1	118%
Cable 2	163%
Cable 3	129%
Cable 4	101%
Cable 5	141%
Cable 6	127%
Cable 7	120%
Cable 8	143%
Cable 9	127%

The low-voltage grid will have capacity problems if this number of PV-systems is implemented. Many cables are overloaded for multiple hours a day. One of the transformer stations in the grid has to deal with overload. The capacity is thus insufficient and this will result in operational problems. The power quality in the grid is good. The grid operator needs to upgrade the grid to keep it in operation. The two approaches and the costs for this investment are mentioned in paragraph 4.3.3.

4.3.2.2. Summer 2015 - 50

The analysis in paragraph 4.3.2.1. shows the worst case scenario of the Aireywijk. The intentions of Morgen Groene Energie are slightly different for this year. Morgen Groene Energie supposes that they could implement 116 PV-systems on the households in the Aireywijk. The demand load will stay the same as in scenario Summer 2015 – 100; however, supply loads are decreased with 50 percent. This decrease of supply affects the assets. In Table 8 and Table 9, the results of these analyses are provided.

Table 8: Results of capacity & PQ analysis – Summer 2015 – 50

Undershoot & overshoot	Total number of assets
Nodes with (too) little voltage	0
Nodes with (too) much voltage	0
Branches with little load	0
Branches with (too) much load	1
Elements with little load	0
Elements with (too) much load	0

Table 9: Asset – maximum overload percentage – Summer 2015 - 50

Asset	Maximum overload percentage
Cable 1	102%

The capacity problems are decreased in this second situation. The transformer station is no longer overloaded and only one cable is overloaded. Endinet still needs to intervene in the grid; however, the challenges have been reduced significantly. The cable with an overload of 102 percent needs to be replaced with a cable with more capacity.

To conclude, the capacity problems significantly decrease in the Aireywijk in the second situation. The supply loads still overload one cable; however, the transformer station has enough capacity. The investments of Endinet are still necessary in spite of the reduced problem. However, these investments are very minimal in this case and thus not interesting for a business case.

4.3.2.3. Winter 2040 – Home charging & Public charging

The Winter 2040 situation is divided in two different situations because electrical vehicles could be charged with 3, 7 and 11 kW. . The Winter 2040 sub-scenarios are given in Table 10.

Table 10: Winter 2040 scenarios with number HP's and EV peak load

Winter 2040	Number of HP	Profile and peak load per EV
Home charging	72	*Liander charge profile - 3.7 kW peak*
Public charging	72	*Liander charge profile - 11 kW peak*

4.3.2.3.1. Winter 2040 – Home charging

The 94 electrical vehicles are charged on one phase at home and thus a peak load of 3.7 kW. The supply due to PV generation will be little or even none. The loads of the demand side are: HP, EV and domestic. The results of the load flow analyses are provided in Table 11: Results of capacity & PQ analysis – Winter 2040 HC.

Table 11: Results of capacity & PQ analysis – Winter 2040 HC

Undershoot & overshoot	Total number of assets
Nodes with (too) little voltage	39
Nodes with (too) much voltage	0
Branches with little load	0
Branches with (too) much load	1
Elements with little load	0
Elements with (too) much load	0

The main problem in the grid is power quality issues. 39 nodes have to deal with (too) little voltage during several time periods. Five distribution boxes do not preform according to the guidelines on power quality. The voltage quality profiles of all these distribution boxes are depicted in Figure 39.

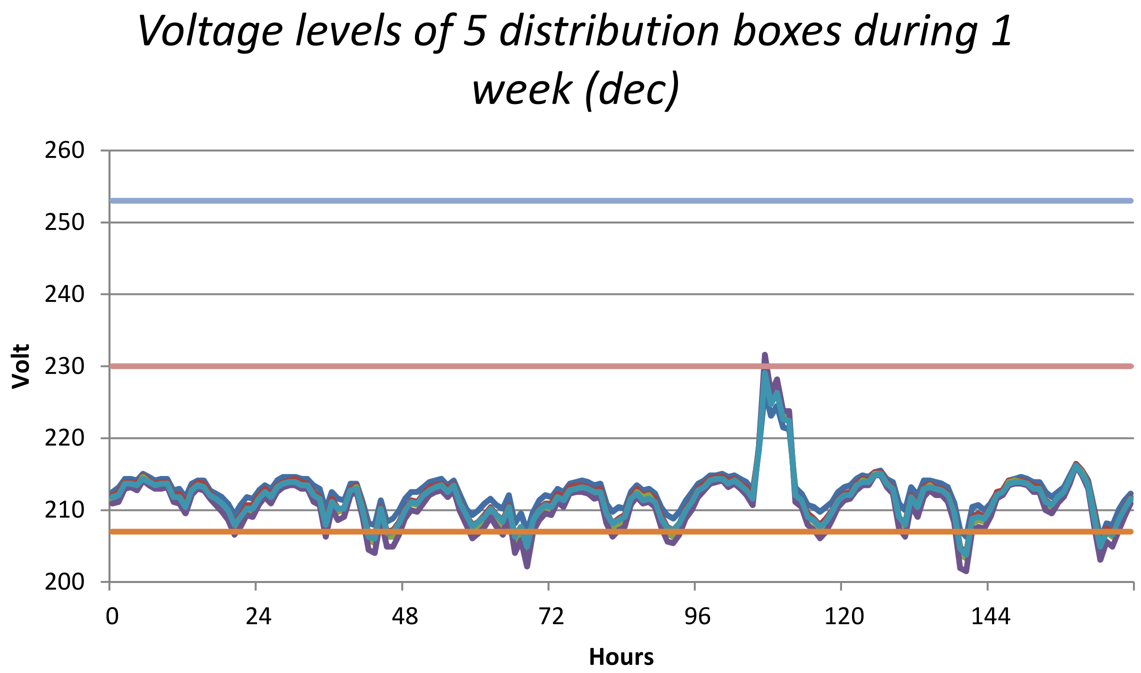

Figure 39: Power Quality – Distribution boxes – blue and orange boundary lines

The voltage quality profile reveals constant under voltage. The demand is so high that the required voltage level is not maintained within the margins. The assets in the grid have low loads apart from the transformer station – Bartoklaan. This transformer station is overloaded as can be seen in Table 12: Overloaded asset(s) - Bartoklaan. The transformer station is overloaded for 7 hours in one week. However, the overload peaks on this transformer station are each day short and not very high. The overload is still unacceptable especially for a meshed grid.

Table 12: Overloaded asset(s) - Bartoklaan

Asset	Maximum overload percentage	Hours in the week with overload
Transformer station	120%	7

To summarize, the first Winter 2040 scenario has shown multiple challenges for the low-voltage grid. The transformer station is overloaded due to demand loads. In many nodes the power quality is insufficient. The grid operator has to invest to maintain the quality of the grid.

4.3.2.3.2. Winter 2040 – Public charging

In this scenario the number of heat pumps is still 72. The electrical vehicles are charged on 'public' charging stations. These stations can charge with a peak load of 11 kW. The charging periods are just a third of the home charging periods. However, the impact of EV loads increase as depicted in Figure 40.

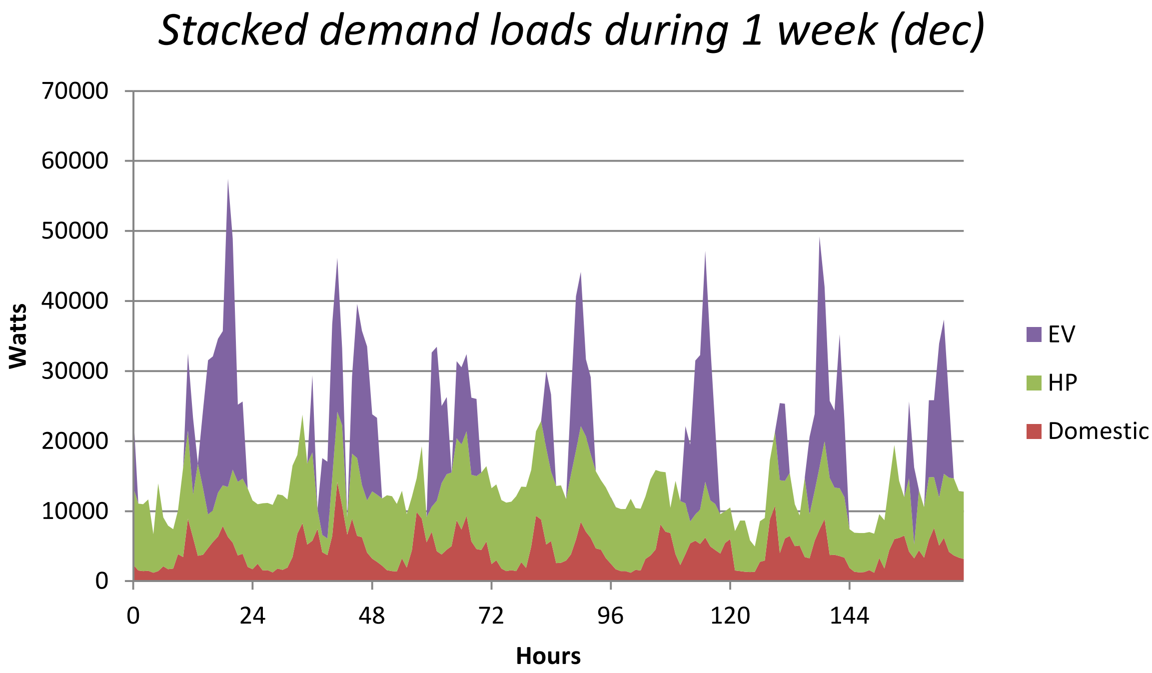

Figure 40: Demand loads in node 32 – Winter 2040 – Public charging

The difference with Winter 2040 – HC is sufficient. The number of nodes with too little voltage is increased with 8 nodes. The branch Bartoklaan is overloaded with a peak overload of 150 percent. Furthermore, the other transformer station is overloaded with 101%. The transformer station will still operate with one percent overload; however, the grid operator only accepts 70 percent of load on a transformer station. Therefore, the grid operator should still invest. The results for all the branches and nodes are depicted in appendix 6.

Table 13: results of capacity and PQ – analysis – December scenario – sub-scenario 2

Undershoot & overshoot	Total number of assets
Nodes with (too) little voltage	47
Nodes with (too) much voltage	0
Branches with little load	0
Branches with (too) much load	3
Elements with little load	0
Elements with (too) much load	0

4.3.2.3.3. Summer 2040 – Home charging

The Summer 2040 – HC scenario contains the same demand loads as Winter 2015 –HC. Furthermore, the supply loads are increased to the Summer situation. These supply loads match with the loads in Summer 2015 – 100. The supply & demand loads are high and heavy for each node in this model. In Table 14 the results of the previous two scenarios are compared with this scenario.

Table 14: Results of Summer 2040 – Home charging compared with W2040 – HC and S2015

Undershoot & overshoot	Summer 2040 – home charging ***Total number of assets***	Winter 2040 – Home charging ***Total number of assets***	Summer 2015 ***Total number of assets***
Nodes with (too) little voltage	3	39	0
Nodes with (too) much voltage	0	0	0
Branches with little load	0	0	0
Branches with (too) much load	10	1	10
Elements with little load	0	0	0
Elements with (too) much load	0	0	0

The number of nodes with (too) little voltage is decreased drastically. Under voltage of these nodes is probably solved due to the high supply by the PV systems. These PV-systems reintroduce the problem of Summer 2015. The supply loads are high and thus ten assets are overloaded. The overload peak on the transformer stations corresponds with the overload peak in Summer 2015. The additional demand does not decrease the supply loads which causes the overloaded transformer station.

4.3.2.3.4. Summer 2040 – Public charging

The supply and demand loads are the highest in this last scenario. The demand loads are matched with the Winter 2040 Public charging scenario and the supply load is matched with the scenario of Summer 2015. The difference with the previous scenario is thus the electrical public charging. The peak load of EV charging is then 11 kW. The results are depicted in Table 15: Results of Summer 2040 – public charging compared with summer home charging.

Table 15: Results of Summer 2040 – public charging compared with summer home charging

Undershoot & overshoot	Summer 2040 – Public charging *Total number of assets*	Summer 2040 – home charging *Total number of assets*
Nodes with (too) little voltage	12	3
Nodes with (too) much voltage	0	0
Branches with little load	0	0
Branches with (too) much load	12	10
Elements with little load	0	0
Elements with (too) much load	0	0

The number of nodes which deal with under voltage increased. The voltage quality is below average and should be solved. The overloaded branches agree with the previous scenarios with much supply. This overload is unacceptable and the cables will fail. The result is a not operating grid. These scenarios proofed that there are new challenges in the low-voltage grid. The three new technologies – PV, EV, and HP – create new challenges in existing low-voltage grids. These grids are not designed on such high loads. The grid operator should upgrade the grid in time. These grid reinforcements could be done is several ways as mentioned in chapter three. In the next paragraph a business case is developed. The scenario of Summer 2015 is used for this business case.

4.3.3. Total cost of Ownership – Business case

In this paragraph the business case for both grid upgrades is discussed. A business case of the Summer 2015 scenario is worked out. The business cases will indicate which approach is less expensive. The business case is the worst case scenario of July – Summer 2015 – 100.

The business case concerns a direct implementation or upgrade of the grid and is worked out for a scope of 30 years. The results are visible in two TCO-tables in appendix 9 & 10. The life-cycle of a battery system is only 15 years and thus the upgrade should be done twice. The lifetime of both investments is thereby 30 years. The results of the business case with help of TCO is depicted in Table 16: TCO results

Table 16: TCO results

Reinforcement approach	Total costs of ownership
Traditional	€ 142.448,-
Energy storage	€ 1.014.545,-

The results are discussed on the basis of the variables. The battery purchase price is 75 percent of the total cost of ownership. This 75 percent includes the second upgrade required after 15 years. The maintenance costs are at both solutions the same. The physical costs of the traditional upgrade are higher due to interventions in the ground. The removal costs are for both approaches the same. The cables are not removed or replaced by newer ones. The removal costs of a transformer station are matched with those costs of an energy storage system. The financing costs are determined based on the internal interest of 4.1 percent. Endinet B.V. pays this interest on the total investment to Alliander N.V. – the owner of Endinet. Alliander receives repayments of the outstanding debt every year; however, these repayments cannot be traced back to a particular investment. The financing costs are stopped after one year because the repayments are not transparent. The repair and downtime costs are not significant as stated in the method parts and thereby not included in the TCO. To finalize this analysis the values are modified to the net present value (NPV). The results of that adjustment are visible in Table 17: NPV. The discount rate is the WACC of Endinet: 4.1 percent.

Table 17: NPV

Reinforcement approach	Sum NPV
Traditional	€ 100.773,-
Energy storage	€ 798.278,-

The costs of energy storage are too high with a factor of 8. In previous Endinet studies this factor was determined around 3. However, the lifetime of the investment was only 15 years. The results of this TCO confirm the earlier findings.

4.4. Conclusion

The completed analyses show multiple results with different conclusions. The results could be divided on four major analyses: LV-segmentation data analysis, Capacity and PQ analysis in Summer 2015, Capacity and PQ analysis in Winter & Summer 2040, and business case analysis with help TCO. Per analysis the conclusions are described.

The first analysis compares general used profiles of EDSN with segmented household's profiles. The data is analyzed with help of MAPE and segmented profiles. The demand of specific household segments is occasionally much higher than the forecast EDSN profile. These higher peaks could cause problems for the assets of a low-voltage grid. If one segment prevails in a neighborhood then the designed capacity based upon EDSN profiles could be insufficient or over dimensioned. Insufficient grid capacity could result in failures of the grid and thus problems for a grid operator. Over dimensions are more expensive then accurate designs. The grid operator should invest social responsible. Both problems could be a result of not using the right design data. Divers data profiles approach the EDSN profiles after a number of 40 households. The difference between the forecasted data and the actual data is then just 20 percent over a whole year. To conclude, The EDSN profile could be used for transformer stations in neighborhoods with household diversity and at least 40 households. Certain grid assets with little household diversity in the bottom of the grid should not use EDSN profiles. More household segmentation data must be examined for more accuracy as grid operator.

The second analysis focusses on a capacity a power quality analysis after implementation of PV-systems in existing residential neighborhoods (the Summer 2015 scenarios). This analysis has two different scenarios in which the penetrations of PV-systems differ. In the worst case scenario the low voltage grid has many problems with overload. Furthermore, the power quality is within the regulations of the authorities. Hence, the grid operator has capacity problems in July due to a PV-system for each household. The generation is too high and the grid could not maintain such loads. In the second sub-scenario the penetration of PV-systems is decreased till 50 percent of all the households. The impact and the problems reduce in the grid; however, the grid operator should upgrade one cable. The impact of PV-implementations in existing grids could cause direct problems in the low-voltage grids. The grid operator should be aware and act in time. Monitoring the implementation of PV-systems on such a scale could be crucial.

The third major analysis consists of two scenarios in 2040 which differ by season and charging rate of electrical vehicles. The loads of heat pumps are acceptable on the low-voltage grid; nonetheless, in combination with electrical vehicles loads troubles occur. The number of electrical vehicles is 94 in the year 2040 in the Aireywijk. These vehicles demand during peak moments much more from the grid than any other appliance. The profiles and the peak loads of charging these vehicles will be crucial to maintain and operate in the grid. The grid has power quality problems and these problems express themselves in low voltages. The demand of the electrical vehicles and heat pumps is so high that the voltage levels drop in many nodes. In this case the grid operator needs to upgrade the capacity and maintain the power quality with additional measures. The impact of EV with possible peak loads of 11 kW per vehicle is high, especially in combination with the present domestic load and heat pumps. Therefore, monitoring these developments is crucial. If many electrical vehicles charges with public charging and a peak load of 11 kW a grid upgrade is inevitable. The demand loads could not be distributed without lack of capacity. The Summer 2040 scenario correspond with the summer scenario of 2015. The problem is not resolved with the additional demand. The power quality problems of the Winter scenarios are mostly resolved with the extra supply in the grid. However, the grid has still ten overloaded assets.

The fourth analysis describes the costs of the grid investments by the grid operator which are necessary as stated in analysis two and three. The costs are determined for a full lifetime and include the possible required upgrades during the lifetime of the first investment. The cost of the reinforcement required for Summer 2015 is calculated. The upgrade in the traditional manner with thicker cables and extra transformer stations is still less expensive than energy storage which is a flexibility solution. The costs are not only initially higher; moreover, the other costs are assumed almost even for both investments. Furthermore, lithium-ion energy storage has only a lifetime of 15 years. The implementation of these battery energy storage systems is not beneficial. The price for kWh storage is still high, despite the decrease of price by tesla to 250 dollars per kWh. The cycle efficiency creates also losses which should be compensated. Furthermore, the energy storage systems could not be discharged or charged in time thus the battery capacity will increase to a form of seasonal storage. If this is necessary then the costs increase for storage systems.

To summarize, the grid operator needs to monitor the new developments very carefully. The loads in the grid should be measured more specific. The implementation of new technologies in society will bring extra demand and supply in the grid. The need for flexibility is clear; however, the costs for these solutions do not outweigh the traditional investments today. Different incentives could change this outcome such as lower prices, higher efficiencies, subsidies of authorities, and policy changes. Until then the grid operator should just invest in grids with more and thicker cables and heavier transformation stations.

4.5. Discussion

The conclusion of this report is useful for grid operators and related parties. However, the input of the data in the model had some limitations. The scarcity of data required much improvisation and modifications. More measurements should be done by the grid operator. The goal of NetbeheerNederland to become a more notifying party in the energy system can thereby be achieved. The measurements and corresponding data should be public. Open data could help for more accurate analysis. The present scarce data is limited in diversity.

The electrical vehicle data is part of a pilot project in Lochem. Electrical vehicles were shared by residents in this pilot project. The obtained data could thereby be different than the actual driving behavior of car owners. The conditions for this pilot could have impact of vehicle use by the residents.

The loads of photovoltaic generation are optimistic. Especially, the peak load of 5, 5 kW per system is on the high end. Furthermore, all the systems do deliver their full power. The systems could not achieve this due to obstacles, the wrong orientation or other reasons. Nevertheless, the initiator of this project stated that they could deliver these systems with the corresponding peak loads. The improved efficiency of PV systems in 2040 is not included. These systems could be replaced then; however, the improved peak load is not modified. This shortcoming could be adjusted with more knowledge of PV-systems and included in future research.

Finally, the total costs of ownership method seem not the right choice. This method does not meet the expected benefits. The variables which are responsible for the high costs are the purchase costs. The other variables are hard to asses or are not very significant. Therefore, the business case only indicates that the price of energy storage is still very high. The limitations discussed in 3.5.2. Benefits and limitations of TCO are applicable on this research. The cost difference match with earlier research by Endinet B.V. Therefore, those results are confirmed and this is valuable.

Acknowledgments

This project was undertaken to design a model of a low-voltage grid to investigate the loads on the low-voltage grid of the future. The datasets used for this goal are obtained from different sources. Endinet B.V. provided a mentor and their data of the grid and case. Paulus Karremans was a great mentor through the complete graduation. The complete team of Asset management helped and guided me during six months. Other grid operators delivered data as well. I am grateful to Liander who provided the electrical vehicle data. Furthermore, I would like to thank E. Klaassen for the provided heat pump data. The study could not been completed without this assistance.

5. Conclusion

In this final chapter the conclusion is drawn for the whole report. Returning to the questions posed at the beginning of this study, it is now possible to state short answers to each research question. Once these questions have been answered the report concludes with the societal, scientific and beneficiary relevance.

Main-question: *Under what circumstances will the grid operator implement storage points in the local low-voltage grid to create more flexibility in the grid of residential neighborhoods?*

The price still determines the investments of a grid operator. A more flexible grid could solve multiple problems. However, if these flexibility options are more expensive than the traditional way of investing there is no need to change their governance. The costs of energy storage are still too high.

Sub-questions: *What are the energy profiles in 2040 in a low-voltage grid in a residential neighborhood?*

The residential neighborhood has a higher demand profile due to the implementation of heat pumps and electrical vehicles. The present domestic demand could decrease due to more efficient appliances or stay stable. However, the number of appliances could increase and therefore the domestic demand increase. Since the introduction of PV-systems and other renewables the low-voltage grid has to deal with decentralized generation. This generation creates the largest problem due to the simultaneity of the systems. The demand technologies such as electrical vehicles have higher peak loads per system; however, the simultaneity of these technologies is much lower than one. The general load due to demand increases in the low-voltage grid. The supply load increases due more renewable systems in the low-voltage grid. A hundred percent penetration of PV-systems in an existing neighborhood creates loads which cannot be maintained by the grid.

What determines the capacity of a low-voltage grid in a residential neighborhood?

The present capacity is determined by the assets in the grid such as distribution boxes, cables, and transformer stations. In the future new flexible additions could increase the capacity. Batteries of electrical vehicles and other storage units could improve the capacity of the grid. These energy storage applications are sometimes flexible or could be a permanent part of the grid. If the new flexibility solutions are not implemented – the business case is not beneficial – then the grid capacity still depends on the 'traditional' assets

Which capacity challenges do occur in the present grid? And which problems will occur in 2040?

The grid capacity is insufficient – in the Summer situation – many cables and transformer stations are overloaded. Furthermore, power quality issues occur during times with high demands: Winter 2040. The grid should be improved to keep it operating. The problems in the Summer situation are caused by the high supply in the grid. This high supply is new in the grid and not experienced before. In the grid of 2040 these problems still occur despite the new demand technologies. The electrical vehicle could be charged during these energy surplus times; however, this approach is not yet matured. The capacity problems in 2040 are caused by too much supply. The power quality issues are a result of the additional demand from electrical vehicles and heat pumps.

Which flexibility options could solve capacity problems in a residential neighborhood in 2040?

Many flexible solutions can contribute to the required capacity. The solution focuses on three different categories with all multiple possibilities. The three domains are: supply, demand, and capacity flexibility. All of those options could solve parts of the puzzle; however, the possible business cases should really determine which solutions will be implemented. The flexibility option of energy storage with lithium-ion batteries is too expensive now.

What actions should be considered to create flexibility in the low voltage grid in a residential neighborhood in 2040?

The no-regret measures are already investigated. The actions which could create more insights are started in the form of pilots. These pilots create extra insights and experience with possible flexibility options. These pilots are also encouraged by the authorities. However, the actions are not applied on a larger scale if the business case of the traditional investments is more beneficial. The goal of a total sustainable energy system will be an extra incentive to create more flexibility in the grid. Then flexibility is a necessity to manage the renewable transition.

Is the implementation of electrical storages systems a serious option for a grid operator?

The grid operator has the value of financial return. Moreover, the grid operator should invest socially responsible because these investments are funded by community money. The option of electrical storage is not a real option due to the high costs today. In the future these prices may decrease and other possible benefits or earnings could create a business case. The price for the required energy storage is too expensive with a factor of eight.

What are the costs and benefits involved by implementation of storage systems in the low-voltage grid?

The implementation costs of energy storage are nearly seven times too expensive. Therefore, the costs should decrease. The benefits are multiple:

- Storage could help with the supply side management in the low-voltage grid;
- Storage could help with the demand side management of the low-voltage grid;
- Storage could help with power quality issues in the low-voltage grid;
- Storage could help with the transition to more sustainability;
- Storage could create more capacity in the grid;
- Storage could be flexible distributed on the grid (EV batteries).

The costs determined in the TCO-sheet are now only compared with a traditional capacity investment. The grid operator invests also in defects which energy storage could solve. The present incurred costs for all these problems may come closer to the total investment costs of this energy storage system.

This study has identified the relevance of segmented data. This data is used in low-voltage grid model. The low-voltage grid is not designed for the future demand & supply loads. Investments of the grid operator are unavoidable. Presently, flexibility option - lithium -ion battery storage – is too expensive. The relevance of this research is discussed in the next three paragraphs.

5.1. Societal relevance

This case study has identified that the present low-voltage grid has too little capacity for future developments. Thereby, the grid operator needs to reinforce the grid to maintain the present grid quality. The high quality of the energy system in the Netherlands became the standard in society. The consumers of electricity expect at least this quality for the future. However, the investments for reinforcing the grid are indirect paid with public money. A grid operator is thus obliged to predict their investment behavior. This study has found that generally the low-voltage grid requires reinforcements. The energy transition affects the whole society and investments – which are unavoidable – are eventually paid by society. Despite its exploratory nature – research on a specific case – this study offers some insights into alternative flexibility solutions. The social responsible value of grid operators is still important for investments decisions. Therefore, this research is crucial to inform the grid operator and to prevent surprises for the society.

5.2. Scientific relevance

In the scientific field many publications describe research on this subject. The energy transition is an important topic. Endinet B.V. already published some papers at the CIRED conference on these kinds of subjects. The (new) developed technologies can only be implemented if their effects are investigated. The commercial market monitors the scientific journals for new possible approaches for solving their problems. This paper creates additional knowledge of load profiles and the use of load profiles. The loads are all based upon actual measurements. This is relatively new due to scarcity of public data. The following conclusions can be drawn from the present study that segmented data can be crucial and that simultaneity of multiple generation loads creates problems. One of the more significant findings to emerge from this study is that the much higher supply and demand loads does not balance themselves due to simultaneity. The power quality problems decrease; however, the shortage of capacity in the grid remains. The low-voltage grid does have capacity problems due to high decentralized generation. This finding of this investigation complements those of earlier studies by Endinet which were published at CIRED 2015.

5.3. Beneficiary relevance

Endinet B.V. is a grid operator with multiple company values as discussed in 2.3.2. Company values of the grid operator. In their mission & vision Endinet stated their relation with society and their vision on the future. This report endorses the relevance of their existence and their mission & vision. This report is shared in their asset management team and discussed in detail. The team was very interested in the result. The acquired knowledge can now be used for future assignments.

Furthermore, other parts of the company are also informed with these findings. The operational department of Endinet B.V. plans reinforcements in detail and in time. They are supplied with knowledge of new risks and troubles in the grid by asset management. This report results in mutual understanding. Other departments already showed much interest in the development of the strategic asset management plan by asset management. The results of this research support the findings in the strategic asset management plan. Thereby, the practical relevance for the company is proven.

To conclude, the results of this research are shared with many related parties in the energy system. The results are presented to multiple national teams which are processing energy system developments. A national consult – Flexnet – uses the results of this report for creating a strategy of a more flexible energy system for all the energy carriers. Parties such as GasTerra, NetbeheerNederland, and ECN are represent in this consult. Their work will eventually be used by all these parties and their findings are important for the energy transition in the Netherlands. Furthermore, the report is shared with parties such as grid operators and the heat pump association to reward and inform them for their share in this report.

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Appendixes

Appendix 1 – Literature study

In chapter three – literature review – the basic findings and results of this literature study are given. Literature study provides insights in the present state of the research done to the subject. Furthermore, possible solutions unfold themselves due to literature study.

The literature study guideline was handed by the department of Construction Management Engineering. The base for such a literature review is explained in the paper of Webster and Watson. In their paper they describe their basic principles for a literature review. The most important thing is to stay neutral and to search forwards and backwards in literature. This forwards and backwards research implies that literature contains sources which lead to other research over time. Further, the use of tables in which literature is divided into concepts is useful. Thereby, the missing pieces could be identified faster and extra research to these subjects could be started.

In this report the input came from several sources. These sources could complement each other and thus they should be examined thoroughly. The sources which are the main input for this report are: scientific literature, reports of (branch) companies, and input from practice due to an internship at Endinet.

The future solutions are mainly described in scientific literature. These solutions are not yet wide spread and some are implemented in practice due to pilot projects. However, these journals show that these technologies have potential. Furthermore, they give an overview of their problem-solving capabilities. Energy storage in the form of battery systems was found due to early literature research. The problem determination was mainly driven by practical experience of the supervisor. The solutions were necessary after the problem was demonstrated. In the parallel literature study the possible solutions were broad. A recent paper of Lund et al. was important as scientific journal. Basically, this paper reviewed on possible flexibility options in the electricity market.

The literature study showed that there are other solutions than the traditional reinforcements of the grid. The chosen battery technology came forward due to the capabilities and problems which it could solve. A business case should be developed and therefor a method is described in the next paragraph.

Appendix 2 – Liander smart meter data compared with actual measurement of Endinet

In this analysis the modeled results on transformer station Bartoklaan are compared with the actual measurement of Endinet B.V. The measurement is executed in September 2014 to gain more insight in the Aireywijk. The modelled load profile on the transformer station is compared with the actual measurement.

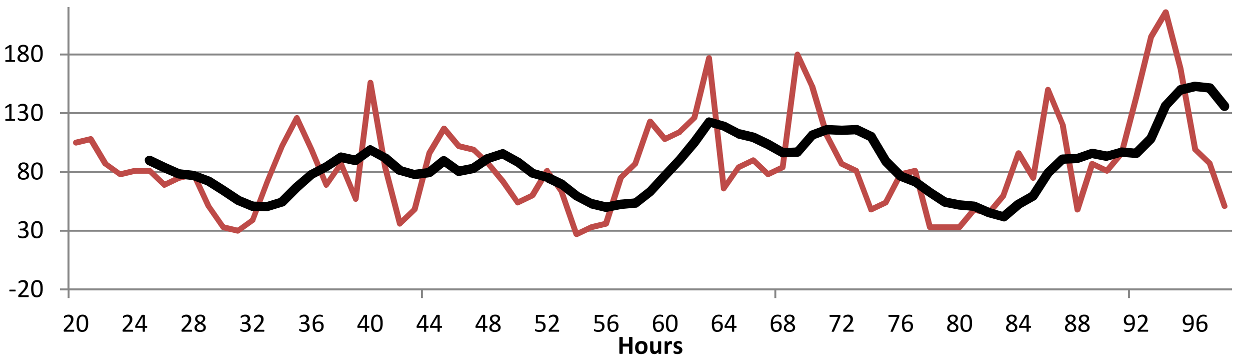


Figure 41: Modelled load on the transformer station – Barotklaan

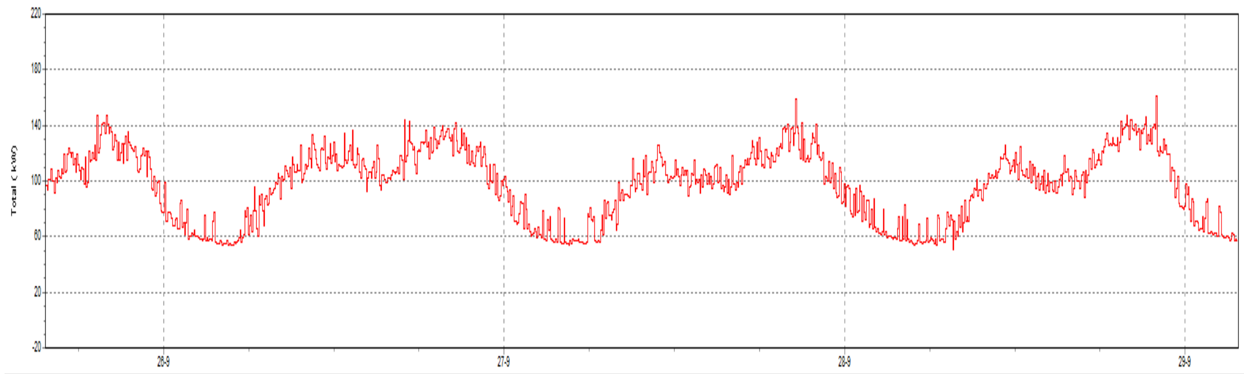


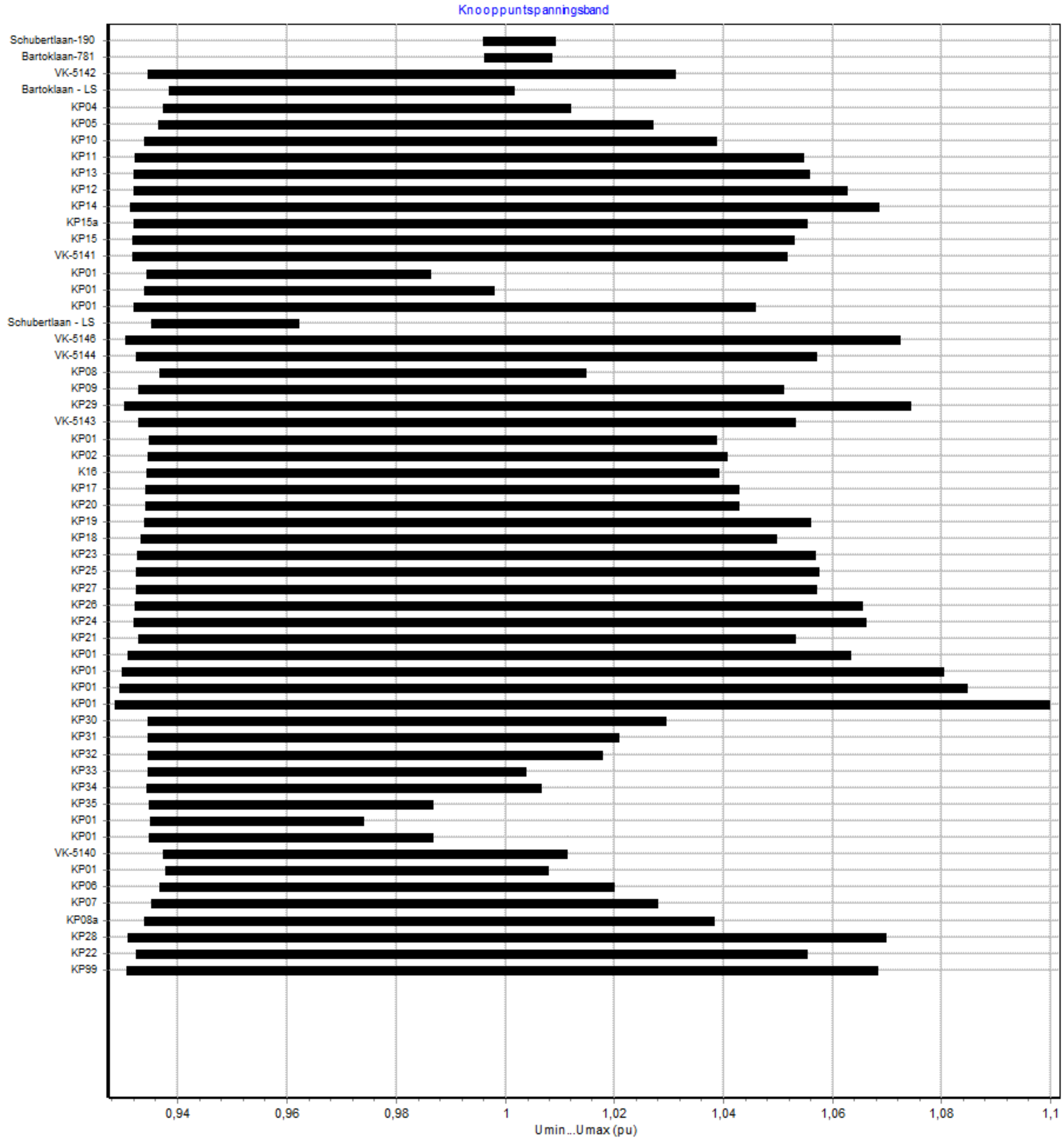
Figure 42: Load profile on the transformer station – Bartoklaan

The two load profiles are depicted in Figure 41 and Figure 42. The modeled version is much more spikey and unpredictable then the measurements. The modeled profile does not match with the actual measurement by the first impression. However, the trend line - the black line – shows many similarities with the actual measurement. The modeled profiles are thereby useful. The spikey results can be explained by the low number of profiles and thus little diversity. The segmented data is useful, however, on the level of a transformer station the load results match much more with an EDSN profile. The correct choice of profile is determined by the scope of the research. The actual case study in the Aireywijk contains low-voltage cables and distribution boxes. This case is located in the lower grid and thus the segmented profiles may lead to other insights. The assets in the low-voltage grid are thereby tested with segmented data. This data seems to be reliable on average.

Appendix 3 – Results – Summer 2015 – 100

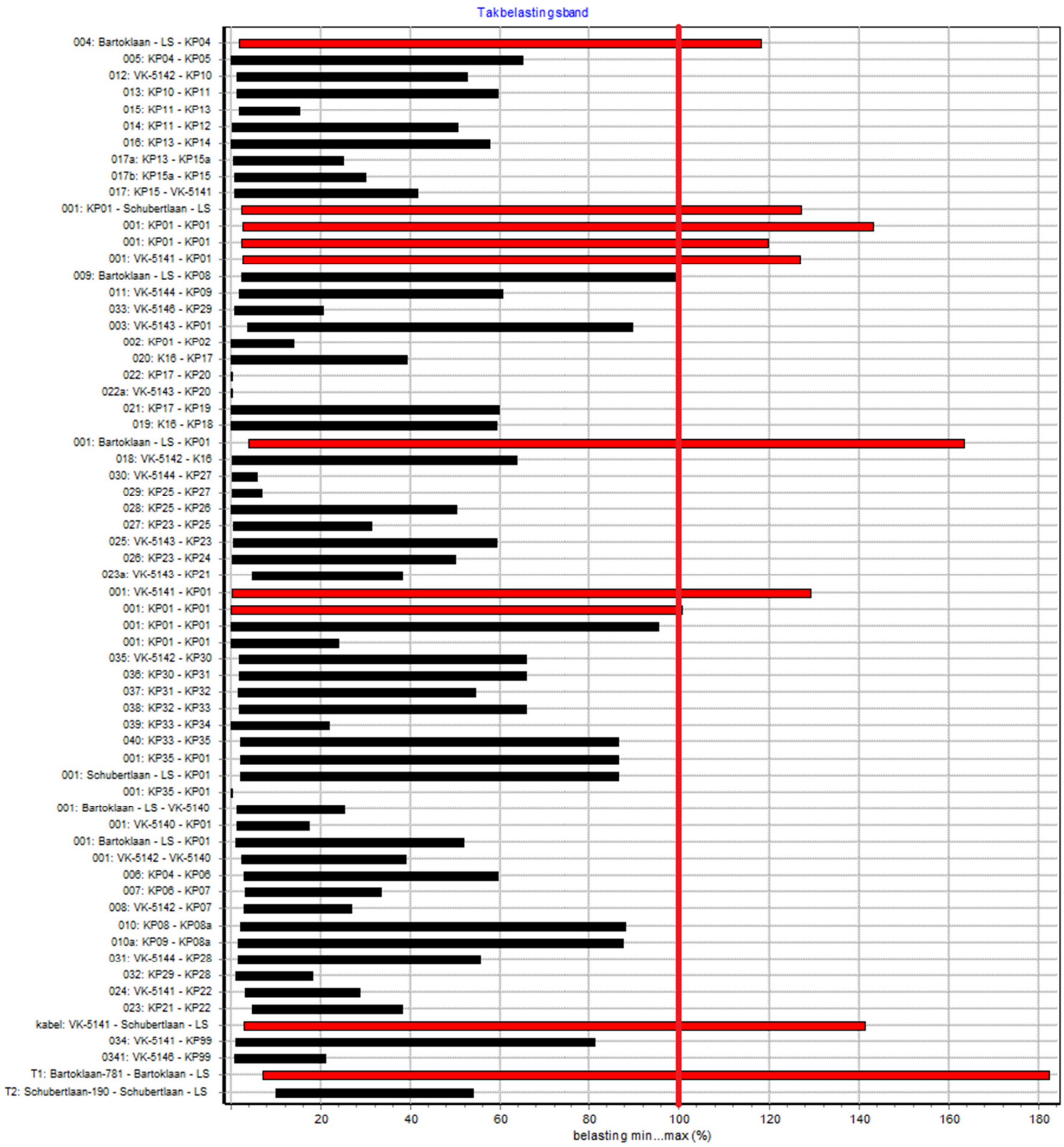
Nodes PQ

– With margins 0.9 up to 1.1 (red line(s))

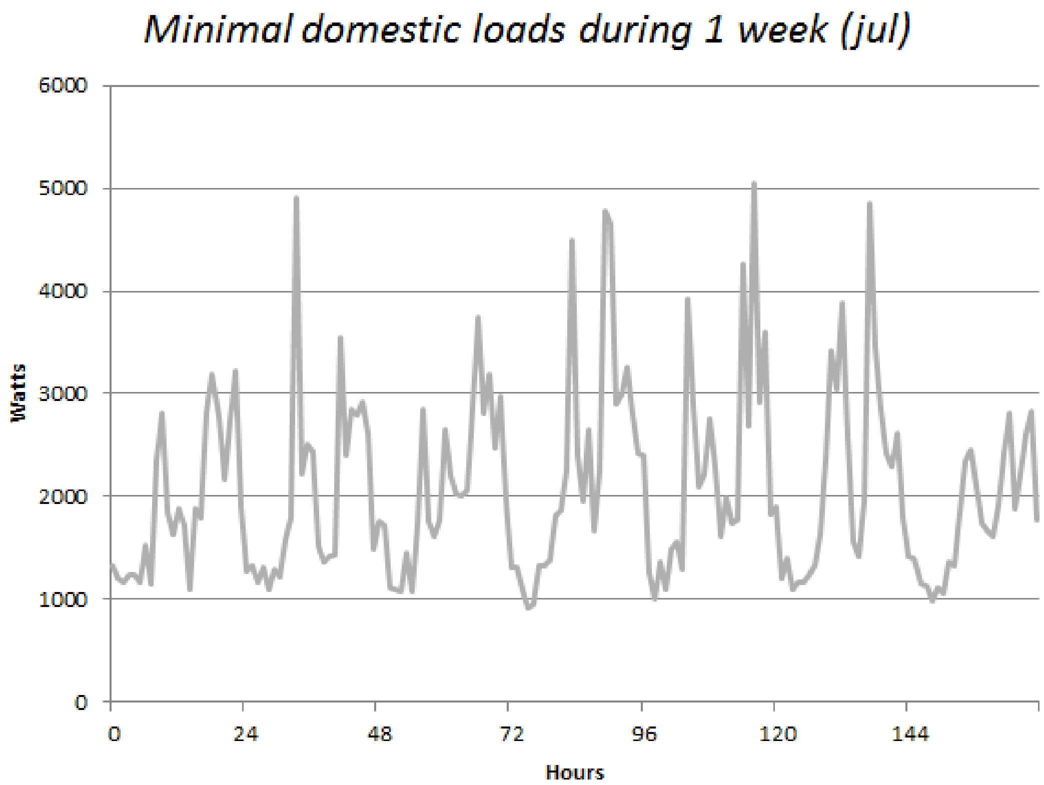


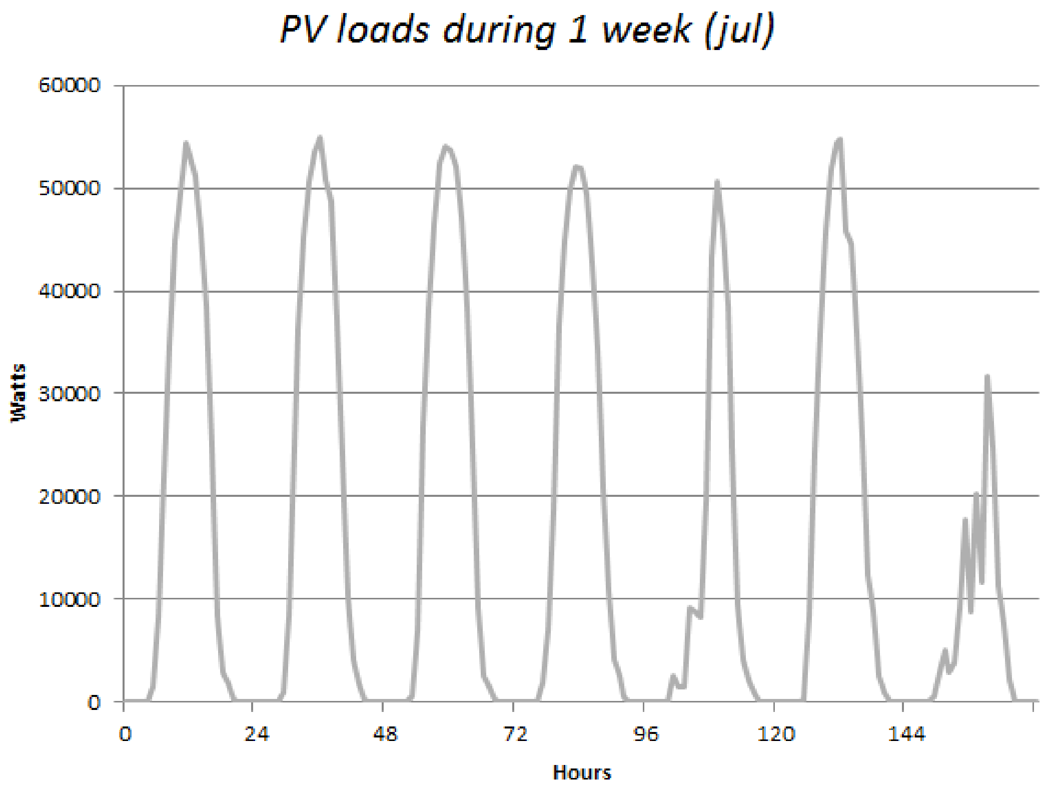
Branch Loads

– With 100 percent load (red line)



Profiles of demand and supply loads on node 32 (an example node)

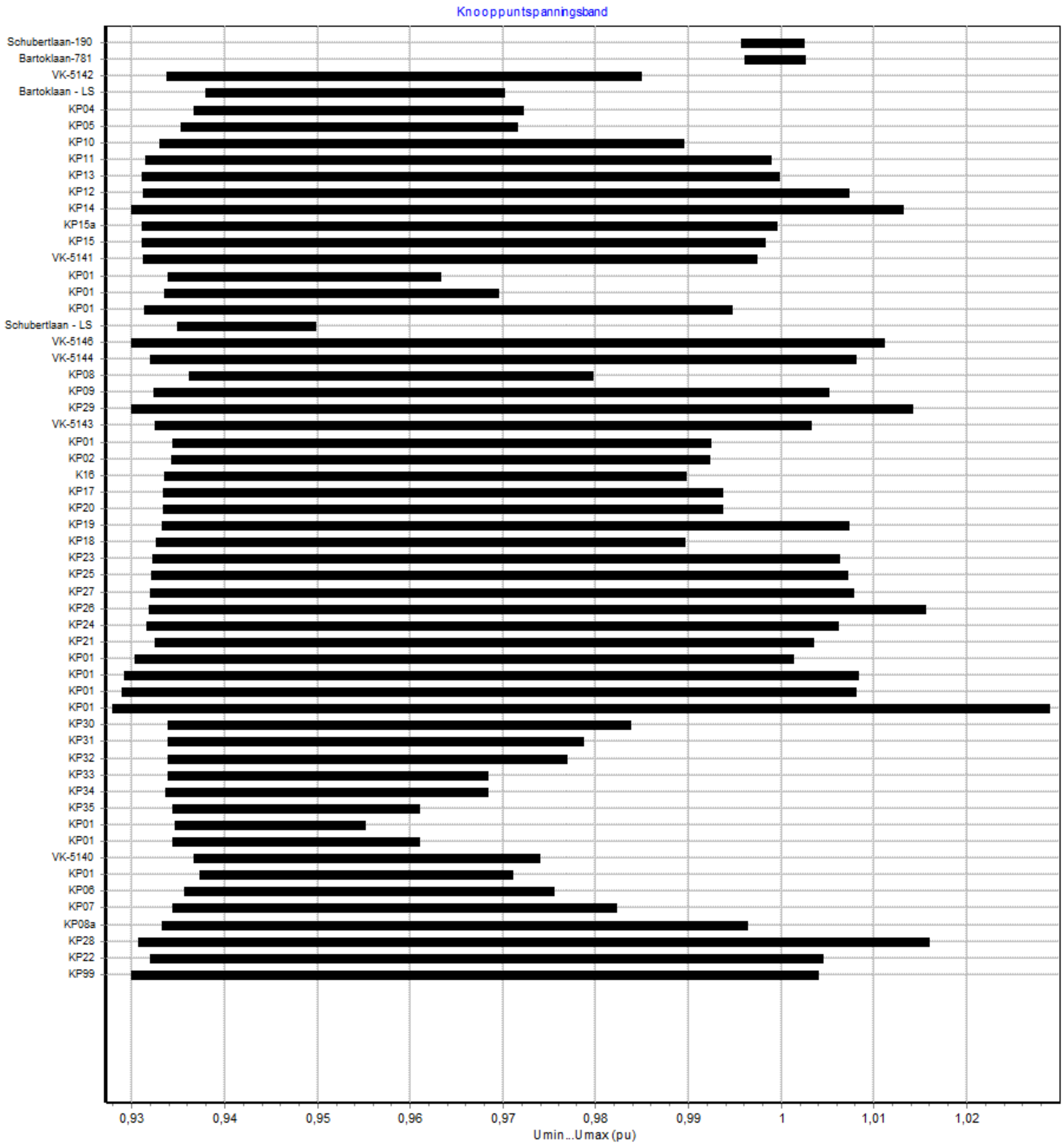




Appendix 4 – Results – Summer 2015 – 50

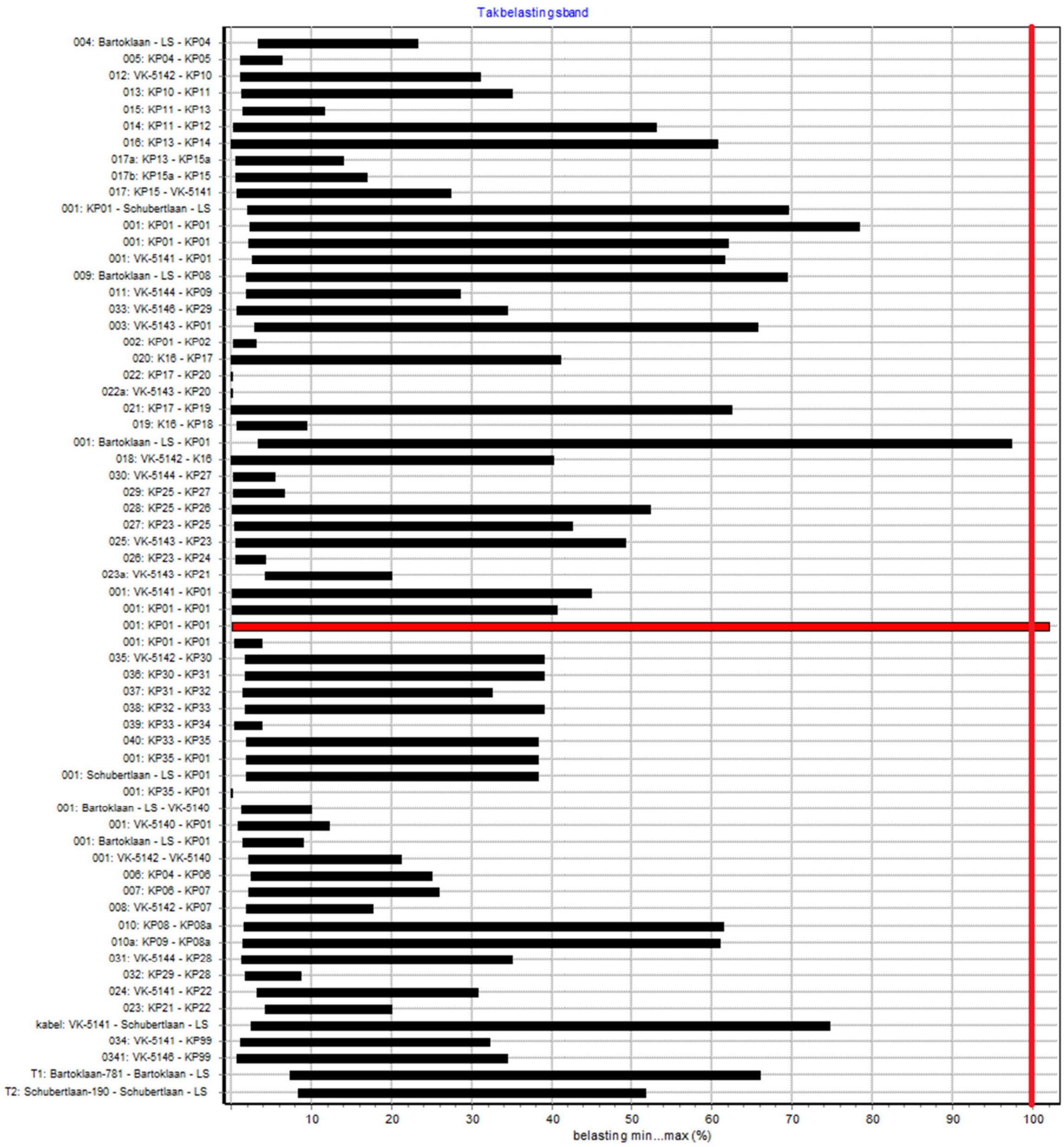
Nodes PQ

– With margins 0.9 up to 1.1 (red line(s))

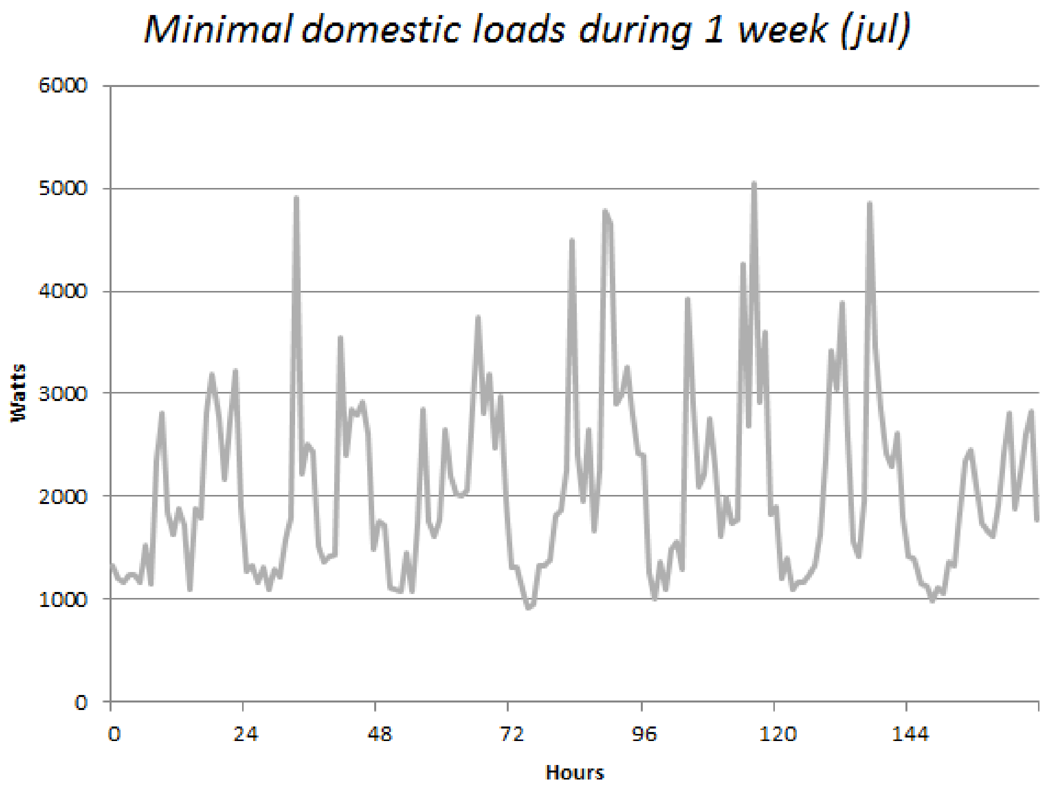


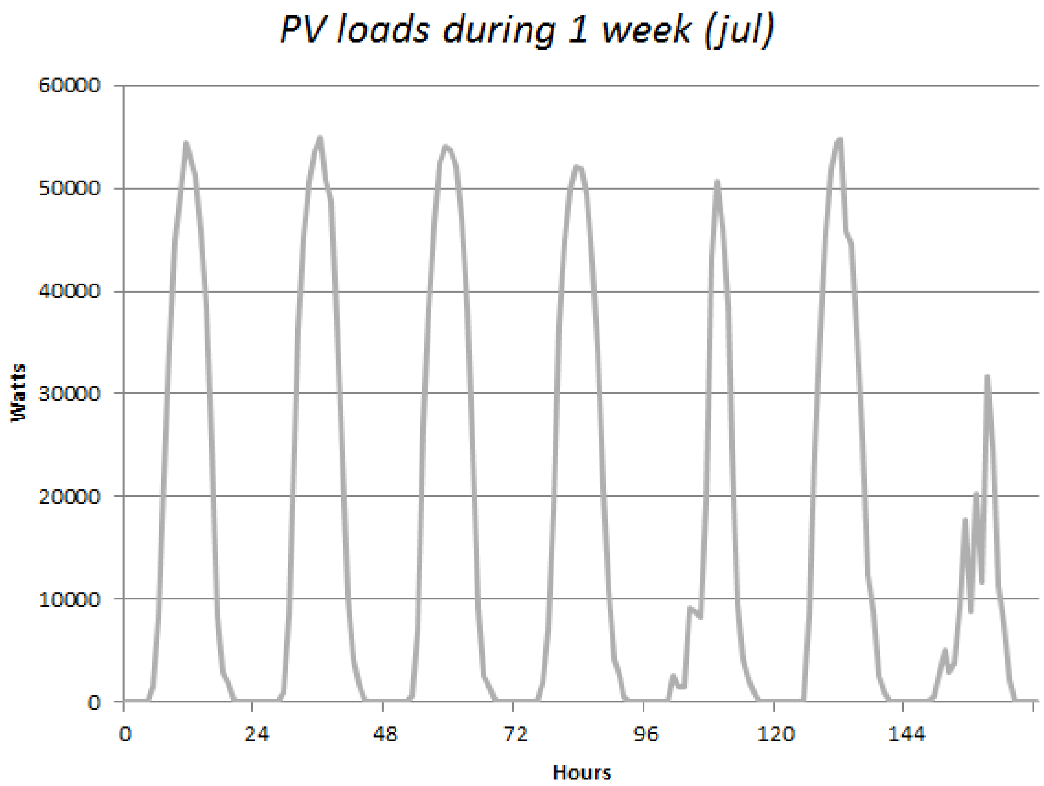
Branch Loads

– With 100 percent load (red line)



Profiles of demand and supply loads on node 32 (an example node)

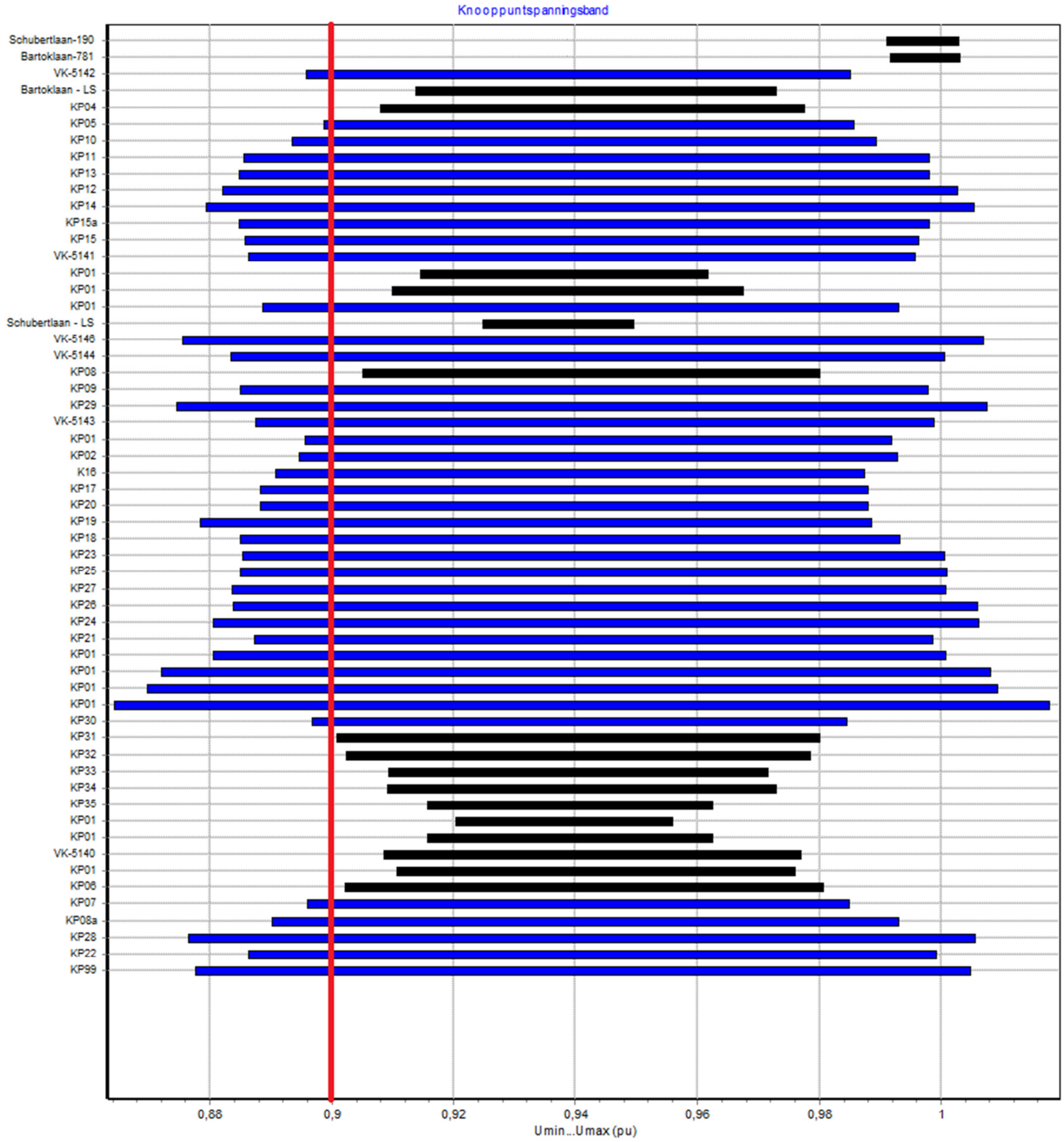




Appendix 5 – Results – Winter 2040 – Home charging

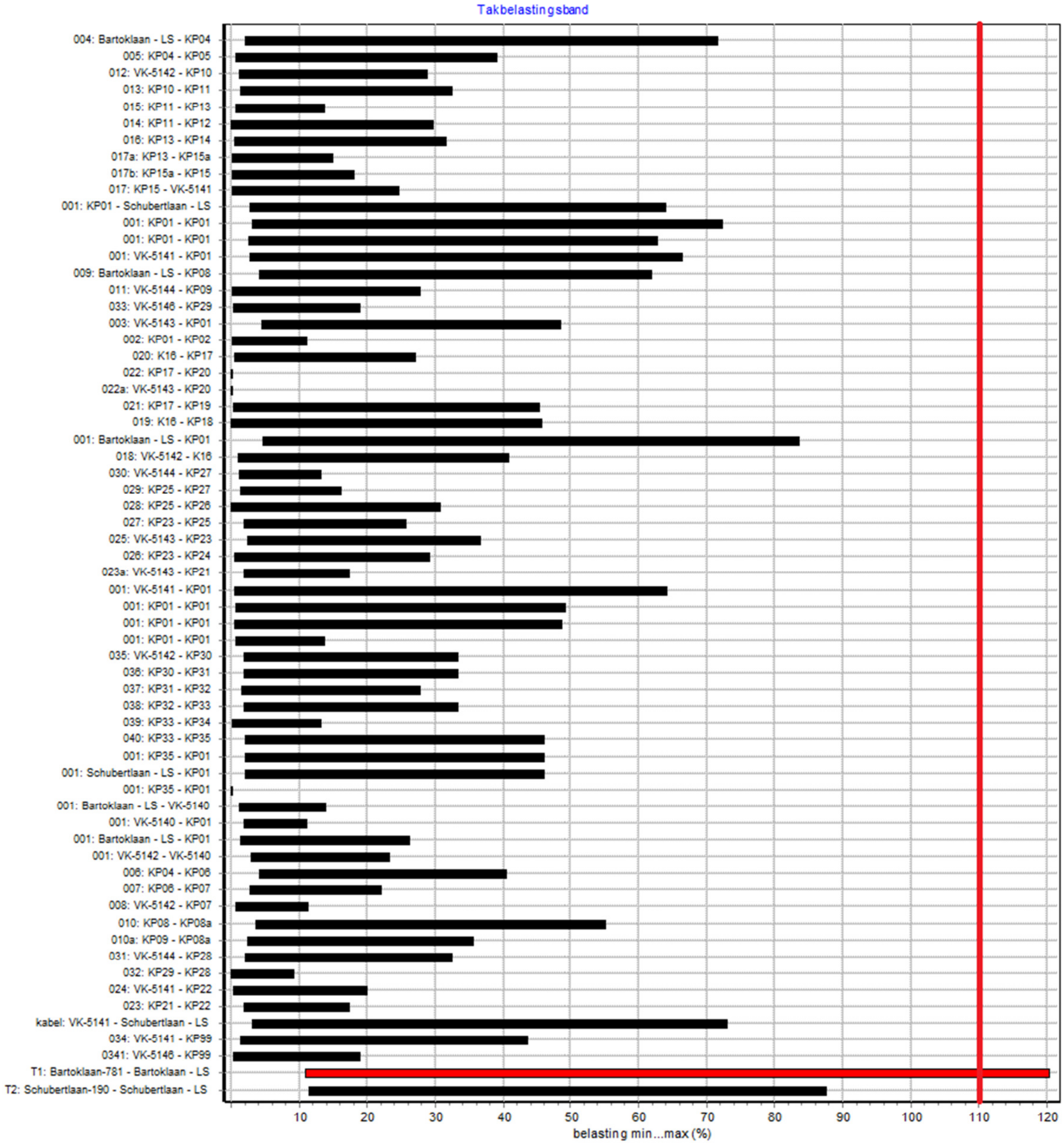
Nodes PQ

– With margins 0.9 up to 1.1 (red line(s))

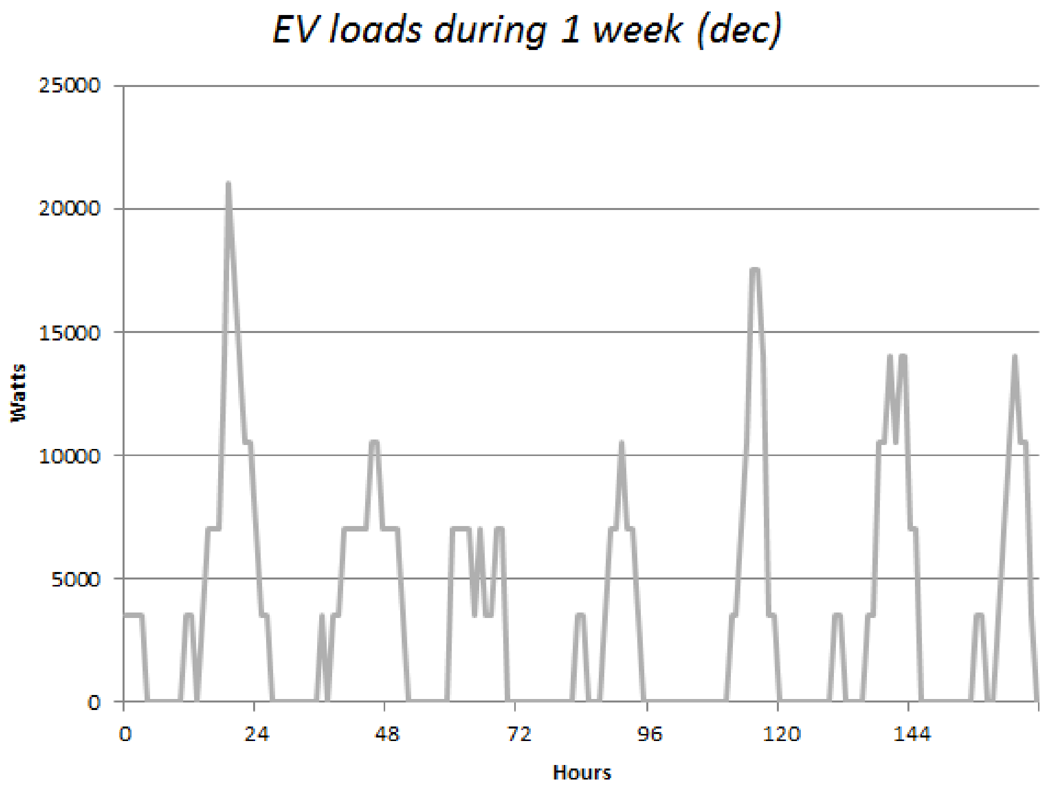


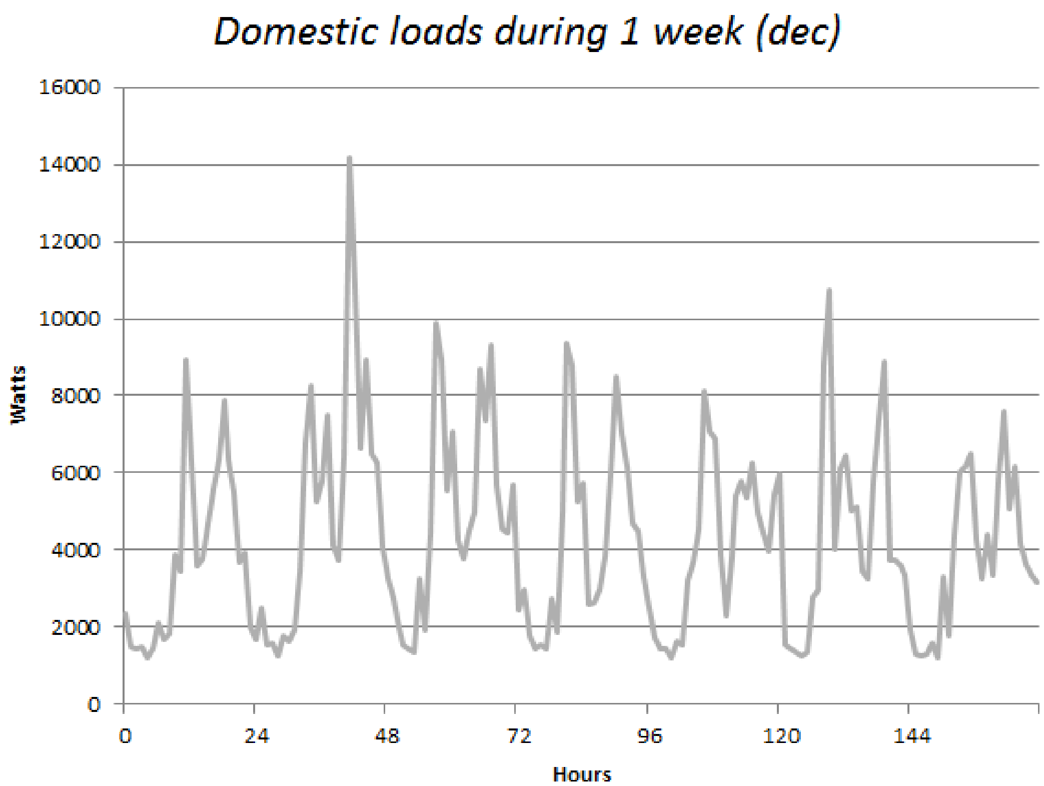
Branch Loads

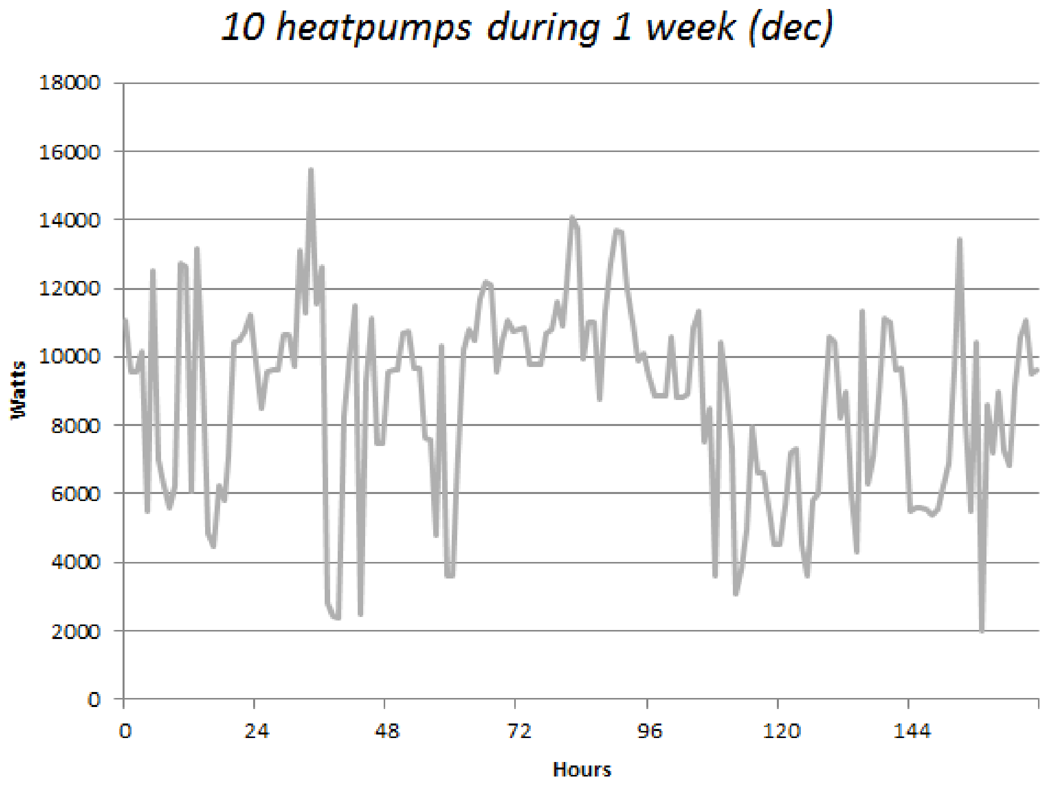
– With 100 percent load (red line)

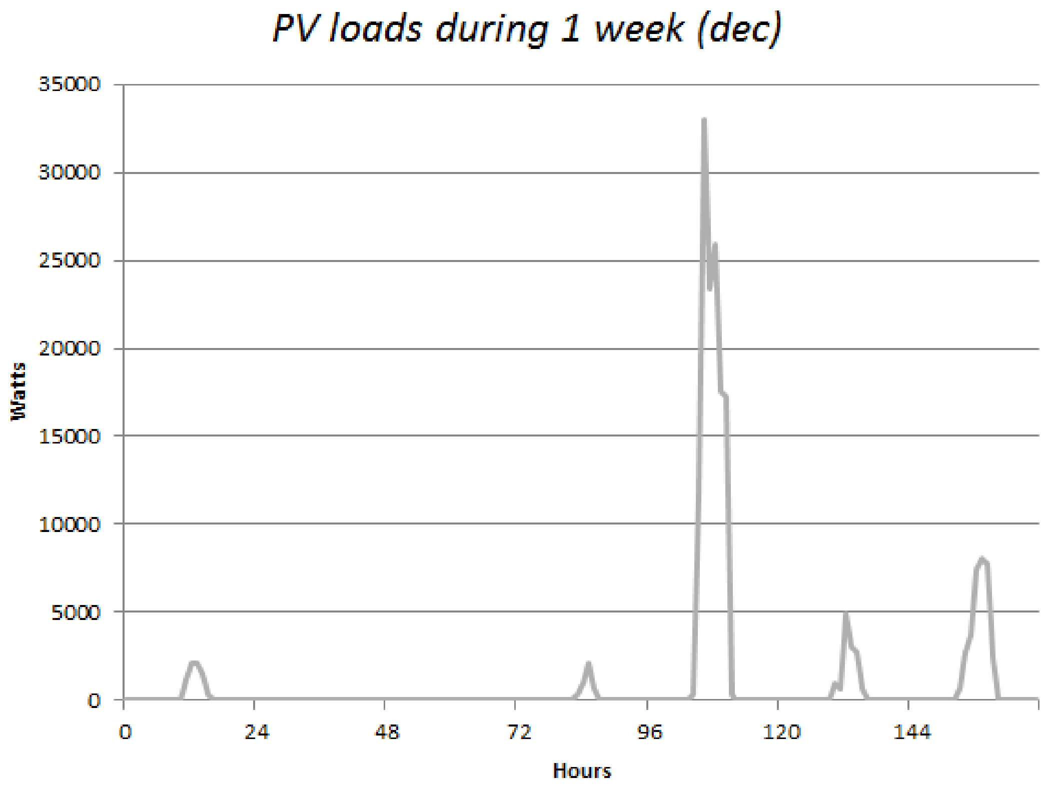


Profiles of demand and supply loads on node 32 (an example node)





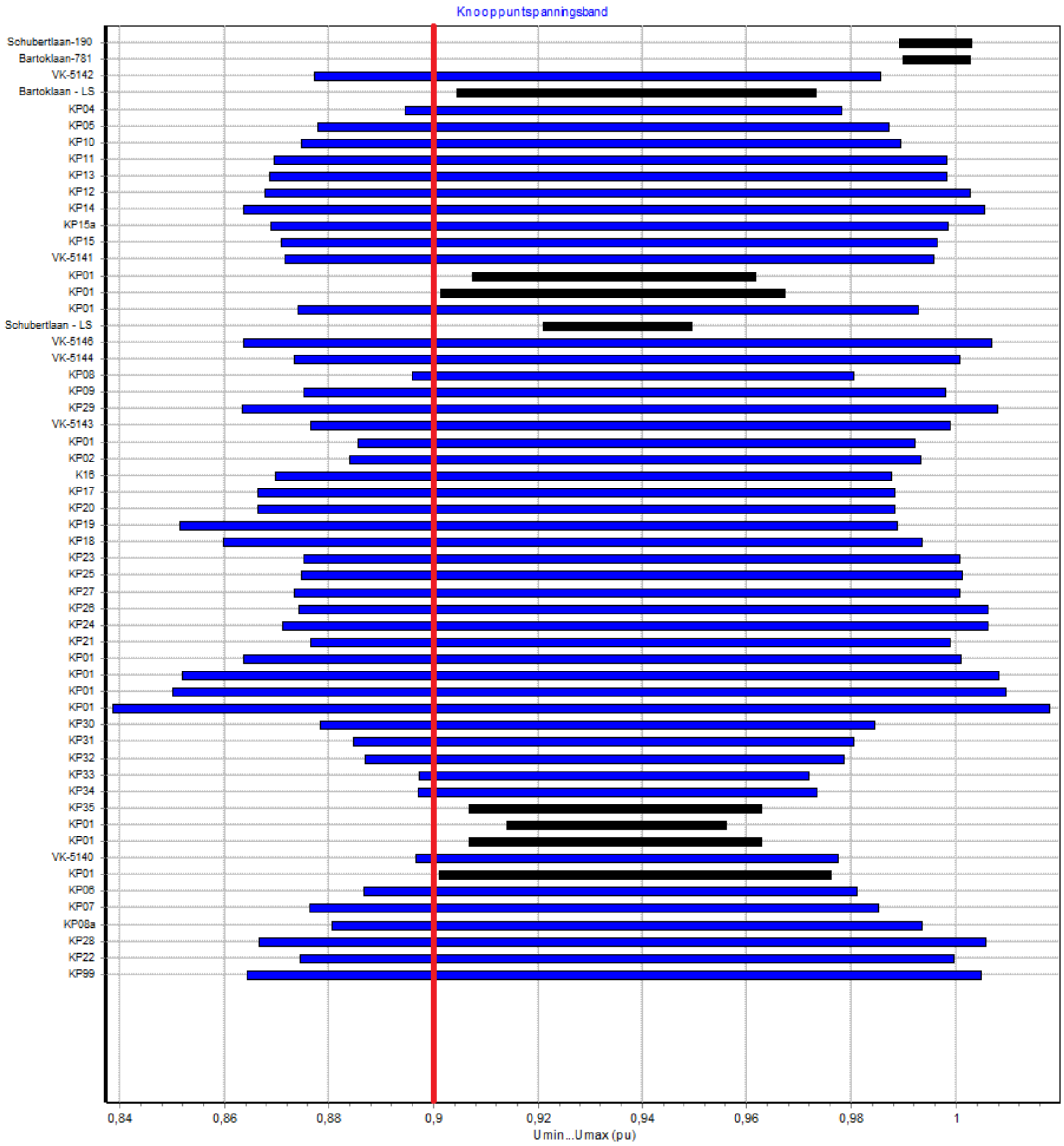

10 heatpumps during 1 week (dec)
Watts
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
24
48
72
96
120
144
Hours


PV loads during 1 week (dec)
Watts
35000
30000
25000
20000
15000
10000
5000
0
0
24
48
72
96
120
144
Hours

Appendix 6 – Results – Winter 2040 – Public charging

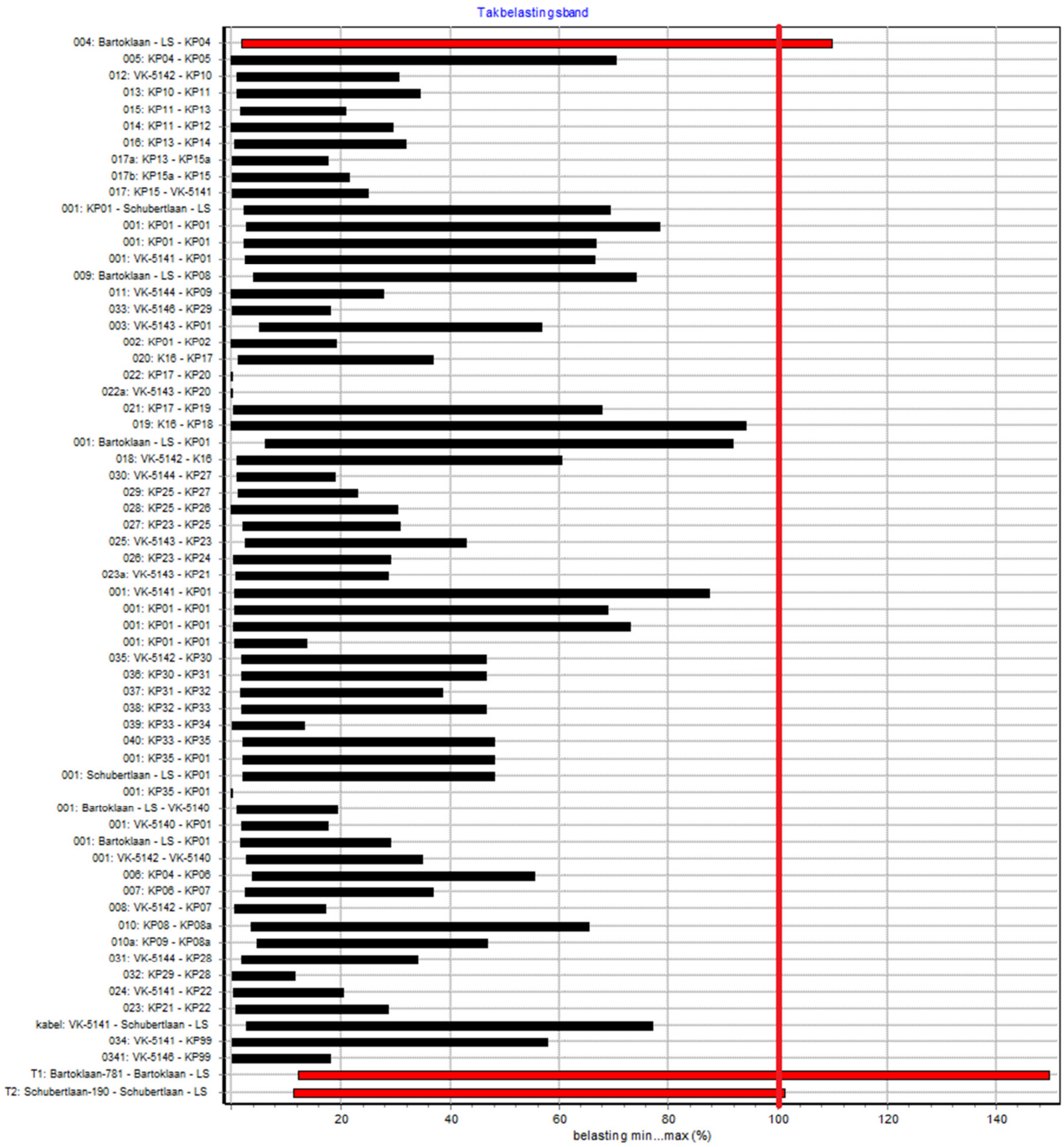
Nodes PQ

– With margins 0.9 up to 1.1 (red line(s))

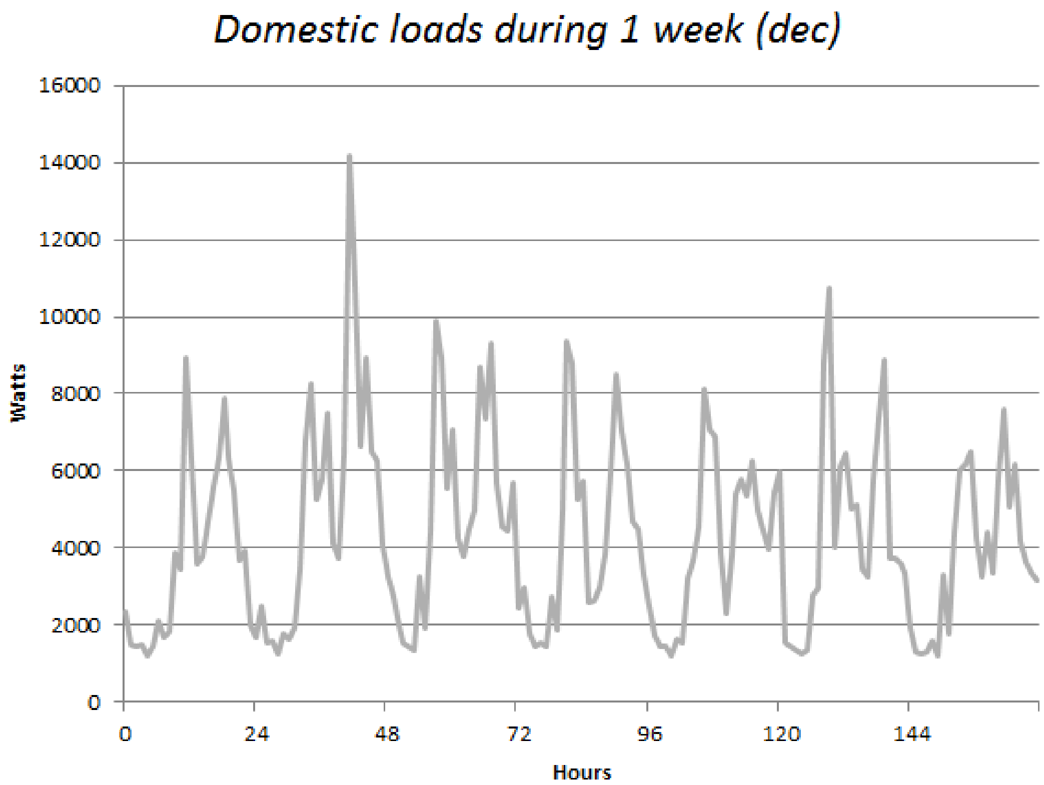


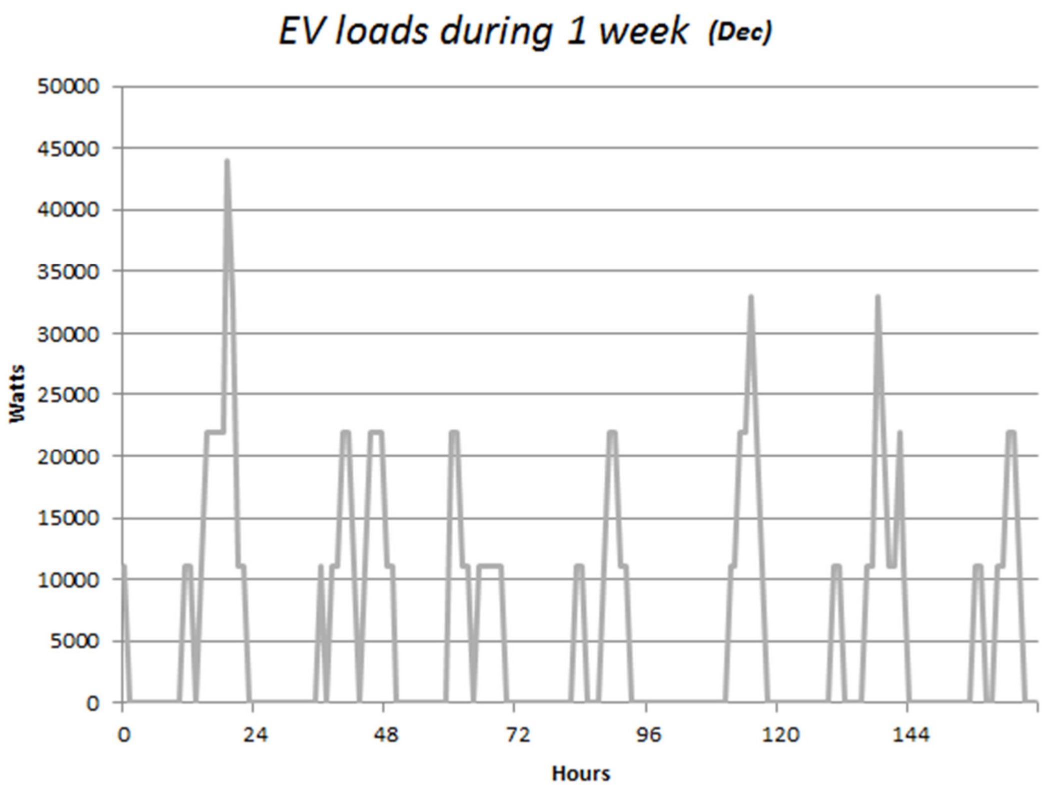
Branch Loads

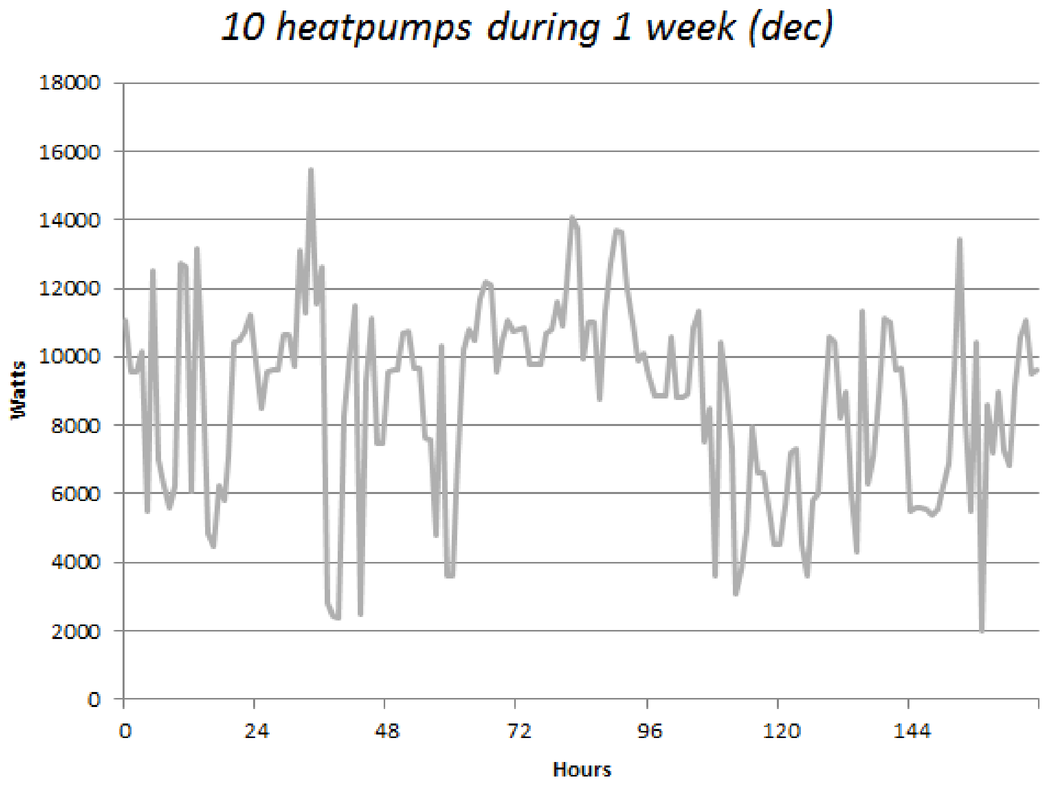
– With 100 percent load (red line)

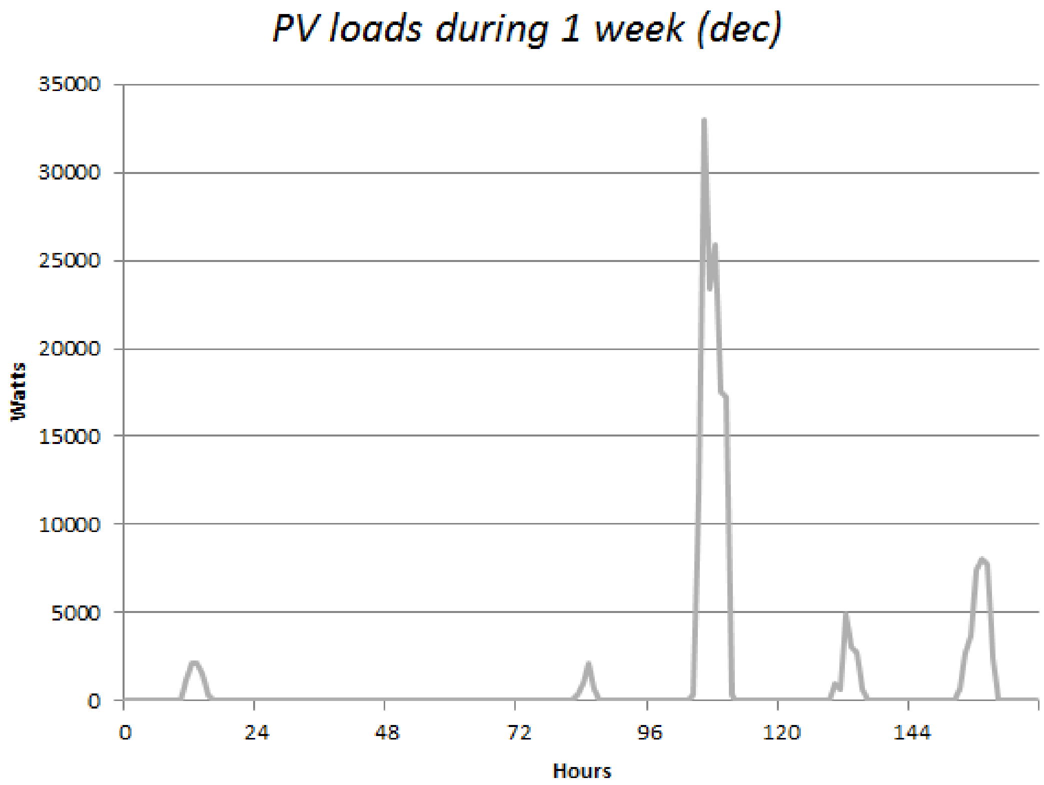


Profiles of demand and supply loads on node 32 (an example node)





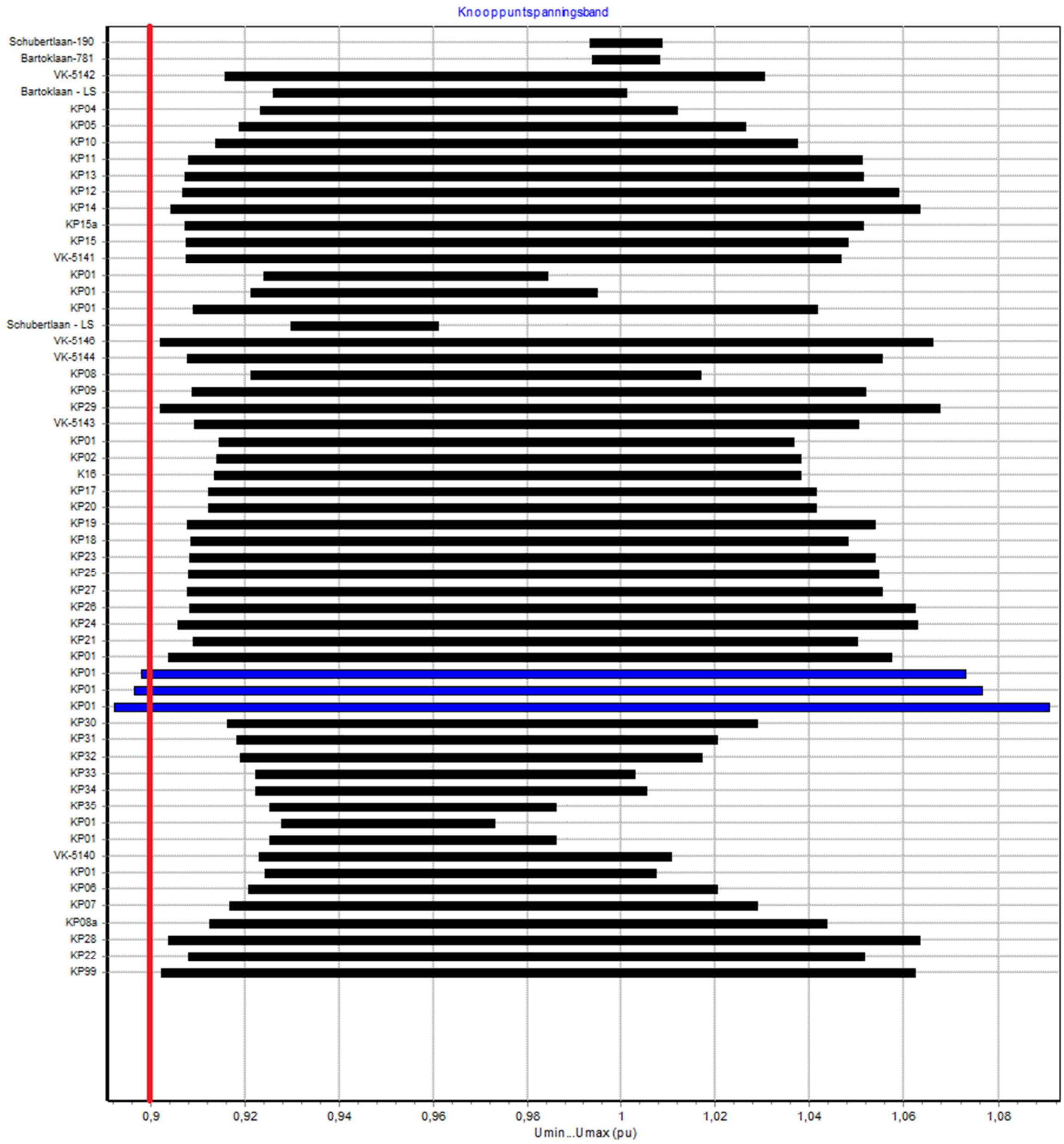

10 heatpumps during 1 week (dec)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Watts
0
24
48
72
96
120
144
Hours


PV loads during 1 week (dec)
35000
30000
25000
20000
15000
10000
5000
0
Watts
0
24
48
72
96
120
144
Hours

Appendix 7 – Results – Summer 2040 – Home charging

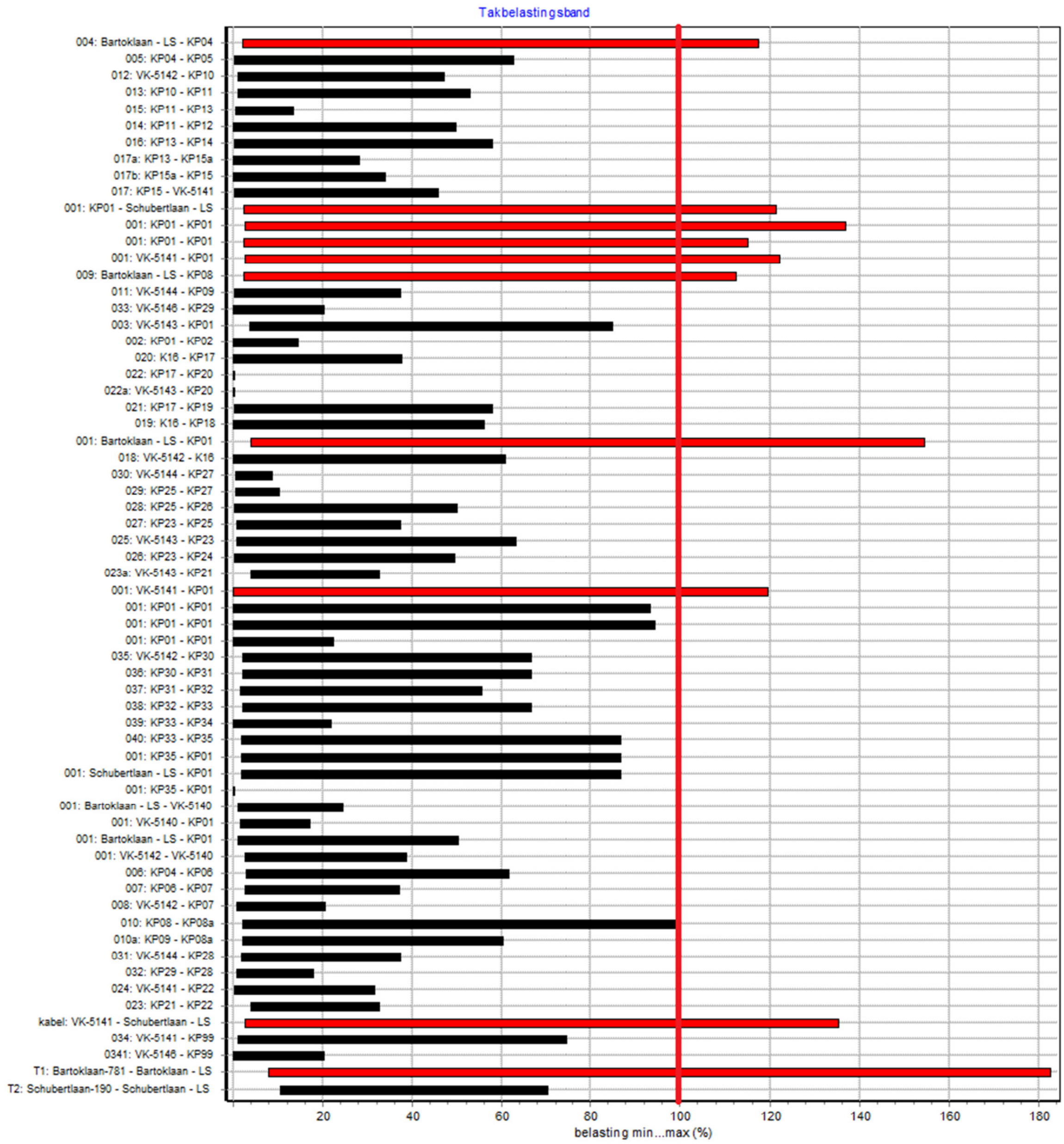
Nodes PQ

– With margins 0.9 up to 1.1 (red line(s))

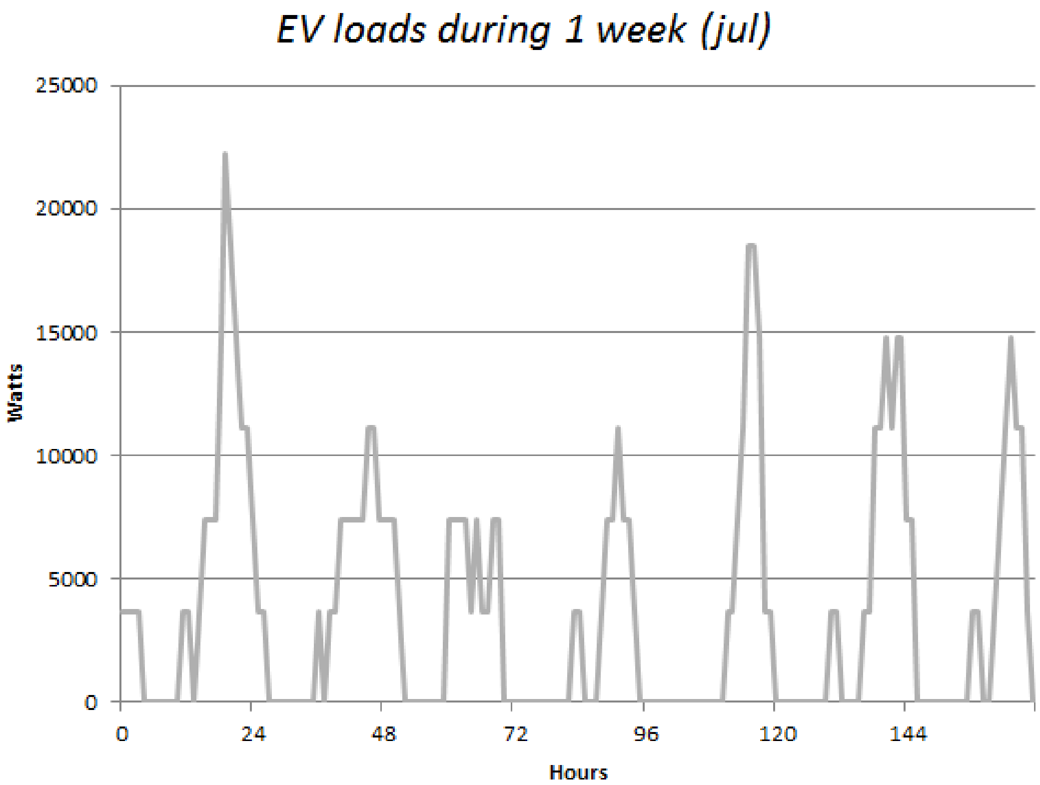


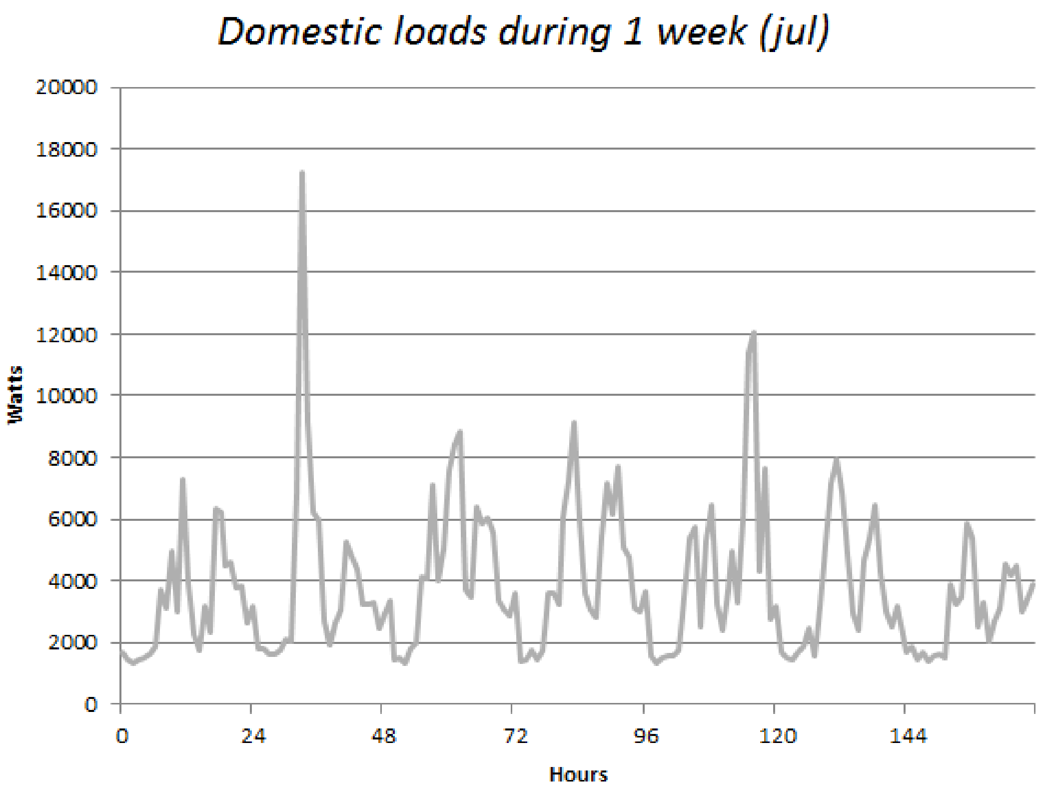
Branch Loads

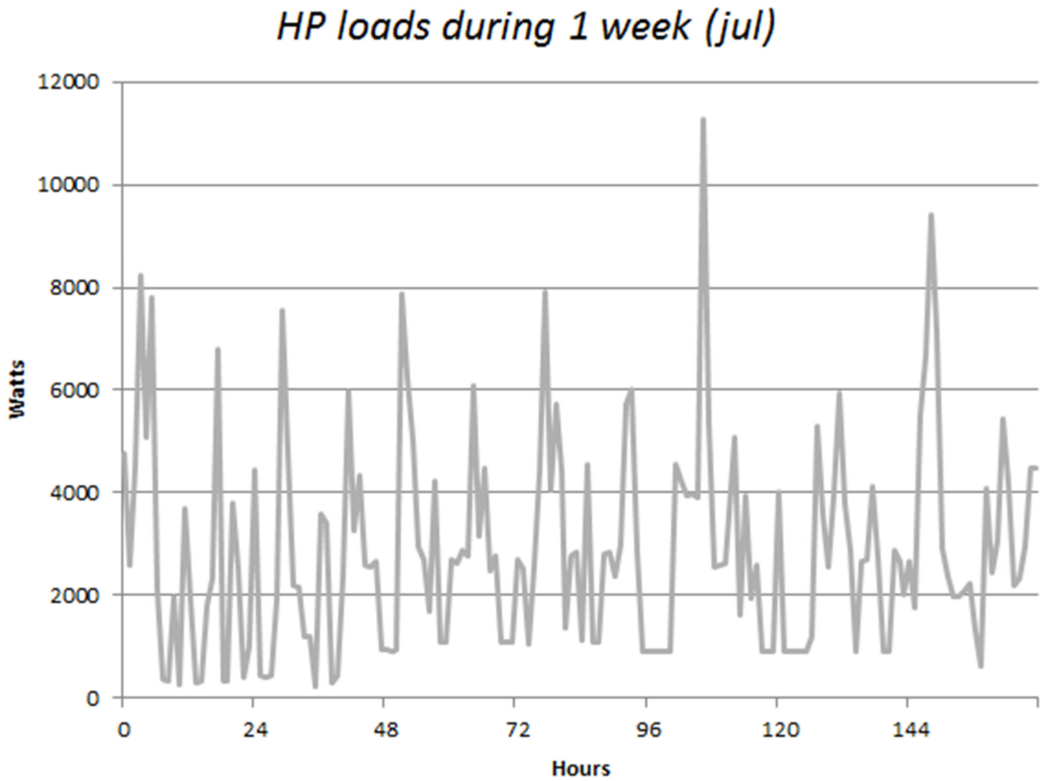
– With 100 percent load (red line) red

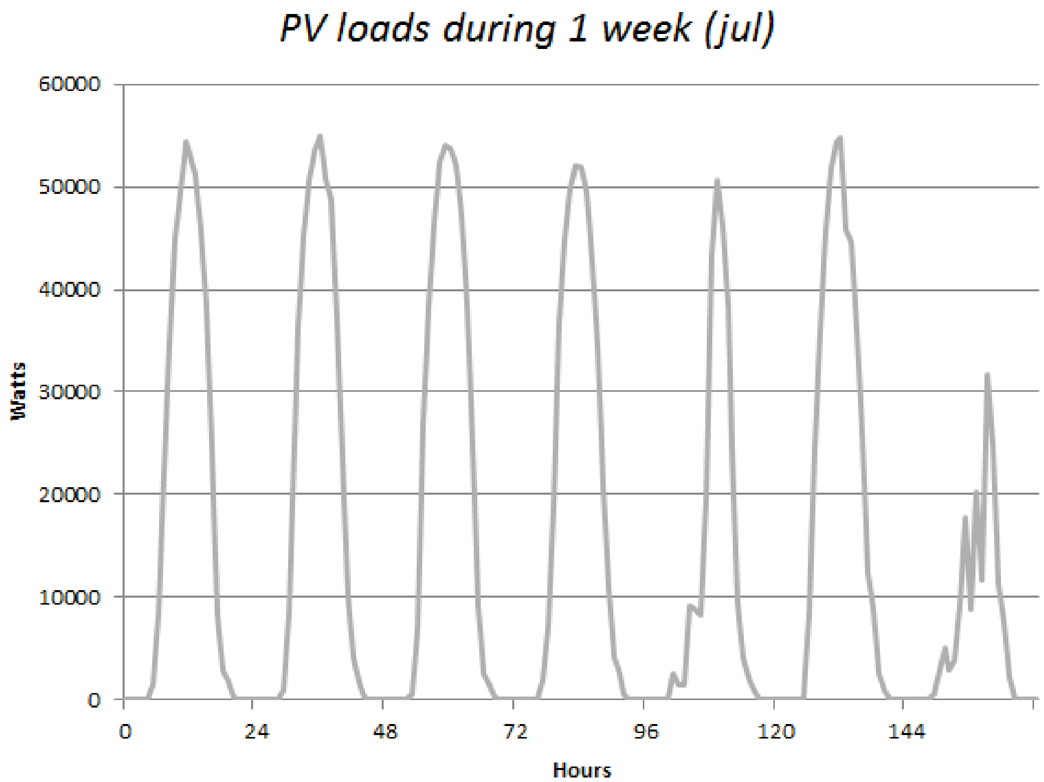


Profiles of demand and supply loads on node 32 (an example node)





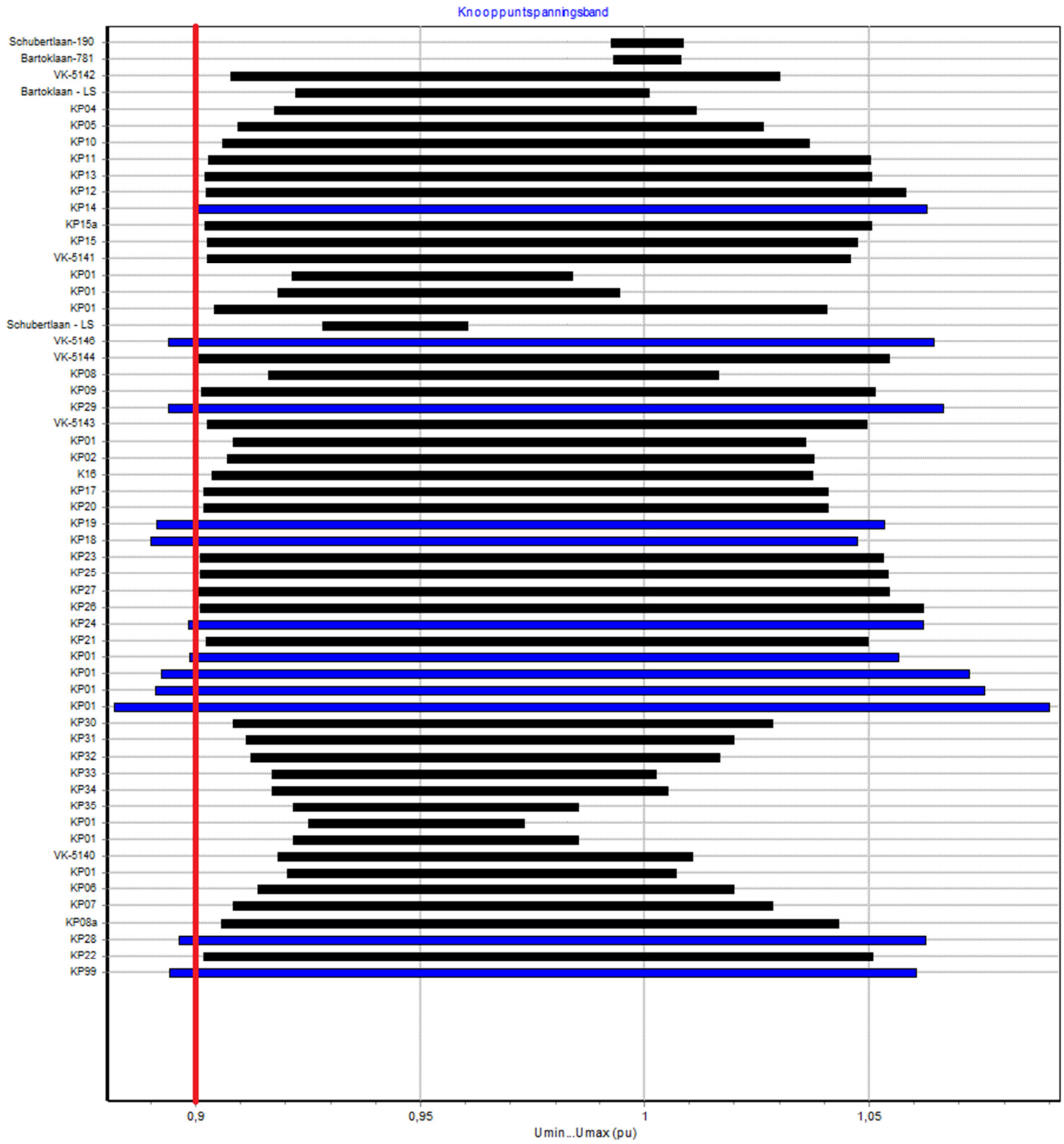

HP loads during 1 week (jul)
12000
10000
8000
6000
4000
2000
0
Watts
0
24
48
72
96
120
144
Hours


PV loads during 1 week (jul)
60000
50000
40000
30000
20000
10000
0
Watts
0
24
48
72
96
120
144
Hours

Appendix 8 – Results – Summer 2040 – Public charging

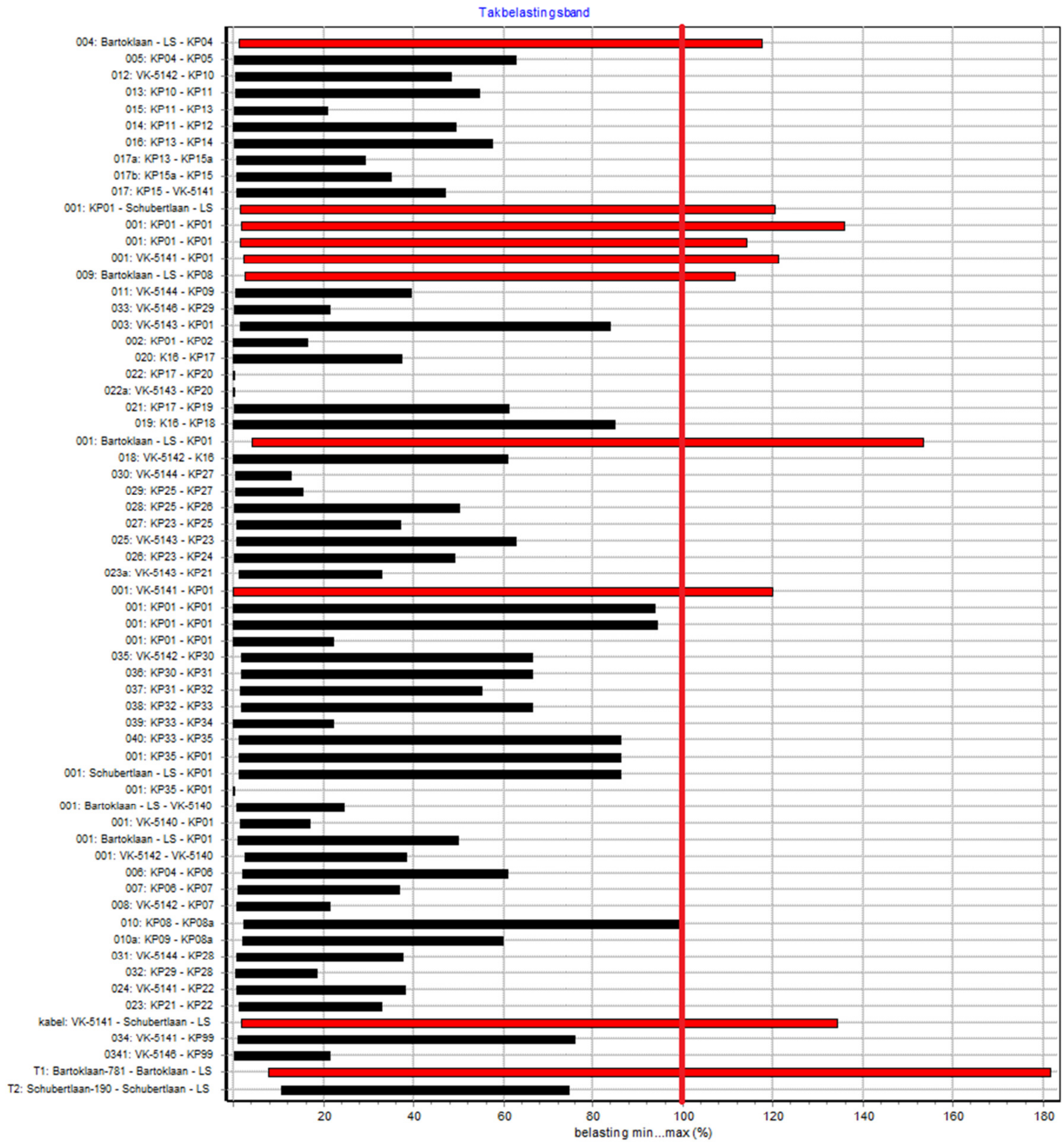
Nodes PQ

– With margins 0.9 up to 1.1 (red line(s))

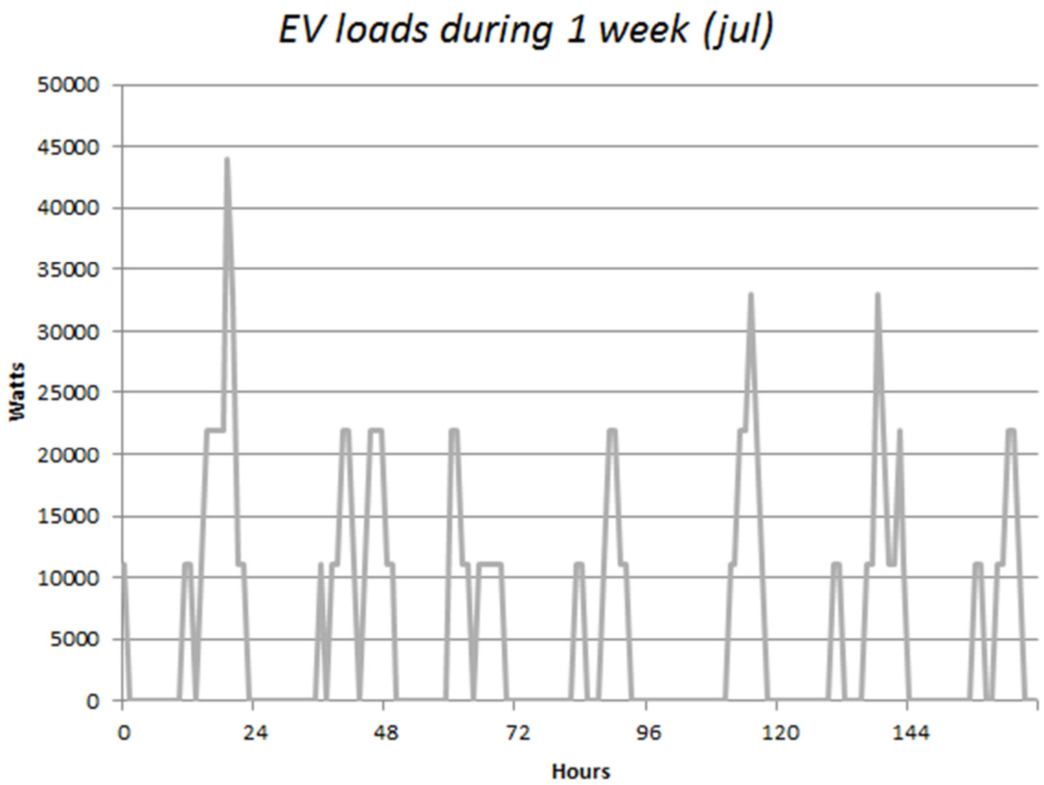


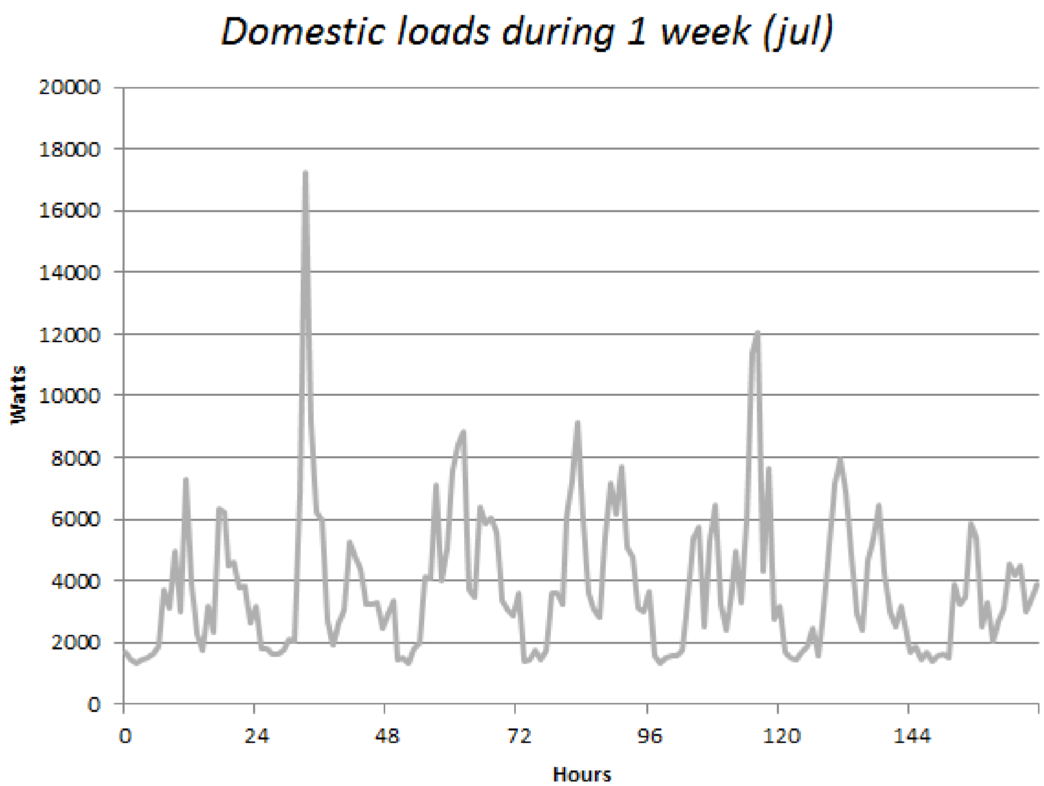
Branch Loads

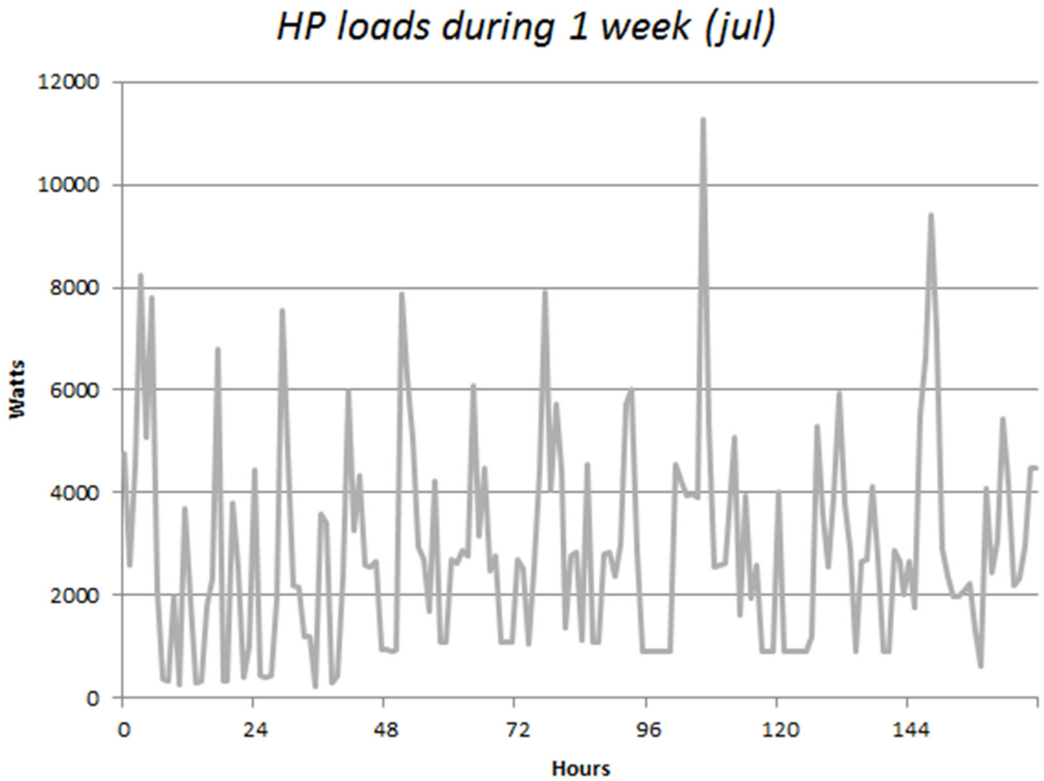
– With 100 percent load (red line)

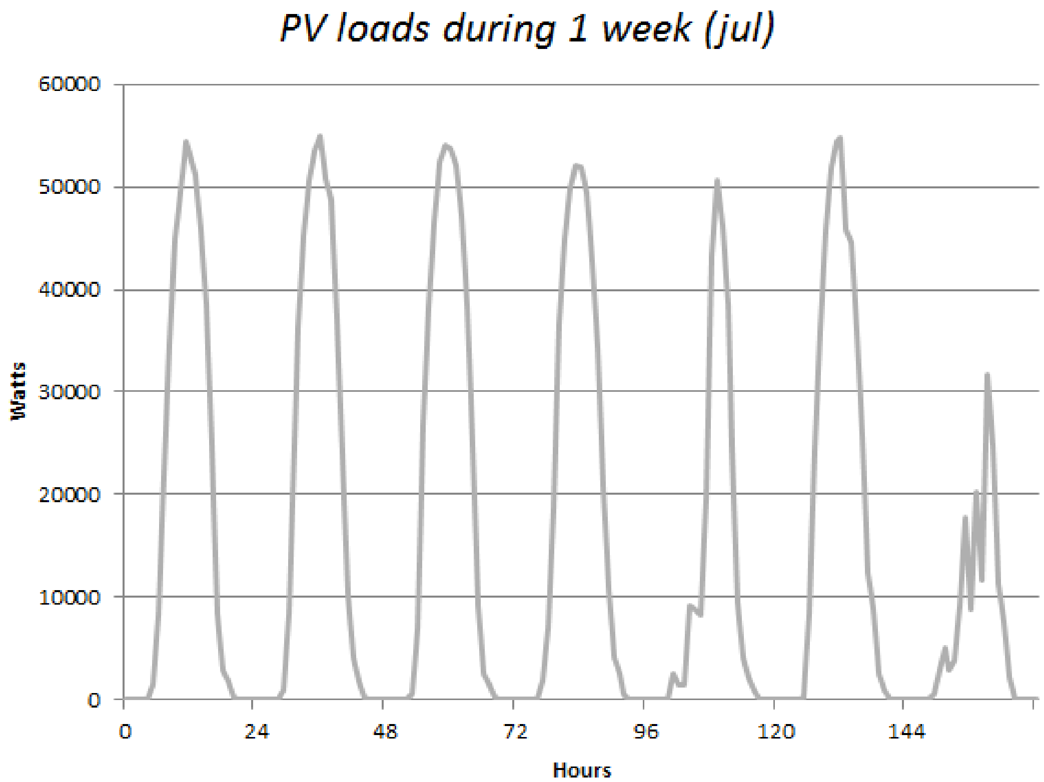


Profiles of demand and supply loads on node 32 (an example node)






HP loads during 1 week (jul)
Watts
Hours
0
2000
4000
6000
8000
10000
12000
0
24
48
72
96
120
144


PV loads during 1 week (jul)
Watts
Hours
0
10000
20000
30000
40000
50000
60000
0
24
48
72
96
120
144

Appendix 9 – TCO – Energy storage

Item:		Energy storage system			Anticipated purchase date:		1-9-2015			
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Year of ownership	Purchase	2nd year	3th year	4th year	5th year	6th year	7th year	8th year	9th year	10th year
Purchase costs										
purchase price	€ 405.742									
physical costs	€ 95.500									
installation costs	€ 16.388									
Additional costs										
financing costs	€ 21.223	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
upgrade costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
maintenance costs	€ 544	€ 544	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544
repair costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
downtime costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
removal costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
total annual costs	€ 539.397	€ 544	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544
	€ 539.397	€ 523	€ 502	€ 964	€ 463	€ 445	€ 427	€ 1.642	€ 394	€ 379
	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Year of ownership	11th year	12th year	13th year	14th year	15th year	16th year	17th year	18th year	19th year	20th year
Purchase costs										
purchase price										
physical costs										
installation costs										
Additional costs										
financing costs	€ -	€ -	€ -	€ -	€ 15.983	€ -	€ -	€ -	€ -	€ -
upgrade costs	€ -	€ -	€ -	€ -	€ 389.818	€ -	€ -	€ -	€ -	€ -
maintenance costs	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088
repair costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
downtime costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
removal costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
total annual costs	€ 544	€ 1.088	€ 544	€ 544	€ 406.344	€ 2.176	€ 544	€ 544	€ 544	€ 1.088
	€ 364	€ 699	€ 336	€ 323	€ 231.517	€ 1.191	€ 286	€ 275	€ 264	€ 507
	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044
Year of ownership	21th year	22th year	23th year	24th year	25th year	26th year	27th year	28th year	29th year	30th year
Purchase costs										
purchase price										
physical costs										
installation costs										
Additional costs										
financing costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
upgrade costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
maintenance costs	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088	€ 544	€ 544
repair costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
downtime costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
removal costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 46.500
total annual costs	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088	€ 544	€ 47.044
										€ 1.014.545
	€ 244	€ 234	€ 225	€ 864	€ 207	€ 199	€ 191	€ 368	€ 177	€ 14.670
										€ 798.278

Appendix 10 – TCO – Traditional

Item:		Traditional improvement			Anticipated purchase date:		1-9-2015			
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Year of ownership	Purchase	2nd year	3th year	4th year	5th year	6th year	7th year	8th year	9th year	10th year
Purchase costs										
purchase price	€ 45.622									
physical costs	€ 9.198									
installation costs	€ 14.878									
Additional costs										
financing costs	€ 2.858	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
upgrade costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
maintenance costs	€ 544	€ 544	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544
repair costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
downtime costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
removal costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
total annual costs	€ 73.100	€ 544	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544
	€ 73.100	€ 523	€ 502	€ 964	€ 463	€ 445	€ 427	€ 1.642	€ 394	€ 379
	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Year of ownership	11th year	12th year	13th year	14th year	15th year	16th year	17th year	18th year	19th year	20th year
Purchase costs										
purchase price										
physical costs										
installation costs										
Additional costs										
financing costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
upgrade costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
maintenance costs	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088
repair costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
downtime costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
removal costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
total annual costs	€ 544	€ 1.088	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088
	€ 364	€ 699	€ 336	€ 323	€ 310	€ 1.191	€ 286	€ 275	€ 264	€ 507
	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044
Year of ownership	21th year	22th year	23th year	24th year	25th year	26th year	27th year	28th year	29th year	30th year
Purchase costs										
purchase price										
physical costs										
installation costs										
Additional costs										
financing costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
upgrade costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	
maintenance costs	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088	€ 544	€ 544
repair costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
downtime costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
removal costs	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ 46.500
total annual costs	€ 544	€ 544	€ 544	€ 2.176	€ 544	€ 544	€ 544	€ 1.088	€ 544	€ 47.044
										€ 142.448
	€ 244	€ 234	€ 225	€ 864	€ 207	€ 199	€ 191	€ 368	€ 177	€ 14.670
										€ 100.773

Appendix 11 – Ascertaining the battery capacity

The overload in the low-voltage grid has to feed the battery and thus the capacity should big enough in the summer situation. In the winter situation the extra demand in the grid should be covered by the batteries. Then these batteries will feed the extra demand and these batteries need to be charged in periods in which the demand is low.

The capacity of these batteries is crucial because this determines the purchase price. First of all, the capacity in the summer is determined. This situation could occur any day now and thus a positive business case could have enormous effect. The capacity is estimated with the help of the load curve on the overloaded transformer station Bartoklaan. In Figure 43 the concept for this determination is sketched.

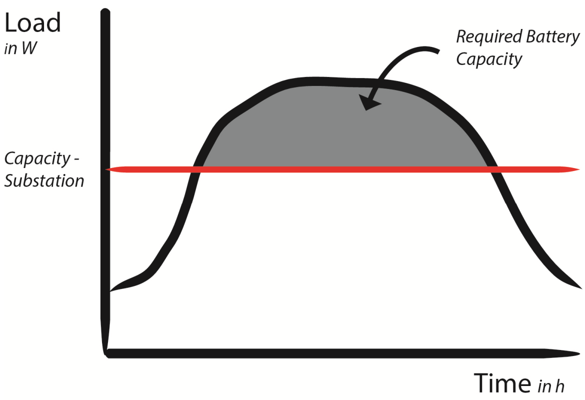


Figure 43: Load on the transformer station and the capacity of the transformer station.

The surface above the substation capacity and underneath the load curve is the required battery capacity. The capacity is then determined in kWh. The surface which determines the battery requirement is calculated with use of Microsoft Excel. The curve could be matched with a trend line in Excel. A trend line with a polynomial functions In this case. Excel could create a function for such a trend line. These steps results in a graph depicted in Figure 44.

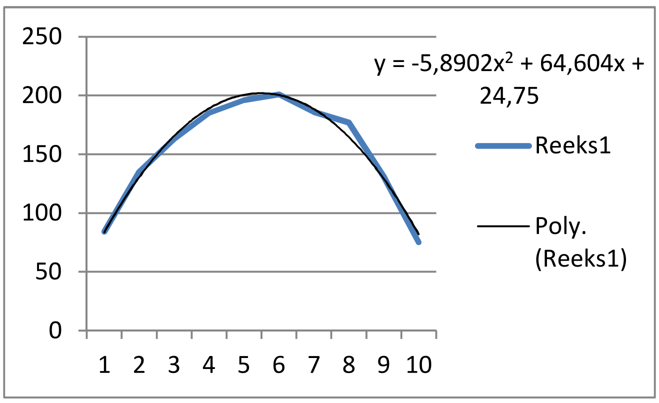


Figure 44: Use of trend line in excel

The blue line is an overload result on the transformer substation. The thin black line is the trend line which approaches the blue line. The formula of *y* is determined by excel based upon this trend line function. A surface determination underneath a function is done with an integral. The mean trend line of several overload situations is integrated into the primitive function. This primitive function can be filled with the boundaries and thus the surface can be determined. The result is the required battery capacity in kW/h.

If the battery capacity is determined then two extra factors should be taken into account: the round trip efficiency and the capacity loss during a lifetime. The chosen battery technology got a round trip efficiency of 92 percent which means that the input will be output with an eight percent loss. Furthermore, this lithium ion system has an end life efficiency of 80 percent. Thus the capacity should be still sufficient at the end of the life cycle. These two factors will have impact on the battery capacity, namely the battery capacity increases significantly. The results and capacity calculations are shown in the next section – results.

The charge-discharge cycle of such systems is an important factor for the end-conclusion. The battery cycle is based upon charging and discharging. The battery requires energy and could provide energy. In a period of 24 hours there is an energy surplus – during the generation of all the solar panels – and an energy shortage due to no generation and more demand. At the moment, this demand is supplied by the production elsewhere. However, this demand could easily be supplied by the full batteries in the future. In such a case the grid could be self-supporting in these periods of the year. Nevertheless, if the batteries could not be discharged before the charging cycle starts again the required battery capacity should increase. The ascertaining of the net load which could be covered by the batteries is calculated in the same way. The result give insight if these batteries could discharge before the charge cycle starts again. In this grid the battery is not capable of discharging in time. This results in more required battery capacity. Seasonal energy storage is unavoidable.

Appendix 12 – Newton-Raphson method

PHASE TO PHASE

De Newton-Raphson loadflow

01-131 pmo

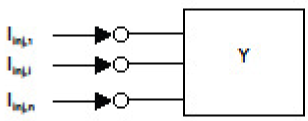
1-5-2001

1 INLEIDING

De methode die in Vision wordt toegepast om de spanningen en stromen in een elektriciteitsvoorzieningssysteem te berekenen is de loadflow volgens Newton-Raphson. De methode is voor het eerst beschreven in 1961 en 1967. De loadflow convergeert snel naar een oplossing en vanaf de introductie van sparse matrixtechnieken en optimale ordening ten behoeve van het eliminatieproces waren geheugenruimte en rekentijd geen probleem meer. De Newton-Raphson loadflow is met succes beproefd en is wereldwijd geaccepteerd. Dit document geeft een korte technische beschrijving.

2 UITGANGSPUNTEN

Het netwerk kan worden beschreven als een systeem met n knooppunten met stroominjecties $I_{inj,i}$, zoals afgebeeld in onderstaande figuur.



Het systeem wordt beschreven door n complexe vergelijkingen. In matrixnotatie:

$\underline{I}_{inj} = [\,Y\,]\,\underline{U}$

Voor het systeem zijn 3 soorten knooppunten gedefinieerd. Voor elk knooppunt is een andere set bekende en onbekende gegevens. Onderstaande tabel geeft een overzicht.

Knooppunt	Type	Bekende parameters	Onbekende variabelen
Swingbus	UT	$\lvert U_i \rvert$	P_i
		$\arg(U_i)$	Q_i
Spanningsgeregelde	PU	$\lvert U_i \rvert$	$\arg(U_i)$
synchrone generator		P_i	Q_i
Belasting	PQ	P_i	$\lvert U_i \rvert$
		Q_i	$\arg(U_i)$

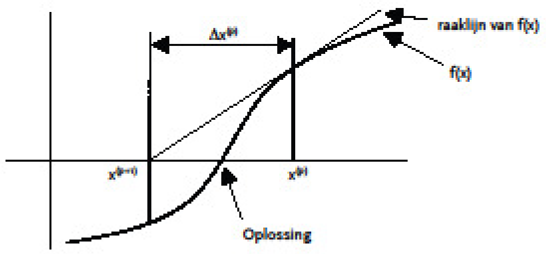
Op het knooppunt "Swingbus" is een netvoeding aanwezig. Modulus en hoek van de spanning zijn gegeven.

Voor een "Generator" knooppunt is het van belang of er een spanningsgeregelde generator is aangesloten. Elk ander type generator maakt van het knooppunt geen "Generator" knooppunt, maar een belastingsknooppunt, omdat die elementen als negatieve belasting worden behandeld.

Elk ander type knooppunt is een belastingsknooppunt. Alleen het gedeelte "Constante P en Q" komt in aanmerking voor de set "Bekende parameters". Het "Constante admittantie" gedeelte van de belasting wordt niet als stroom geïnjecteerd, maar komt in de systeemmatrix [Y].

3 OPLOSMETHODE

De oplosmethode in het algemeen is redelijk goed beschreven in het boek "Computer Analysis of Power Systems" van Arrilaga en Arnold. De methode volgens Newton-Raphson zoekt het nulpunt van de functie: $f_k(x_m) = 0$, voor alle k en alle m. Bij elke iteratie wordt het niet-lineaire vraagstuk benaderd door een lineaire matrixvergelijking. De benadering wordt geïllustreerd met een vergelijking met één variabele. In onderstaande figuur is $x^{(p)}$ een benadering van de oplossing, met fout $\Delta x^{(p)}$ bij iteratie p.



In dat geval is:

$$f(x^{(p)} + \Delta x^{(p)}) = 0 \qquad (1)$$

Deze vergelijking kan worden beschreven in een Taylor reeksontwikkeling:

$$f(x^{(p)} + \Delta x^{(p)}) = f(x^{(p)}) + \Delta x^{(p)} f'(x^{(p)}) + \frac{(\Delta x^{(p)})^2}{2!} f''(x^{(p)}) + \ldots \qquad (2)$$

Indien de initiële schatting van de variabele $x^{(p)}$ zich in de buurt van de oplossing bevindt, is $\Delta x^{(p)}$ relatief klein en kunnen alle hogere termen van de Taylor reeksontwikkeling worden verwaarloosd. We krijgen dan:

$$f(x^{(p)}) + \Delta x^{(p)} f'(x^{(p)}) = 0 \qquad (3)$$

of:

$$\Delta x^{(p)} = -\frac{f(x^{(p)})}{f'(x^{(p)})} \qquad (4)$$

De nieuwe waarde van de variabele voor de volgende iteratie (p+1) wordt dan verkregen via:

$$x^{(p+1)} = x^{(p)} + \Delta x^{(p)} \qquad (5)$$

Vergelijking (3) kan ook geschreven worden als:

$$f(x^{(p)}) = -J\Delta x^{(p)} \qquad (6)$$

Waarin J de vierkante Jacobiaan is van eerste orde partiële differentiaalvergelijkingen van de functies $f_k(x_m)$. De elementen van J zijn gedefinieerd door:

$$J_{km} = \frac{\partial f_k}{\partial x_m} \qquad (7)$$

En representeren de hellingen van de rakende hyperoppervlaktes, die de functies $f_k(x_m)$ benaderen in elk iteratiepunt.

In formulevorm een stelsel van 2n vergelijkingen en 2n onbekenden:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \cdot \begin{bmatrix} \Delta\theta \\ \Delta|U| \end{bmatrix} \qquad (8)$$

De Newton-Raphson methode convergeert kwadratisch indien:

- de functies continue eerste afgeleiden hebben in de buurt van de oplossing,
- de Jacobiaan niet-singulier is en
- de initiële schattingen van x zich dicht bij de actuele oplossingen bevinden.

Echter, de methode is gevoelig voor het gedrag van de functies $f_k(x_m)$ en voor hun formulering. Hoe lineairder ze zijn, deste sneller en betrouwbaarder de methode convergeert. Discontinuïteiten in de functies in de buurt van de oplossing zijn oorzaak van convergentieproblemen, totale onoplosbaarheid of een niet bruikbare oplossing.

Het oplosalgoritme komt in het kort neer op het onderstaande schema:

Reset aantal iteraties op 0		
Initialiseer RHSMax op 1+Eps		
Zolang RHSMax > Eps & aantal iteraties niet te groot, doe:		
	Bereken sparse Jacobiaan	
	Bereken Mismatches	
	Indien de Mismatch plotseling veel groter wordt, is er sprake van divergentie	
	Indien de oplossing nog niet gevonden is:	
		Maak de hoofddiagonaal elementen van Swing en Generatorknooppunten groot
		Factoriseer de Jacobiaan t.b.v. de LU-decompositie: Jacobiaan wordt [L][U]
		Los het systeem op uit met behulp van y = [L][U] x
		Bereken de knooppuntspanningen

Het volgende hoofdstuk gaat kort in op de onderdelen van het algoritme.

4 DE VERGELIJKINGEN IN RELATIE TOT HET SYSTEEM

De vermogensinjectie op een knooppunt i is beschreven als:

$$N_i = u_i \cdot i_{inj,i}{}^* = u_i \left[\sum_{j=1}^{n} y_{ij} u_j \right]^*$$

$$\begin{aligned} &met: \\ &u_i = |u_i| e^{j\theta_i} \\ &\theta_{ij} = \theta_i - \theta_j \\ &y_{ij} = |y_{ij}| e^{j\gamma_{ij}} \end{aligned} \qquad (9)$$

4.1 Berekening van de Jacobiaan

Voor het bepalen van de afgeleiden wordt bovenstaande uitdrukking omgezet:

$$N_i = \sum_{j=1}^{n} |u_i||y_{ij}||u_j| e^{j(\theta_i - \theta_j - \gamma_{ij})} = |u_i|^2 |y_{ii}| e^{j(-\gamma_{ii})} + \sum_{j=1, j\neq i}^{n} |u_i||y_{ij}||u_j| e^{j(\theta_i - \theta_j - \gamma_{ij})} \qquad (10)$$

Bovenstaande vergelijking wordt eerst afgeleid naar θ_i en $|u_i|$ voor de (sub)diagonaal elementen:

$$\begin{aligned} \frac{\partial N_i}{\partial \theta_i} &= j \sum_{j=1, j\neq i}^{n} |u_i||y_{ij}||u_j| e^{j(\theta_i - \theta_j - \gamma_{ij})} = j \sum_{j=1, j\neq i}^{n} u_i (y_{ij} u_j)^* \\ \frac{\partial N_i}{\partial |u_i|} &= 2|u_i||y_{ij}| e^{j(-\gamma_{ii})} + \sum_{j=1, j\neq i}^{n} |y_{ij}||u_j| e^{j(\theta_i - \theta_j - \gamma_{ij})} = 2|u_i| y_{ij}^* + \frac{1}{|u_i|} \sum_{j=1, j\neq i}^{n} u_i (y_{ij} u_j)^* \end{aligned} \qquad (11)$$

En vervolgens naar θ_j en $|u_j|$ voor de niet-(sub)diagonaal elementen:

$$\begin{aligned} \frac{\partial N_i}{\partial \theta_j} &= -j |u_i||y_{ij}||u_j| e^{j(\theta_i - \theta_j - \gamma_{ij})} = -j \cdot u_i (y_{ij} u_j)^* \\ \frac{\partial N_i}{\partial |u_j|} &= |u_i||y_{ij}| e^{j(\theta_i - \theta_j - \gamma_{ij})} = \frac{1}{|u_j|} u_i (y_{ij} u_j)^* \end{aligned} \qquad (12)$$

De resultaten van vergelijkingen (11) worden op de hoofddiagonalen van de sub-matrices J_1, J_2, J_3 en J_4 ingevuld. Het reële deel van de eerste vergelijking van (11) in J_1, het reële deel van de tweede vergelijking van (11) in J_2, het imaginaire deel van de eerste vergelijking van (11) in J_3 en het imaginaire deel van de tweede vergelijking van (11) in J_4.

4.2 Berekening van de Mismatches

Aan de hand van de Mismatches wordt bekeken of een oplossing gevonden is. Indien de methode een correct startpunt had, is de oplossing vrijwel zeker de juiste. De vector $\underline{\Delta x}$ bevat de hoeken en de moduli van de spanningen in het netwerk.

$$\underline{\Delta x} = \begin{bmatrix} \Delta\theta \\ \Delta|U| \end{bmatrix} \qquad (20)$$

Voor alle knooppunten wordt het maximum van de absolute waarden van de hoeken bepaald en voor alle belastingsknooppunten wordt het maximum van de moduli van de spanningen bepaald. Indien beide maxima kleiner zijn dan de tolerantie (Eps), verandert de oplossingsvector $\underline{\Delta x}$ niet meer en is een oplossing gevonden.

4.3 Berekening van de knooppuntspanningen

De knooppuntspanningen worden berekend uit de elementen van de oplossingsvector, door de bestaande spanningsvector te vermenigvuldigen met de elementen uit vector $\underline{\Delta x}$.

$$u_i := u_i \cdot \left(1 + \frac{\Delta u_i}{|u_i|}\right) \cdot e^{j\Delta\theta_i} \qquad (21)$$

Voor generatoren wordt dan de spanning bijgesteld in verband met de gewenste maximale en minimale spanning, die volgt uit de spanningsstatiek.

$$\begin{aligned} U_{\max,i} &= U_{ref,i} - statiek \cdot Q_{\min,i} \\ U_{\min,i} &= U_{ref,i} - statiek \cdot Q_{\max,i} \end{aligned} \qquad (22)$$

Als de spanning buiten de grenzen dreigt te liggen, wordt de nieuwe spanning:

$$u_i := u_i \frac{U_{\max,i}}{|u_i|}$$

$$of \qquad (23)$$

$$u_i := u_i \frac{U_{\min,i}}{|u_i|}$$

Voor een Swingknooppunt blijft de spanning gelijk aan de gegeven waarde.

Appendix 13 – Nederlandse samenvatting

Er zijn veranderingen gaande in het energiesysteem. De huidige structuur wordt steeds complexer door gedecentraliseerde opwek en de benodigde flexibiliteit. De vraag last neemt toe bij de introductie en hogere penetratie van elektrische voertuigen en warmtepompen. Het elektriciteitsnet wordt beheerd door de netbeheerder in de westerse maatschappij. De omstandigheden in het net veranderen en de netbeheerder is verplicht daar op tijd op te reageren. De hoofdvraag van dit onderzoek is: onder welke omstandigheden zal de netbeheerder energy opslag implementeren in het laagspanningsnet om meer flexibiliteit te creeeren in laagspanningsnetten?

Ten eerste, het energiesysteem wordt steeds duurzamer. Meerdere technologieën gebruiken elektriciteit in plaats van uitstotende bronnen. De verduurzamingsverschuiving in het system gaat misschien langzamer dan gehoopt. Echter de Nederlandse ambitie lijkt verder te rijken met het energieakkoord. De belanghebbende partijen hebben zich te conformeren aan de doelen die opgesteld zijn in dit akkoord. De netbeheerder is verantwoordelijk voor een deel van het energie systeem, namelijk het medium- en laagspanningsnet. Belangrijke bedrijfswaarden hierbij zijn: veiligheid, leveringszekerheid, financieel rendement en service. Endinet B.V. is de netbeheerder van Eindhoven. Hun missie is: *Ook morgen de energieke verbinding met de samenleving in onze regio.* De toekomstige scenario's voor het net zijn vastgelegd in een pas ontwikkeld strategisch asset management plan. Verschillende inzichten in de toekomst zijn nuttig om verstandige en sociaal verantwoorde investeringen te doen. Het onderzoek is gedaan vanuit het standpunt van een westerse netbeheerder.

Ten tweede, de mogelijke capaciteitsproblemen in het laagspanningsnet zijn omschreven in de literatuur analyse van dit onderzoek. De lasten door vraag in het laagspanningsnet neemt toe mede dankzij een hoger aantal bronnen met vraag zoals elektrisch vervoer en warmtepompen. De huidige huishoudelijke vraag is klein vergeleken met de lasten die deze nieuwe technologieën kunnen veroorzaken. Verder creëert decentrale productie aan de aanbodkant hoge en nieuwe lasten. De toekomstige lasten kunnen makkelijke gedragen worden als het net op de traditionele manier wordt verzwaard. Echter ontwikkelingen in het net maken het mogelijk om steeds flexibelere oplossingen te kiezen. Deze flexibele oplossingen zijn opgedeeld in drie categorieën: vraag-, aanbod- en capaciteit flexibiliteit. Vraagsturing probeert de lasten in het laagspanningsnet op een andere manier te sturen. Aanbod flexibiliteit probeert een zo hoog mogelijke leveringszekerheid te creëren. Verder kan ook het laagspanningsnet op een andere manier worden uitgebreid worden qua capaciteit. Deze uitbreidingen zijn vaak een stuk slimmer dan de traditionele assets. Energy opslag kan voor alle drie de categorieën een bijdrage leveren. Lithium-ion batterijen zijn momenteel superior ten opzichte van andere batterijen. De hoge prijs is nog steeds op belemmering voor deze technologie. Echter Tesla heeft kort geleden een nieuw systeem op de markt gebracht die de prijzen flink reduceren. Deze technologie wordt daarom gekozen als tegenhanger voor de traditionele verzwaring van het laagspanningsnet. Deze oplossingen worden uitgewerkt in een business case met behulp van Total cost of ownership.

Ten derde, het daadwerkelijke onderzoek probeert een model te creëren van een huidig- en toekomstig laagspanningsnet. De vraag en aanbod lasten zijn gebaseerd op werkelijke metingen in het net. Het gebruik van gemiddelde of geaggregeerde profielen is zoveel mogelijk vermeden. Deze profielen zijn geschikt voor hogere niveaus in het net. De lasten op het laagspanningsnet zijn bepaald voor verschillende scenario's: Zomer 2015, Winter 2040 en Zomer 2040. De aanbodkant bevat lasten van zonopwekking doormiddel van zonnepanelen. De vraagkant bevat de huidige huishoudelijke vraag en in toekomstige scenario's zijn ook de lasten van elektrisch vervoer en warmtepompen meegenomen. De capaciteit van het laagspanningsnet in 2015 blijkt onvoldoende doordat er meerdere assets overbelast zijn door de opwek van de zonnepanelen. In het scenario van de winter in 2040 zijn er voornamelijk spanningsproblemen. De spanningskwaliteit is ondermaats en dat geld voor veel knooppunten in het net. Een combinatie van beide problemen is zichtbaar in het zomer scenario van 2040. De problemen worden vooral veroorzaakt en niet wegenomen door het verschil in gelijktijdigheid van de bronnen. Er ontstaan niet zulke grote verschillen door een andere laadmethode met een hogere pieklast. Hierbij speelt ook wederom de gelijktijdigheid, die erg laag is, een rol. De problemen nemen wel af naarmate er bijvoorbeeld minder zonnepanelen worden geïnstalleerd.

Ten vierde, de capaciteitsverzwaringen die noodzakelijk zijn in het eerste scenario – zomer 2015 - zijn gedaan doormiddel van twee verschillende oplosmethodes. De eerste oplossing verzwaart het net op een traditionele manier met zwaardere assets en dikkere kabels. De tweede oplossing verzwaart het net met energie opslag in de vorm van lithium-ion batterijen. De kosten voor beide oplossingen zijn berekend doormiddel van de methode van total cost of ownership. Momenteel zijn de kosten van energie opslag in de vorm van lithium ion batterijen bijna zeven keer te hoog. Daarom is de huidige werkwijze van de netbeheerder nog steeds de juiste. De investeringen van de netbeheerder moeten sociaal verantwoord en daarbij speelt kosten een belangrijke rol.

Tot slot, de netbeheerder is verplicht de ontwikkelingen in markt te volgen. Nauwkeurige data vanuit de netbeheerders is van enorm belang om tot de juiste beslissingen te komen. Daarmee kan de netbeheerder de andere gelieerde partijen informeren wat ook past bij de nieuwe rol als netwerkbeheerder. De huidige ambities van de netbeheerder conformeert zich ook aan deze ambities en hun rol in de energie transitie. Onderzoek naar dit soort vraagstukken is cruciaal om tot de juiste besluitvorming te komen. De netbeheerders zijn al tijdig bezig met het volgen van deze ontwikkelingen en delen dat binnen NetbeheerNederland. Uiteindelijk is gedeelde kennis. Macht voor de toekomst.