Flexibility system design for electric vehicles.

Performing congestion management for the DSO

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Elaadnl

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Performing congestion management for the DSO

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Summary

The climate change is one of the major topics on the political agenda. This has resulted in the Paris agreement which is ratified by 148 parties worldwide. This agreement states that the worldwide temperature increase needs to stay below 2 ℃. This has resulted in regulation to lower the use of fossil fuels and to increase the energy efficiency. For centuries, the world has been heavily relying on fossil fuels which has led to a high level of prosperity. However, the world is running out of fossil reserves. The transition towards renewables is therefore not only an environmental issue but is a necessity to keep the same level of quality of life. Even though, wind and sun have the prospect to deliver abundant amount of electricity, this requires a major change in the electricity system. Hence, the transition to renewables will cause a disruption of one of the fundamentals of our society.

The increase of renewable generation in the installed capacity leads to a higher reliance on weather conditions and a lower controllability of the power system, resulting in a higher volatility in electricity prices. Additional to this, there is a need for a higher energy efficiency which leads to an electrification of household appliances. An example is the electrification of transport. This leads to a reduction of fossil fuels like gasoline, but to an increase in demand for electricity. It is expected that electric cars will increase the pressure on the peak load of the local electricity network and installed generation capacity. The electric vehicle demands for a high-power consumption in comparison to the current household appliances for a long period of time in the capillaries of the electricity network. These developments of electric vehicles can lead to both a challenge as an opportunity, while the electric vehicle can also be used for flexibility on the demand-side. Flexibility is seen as a power modification sustained at a given moment for a given duration at a particular location within the network.

Flexibility is of interest of three different parties: the transmission system operator (TSO), balance responsible party (BRP) and distribution system operator (DSO). The TSO needs flexibility for balancing services while renewable generation has an intermittent nature and is not controllable. The BRP wants to use flexibility on the demand-side to adjust their portfolio while sustainable production is less predictable. At last, the DSO wants to use flexibility because of the increase in adoption of PV, electric heating and EV which can lead to an overload in the existing cables and transformers. The first two parties have challenges that are interrelated and have a system framework to manage the changes in demand and supply. However, the need for flexibility will increase with the adoption of renewable generation which could result in a need for a flexibility market. However, the challenge for the DSO has a locational component for which this existing framework is not useful. If the DSO detects an overload in its network, the overload needs to be solved by changing the load on that specific cable or transformer. Therefore, there is a need for a new mechanism which can provide demand-side flexibility.

According to literature, there are several market mechanisms to unlock flexibility on the demand-side. Four of these are elaborated in this thesis: price-based mechanism, variable connection capacity, direct control and the flexibility market. All these market mechanisms have pros and cons. To be able to compare the mechanisms different aspects are described. These aspects are based on the Smart Grid Architecture Model (SGAM) which is developed to support the design of smart grid use cases. The SGAM consists of five layers: business-, function-, information-, communication- and component layer. An agent-based simulation is developed to describe some of the aspects. Agent-based simulations make it possible to model a complex social-technical system with many interrelated variables. This gives the opportunity to model the interactions between different levels in society, such as the interrelation between the national electricity market to local charging behavior of people regarding electric vehicles. In this simulation a neighborhood in ‘s-Hertogenbosch is modelled and nine scenarios of market mechanisms are compared.

The results in the simulation show that market mechanisms with static profiles, capacity or price-based, lead to static reactions of the EVs. This can be explained by the high level of flexibility of EVs which gives the opportunity to postpone their charging until the cheapest moment or to the moment the capacity profile ends. This leads to a high level of simultaneous charging and therewith to high loads on the network and high electricity prices. Next to this, the simulation shows that market mechanisms with dynamic prices based on a spot market lead to a damping effect of the load profile on the transformer which will lead to benefits for the TSO, DSO, BRP as the consumer. In combination with the evaluation of the aspects, this leads to the conclusion that market mechanisms with a static approach are not useful for both the DSO as BRP for their challenges. An approach with dynamic prices is useful for all parties but need to be added with a congestion control mechanism of the DSO to maintain a high reliability of the network. This results in a conclusion that a market mechanism with spot market charging in combination with a flexible capacity contract is most suitable. The capacity contract gives the DSO the opportunity to send capacity constraints to flexible appliances when overload is detected. The simulation indicates that this is an occasional matter when price sensitivity of consumers is sufficient.

This has resulted in a functional, physical and technical system design which optimizes the charging profiles of the EV based on the input of the EV driver, BRP and DSO. This results in a system in which the EV driver does not need to change its mobility behavior to offer flexibility. The BRP has the possibility to use flexibility for adjustment of their portfolio and the DSO has a high level of reliance to avoid congestion.

Samenvatting

Klimaatverandering is een van de belangrijkste onderwerpen op de internationale politieke agenda. Dit heeft geresulteerd in het Klimaatakkoord van Parijs 2020-2050 waarin een wereldwijde overeenkomst is gesloten tussen 148 landen. Deze overeenkomst stelt dat de wereldwijde temperatuurstijging ruim onder 2 ℃ moet blijven. Hieruit is regelgeving ontstaan om het gebruik van fossiele brandstoffen te verminderen en de energie-efficiëntie te verhogen. Al eeuwenlang gebruikt de westerse samenleving fossiele brandstoffen alsof deze ongelimiteerd aanwezig zijn maar de fossiele reserves raken op. De overgang naar hernieuwbare energiebronnen is daarom niet alleen een milieukwestie, maar ook een noodzaak om hetzelfde niveau van kwaliteit van leven te behouden. Hoewel wind en zon de potentie hebben om een overvloedige hoeveelheid energie te leveren, vereist dit een grote verandering in het energiesysteem. De overgang naar hernieuwbare energie zal een verstoring veroorzaken in één van de fundamenten van onze samenleving.

De toename van geïnstalleerde productiecapaciteit voor hernieuwbare energie leidt tot een grotere weersafhankelijkheid en een lagere beheersbaarheid, dat zorgt voor een hogere volatiliteit in energieprijzen. Verder is er behoefte aan een hogere energie-efficiëntie wat elektrificatie van huishoudelijke apparaten tot effect heeft. Een voorbeeld is de elektrificatie van transport, wat leidt tot een reductie van fossiele brandstoffen zoals benzine, maar tegelijkertijd tot een toename van de vraag naar elektriciteit. Verwacht wordt dat elektrische auto's de druk op de piekbelasting van het lokale elektriciteitsnet en de geïnstalleerde productiecapaciteit zullen verhogen. De elektrische auto vraagt gedurende langere tijd om een hoog stroomverbruik in de haarvaten van het elektriciteitsnet. Deze ontwikkelingen van elektrische voertuigen kunnen zowel een uitdaging als een kans betekenen, aangezien de elektrische auto kan worden gebruikt voor flexibiliteit aan de vraagzijde. Flexibiliteit wordt gezien als de mogelijkheid om de vraag naar elektriciteit te kunnen veranderen, met betrekking tot het moment, het vermogen en de locatie van het gebruik.

Flexibiliteit is van belang voor drie verschillende partijen: de transmissienetbeheerder, de programmaverantwoordelijke en de regionale netbeheerder. De transmissienetbeheerder heeft flexibiliteit nodig voor het balanceren van het elektriciteitssysteem, omdat de productie van hernieuwbare energie een onregelmatig karakter heeft en niet controleerbaar is. De programmaverantwoordelijke wil flexibiliteit aan de vraagzijde gebruiken om zijn portfolio aan te passen, aangezien duurzame productie minder voorspelbaar is. Daarnaast wil de regionale netbeheerder flexibiliteit gebruiken vanwege de toename van zonnepanelen, elektrische verwarming en elektrisch vervoer, wat kan leiden tot een overbelasting van de bestaande kabels en transformatoren. De transmissienetbeheerder en de programmaverantwoordelijke hebben uitdagingen die met elkaar samenhangen en hebben een systeem om de veranderingen in vraag en aanbod te beheersen. De behoefte aan flexibiliteit zal echter toenemen door de stijgende hoeveelheid hernieuwbare energie in het elektriciteitssysteem. Dit zou kunnen resulteren in een behoefte aan een flexibiliteitsmarkt. De uitdaging voor de DSO heeft een locatiecomponent waarvoor dit bestaande systeem niet toepasbaar is. Als de regionale netbeheerder congestie heeft, moet de overbelasting worden opgelost door de belasting op de overbelaste kabel of transformator te wijzigen. Daarom is er behoefte aan een nieuw mechanisme dat flexibiliteit kan bieden aan de vraagzijde.

Volgens de literatuur zijn er verschillende mechanismen om flexibiliteit te kunnen ontsluiten. Vier hiervan zijn uitgewerkt in dit proefschrift: een prijs gebaseerd mechanisme, variabele aansluitcapaciteit, directe controle aan de vraagzijde en een flexibiliteitsmarkt. Al deze marktmechanismen hebben voor- en nadelen. Om de mechanismen te kunnen vergelijken, worden verschillende aspecten beschreven. Deze aspecten zijn gebaseerd op het Smart Grid Architecture Model (SGAM), dat is ontwikkeld om het ontwerp van smart grid use-cases te ondersteunen. Het SGAM bestaat uit vijf lagen: bedrijfs-, functie-, informatie-, communicatie- en componenten laag. Om een aantal aspecten te kunnen beschrijven, wordt een agent-based simulatiemodel gebruikt. Agent-based simulaties maken het mogelijk om een complex sociaal-technisch systeem te modelleren met veel onderling verbonden variabelen. Dit biedt de mogelijkheid om de interacties tussen verschillende niveaus in de samenleving te modelleren, zoals de nationale elektriciteitsmarkt in relatie tot het gedrag van mensen bij het lokaal opladen van elektrische voertuigen. In deze simulatie wordt een wijk in ‘s-Hertogenbosch gesimuleerd en worden negen scenario's van marktmechanismen vergeleken.

De resultaten in de simulatie laten zien dat marktmechanismen met statische profielen, capaciteit of prijs gebaseerd, leiden tot statische reacties van de elektrische auto. Dit kan worden verklaard door de hoge mate van flexibiliteit van elektrische voertuigen, waardoor ze de mogelijkheid hebben om het opladen uit te stellen tot het goedkoopste moment of tot het moment dat de restrictie op capaciteit eindigt. Dit leidt tot een hoog niveau van gelijktijdig laden en daarmee tot hoge belastingen op het elektriciteitsnetwerk en daarnaast kan het leiden tot hoge elektriciteitsprijzen. Bovendien laat de simulatie zien dat marktmechanismen met dynamische prijzen op basis van een spotmarkt leiden tot een dempend effect van het belastingprofiel van de transformator, wat voordelen zal opleveren voor zowel de regionale netbeheerder, programmaverantwoordelijke als de consument. In combinatie met de evaluatie van de aspecten leidt dit tot de conclusie dat marktmechanismen met een statische benadering niet nuttig zijn voor zowel de regionale netbeheerder als de programmaverantwoordelijke voor hun uitdagingen. Een dynamische benadering doormiddel van prijzen is bevorderlijk voor beide partijen, maar er moet een besturingsmechanisme voor de DSO worden toegevoegd om de hoge betrouwbaarheid van het netwerk te behouden. Dit leidt tot de conclusie dat een marktmechanisme met spotmarktprijzen in combinatie met een flexibel capaciteitscontract het meest nuttig is. Het capaciteitscontract geeft de regionale netbeheerder de mogelijkheid om capaciteitsbeperkingen toe te passen wanneer congestie optreedt. Dit gebeurt door een signaal te sturen naar flexibele apparaten wanneer overbelasting wordt gedetecteerd. De simulatie geeft aan dat dit incidenteel gebeurt mits de prijsgevoeligheid van consumenten voldoende is.

Dit heeft geresulteerd in een functioneel, fysiek en technisch systeemontwerp waarin de laadprofielen van de EV worden geoptimaliseerd op basis van de input van de EV-rijder, programmaverantwoordelijke en netbeheerder. Het systeem gaat uit van het feit dat de EV-rijder zijn mobiliteitsgedrag niet hoeft te veranderen om flexibiliteit te kunnen bieden. De programmaverantwoordelijke heeft de mogelijkheid om flexibiliteit te gebruiken voor het aanpassen van zijn portfolio en de regionale netbeheerder kan congestiemanagement toepassen met een hoge betrouwbaarheid.

Contents

1. Introduction

The energy system is in transition from a high dependency on fossil fuels to a clean and renewable system. This is caused by the growing effects of the global warming. To limit global warming countries have made policies to reduce greenhouse gases (GHG) as it is currently expected to be the main cause behind the global warming [1]. This is ratified in the Paris agreement by 148 parties. In the Paris agreement the parties have agreed to keep the global temperature rise well below two degrees Celsius relative to the pre-industrial levels [2]. At this moment the global temperature rise is at 1.1 ℃ above pre-industrial level [3]. The expectation is that this will continue to rise in the coming decades, with an average of 0.1 ℃ to 0.2 ℃ per decade [3]. CO_2 is the gas that has the biggest anthropogenic factor of all GHG gases [1] [4]. CO_2 is emitted by combustion of fossil fuels, wood and other materials that holds carbon. Next to the challenges of emissions, there is a depletion of fossil reserves. The common opinion is that there will be a depletion within decades for gas and oil, and within centuries also for coal [5] [6]. Fact is that society is still relying heavily on fossil resources like oil, gas and coal, which are one of the main sources for pollution. Since 1991 the European Union (EU) has started many climate-related initiatives to lower the emissions and reliance on fossil fuels.

In the EU, there was a 17% renewable energy share in the gross final energy consumption in 2017 [7]. For 2020 there is a target to reach 20% in all EU countries and in 2030 this is 32%. This is recently adjusted and in the latest agreement there is a clause for an upwards revision of renewable energy share in 2023 [7]. Although the EU has set strict targets for all its members, the Netherlands is running behind - see Figure 1. Up to date, the Netherlands has a 6% generation of renewable sources compared to the gross final consumption [8]. The countries in the picture who have a high percentage of renewable energy generation mainly benefit from the possibility to use hydro or geothermal power.

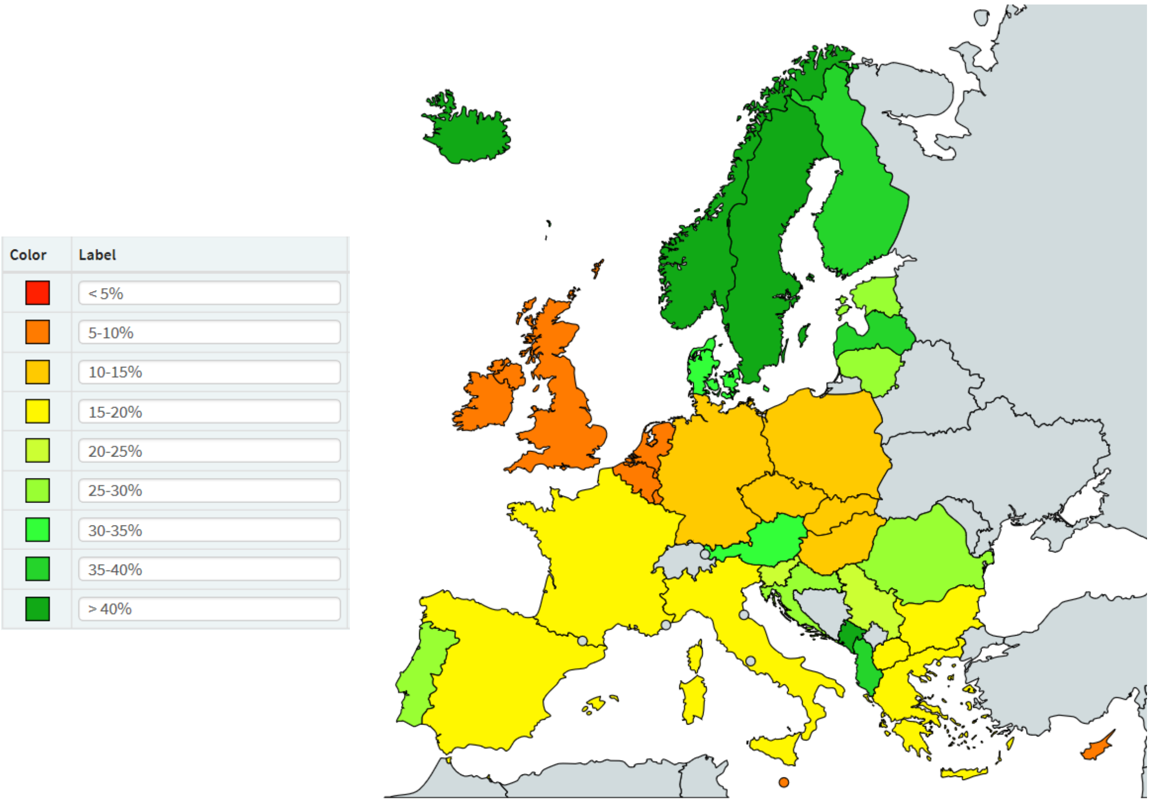

Figure 1, Share of renewable energy in gross final energy consumption of 2016 [8].

However, this is not possible for the Netherlands because of the geography of the country. Therefore, the biggest opportunity is to implement wind turbines and photo voltaic (PV) panels. Next to this, a reduction in total energy use is important for reaching the EU targets. Which has caused energy efficient technologies to be developed, of which the electric vehicle (EV) is popular in the Netherlands. In December 2017, the Netherlands had the second place in Europe when relative number of EVs sold is considered [9]. Only Norway scored better. This makes the Netherlands one of the front runners in EVs.

1.1. Disruption of the power sector

Our society is built on the unlimited availability of fossil energy, which has resulted in high levels of development in the last centuries. The transition to renewables will therefore cause a disruption of one of the fundamentals of our society. Although the wind and sun have the possibility to give us abundant amounts of energy, this asks from us a major change in the current power system. For example, our network topology is designed in a way that it guarantees a high level of security of supply against lowest societal costs. This has resulted in a centralized top-down structure. Which means production of electricity is executed centrally with large-scale generators. The generated electricity is transported with the high-voltage network to the distribution network which delivers the electricity to the end-users. While large-scale storage of electricity is not cost-efficient, the supply and demand of electricity always need to be in a balance. In the traditional system this balance is obtained by ramping-up and down the power output of fossil generators on the supply-side to follow the demand of electricity.

With the upcoming transition to renewable electricity this traditional system is no longer the most cost efficient. This results from the implementation of decentralized electricity generation on consumer level and the implementation of utility-scale wind turbines and PV panels. These forms of electricity generation will depend heavily on weather conditions and are therefore less controllable. In addition to this, the reduction of fossil fuels and the growing need to energy reduction has led to an electrification of household appliances, for example for transport - see Figure 2. This shifts the demand for fossil fuels to electricity, which leads to an increase of electricity demand while lowering the total energy consumption. In addition to this, electric transport will cause a heavy pressure on the electricity network. It will increase the peak load demand for both generation and network capacity.

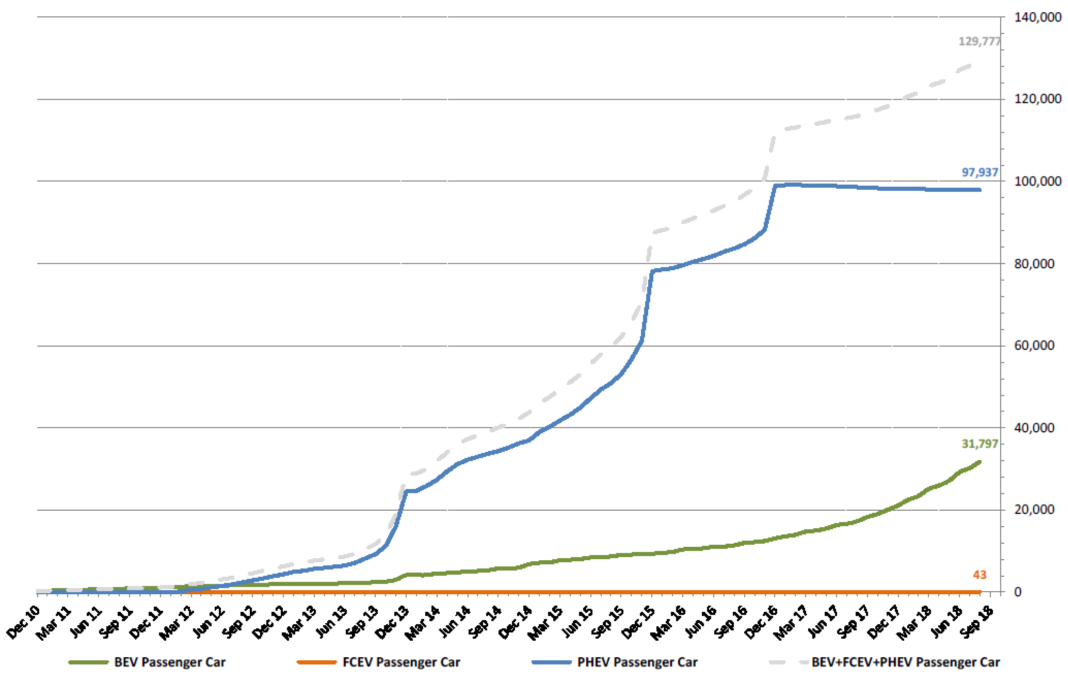

Figure 2, Adoption of electric cars in the Netherland in the period 2010 to September 2018 [10].

The conventional method of designing the network and installed generation capacity is based on the peak load demand. However, the need to capacity will increase through the adoption of electric transport, this will also cause an opportunity. The electrification of transport will lead to an increase in the amount of flexibility on the demand-side. Flexibility is defined in this thesis as “a power adjustment sustained at a given moment for a given duration from a specific location within the network” [11]. EVs drive on average low distances, 38 km per day [12], and are therefore standing idle for about 23 hours a day. This leads to the possibility to change the demand from peak hours to off-peak hours. Which gives the power sector the opportunity to use flexibility in both supply as demand-side. The flexibility can only be used when the EV driver is willing to use the flexibility service. Therefore, the EV driver needs to get a benefit for using the service. Research has found that both the consumer as the energy companies can have an advantage if technologies for changing energy demand are designed attractive and user-friendly [13]. This report will focus on developments in the power and transport sector by proposing a system design to unlock flexibility of EVs for the electricity sector.

1.2. Company information

This PDeng has been executed for two parties: ElaadNL and Enexis. First the company information of ElaadNL will be described followed by the information about Enexis.

ElaadNL

ElaadNL is the knowledge and innovation center in the field of Smart Charging infrastructure in the Netherlands and is an initiative of the Dutch grid operators. The emergence of electric mobility (e-mobility) and sustainable charging is a significant development for the electricity grid. Through their mutual involvement via ElaadNL, the grid operators acquire an overview of the measures to be taken to ensure that the network remains reliable and affordable, whilst enabling the development of e-mobility. Innovative solutions are explored that could generate great benefits for society. 'Smart charging' can contribute to make optimal use of the existing electricity grid.

Enexis

Enexis is a distribution network operator in the east of the Netherlands. Enexis manages 2.8 million connections to the electricity network and 2.3 million gas connections in the Dutch provinces Groningen, Drenthe, Overijssel, Noord-Brabant and Limburg. The total electricity network of Enexis is 139.000 km long and 34.500 GWh was transported in 2017. There are 4,500 employees who together ensure stable and reliable grid and the future of the energy supply. Enexis encourages, coordinates, enables and funds initiatives and uses knowledge, skills and strengths of their employees to boost the energy transition to make sustainable energy possible together. Enexis had in 2017 a total outage time of 15,2 minutes per connection, which means that the network has a reliability close to 100%. For well over a century, Enexis has operated at the center of society to ensure a reliable energy supply and provide services that Enexis believe make people's lives easier and more comfortable. Enexis has invested 423 million Euros in the electricity network in 2017.

1.3. Description and objective of the design issue

The energy transition is seen as a complex system in which many variables are interrelated. To picture the interrelation of the variables in the energy transition, a causal loop diagram is created, which can be seen in Figure 3. A causal loop diagram consists of nodes and edges. Nodes characterize the variables in the system and edges the connection or relation between two variables. If the edges are marked positive (+) then there is a positive relation between the variables, a negative mark (-) relates to a negative relation. Most important in this diagram is that electric cars are positively influencing both the flexibility demand and flexibility supply, this will be explained in the next paragraph.

When starting at the top left hand, *sustainable energy developments* is the first node of the causal loop diagram. *Sustainable energy developments* have a positive influence on *lower costs of sustainable energy* which leads to an increase of the amount of installed capacity of solar and wind generation. This together leads to a higher *amount of sustainable energy* in the energy system. When the *amount of sustainable energy* increases, *volatility* in energy prices will increase while the natural resources like wind and sun cannot be controlled. This leads to a higher *demand for flexibility* and to a negative effect on the *network efficiency*. A higher *amount of sustainable energy* also leads to a lower amount of *flexible supply* while currently the flexibility of electricity is entirely based on natural gas generators. Therefore, sustainable energy asks for more flexibility in the demand which leads to more *battery development* while storage can provide this flexibility on the demand side. When the battery development increases this leads to lower costs and better *battery performance* which can be expressed in the amount of storage and therewith *range of an EV*. This will influence the *number of EVs* on the market, which increases the amount of *flexibility supply*. On the contrary, the higher *number of EVs* on the market will also lead to more *charge sessions* which leads to more pressure on the electricity grid. This causes a bigger need for *flexibility demand*. Which indicates that EVs can be a potential problem while they can cause capacity problems in the electricity network but are in the same time their potential solution by having a high potential in flexibility supply. Therefore, the flexibility that can be provided by the EV is an opportunity for the power sector to turn a problem in a chance.

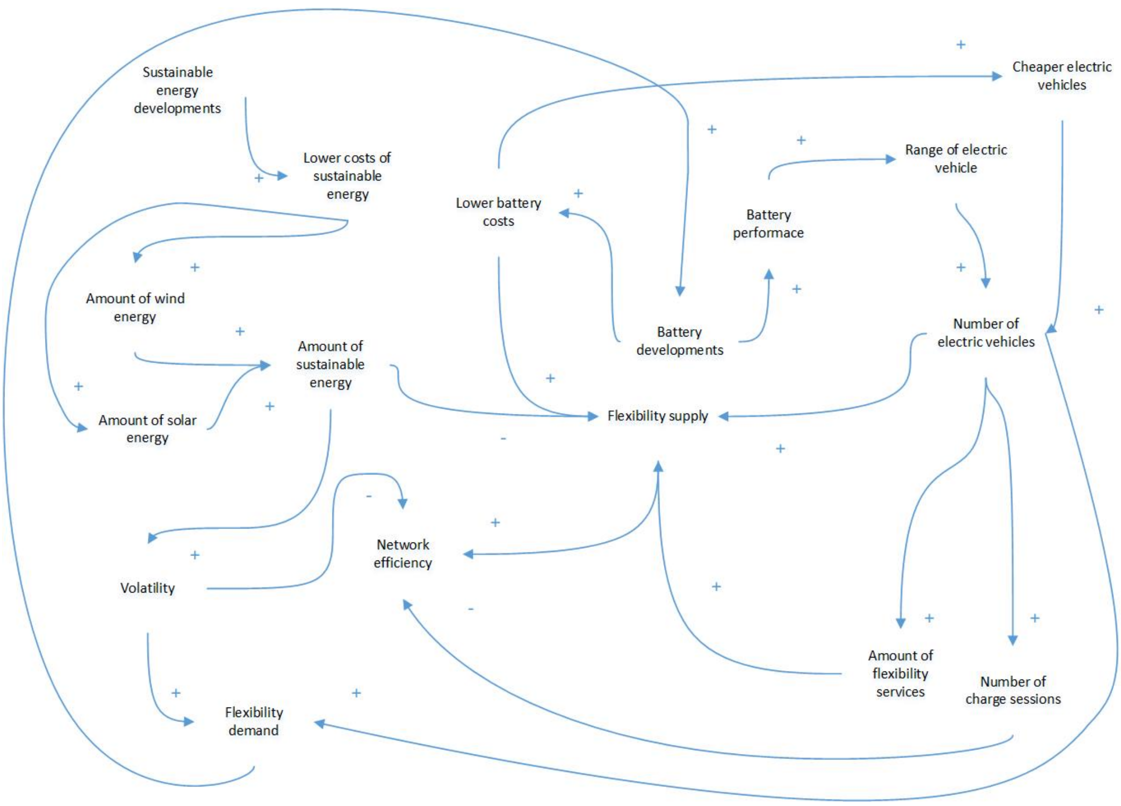

Figure 3, Causal Loop Diagram, the interrelation of variables in the energy transition in relation to the mobility sector.

This PDeng thesis will present a system design for the use of flexibility of EVs. The design objective that is central in this thesis is:

"What does the functional, physical and technical system design of a flexibility system for EVs look like to reach the goals of the actors involved".

To investigate the context of the design issue, a literature review has been executed. Main topics of this review are the energy transition and its challenges, the structure of the power system, the EV market and the electricity network. The reason to choose for a literature review is that many scholars and industry experts have reviewed and investigated these subjects. This will give a head start to this PDeng. Next to a literature study many insights of experts in the field are incorporated, this information has been retrieved in dialogue sessions, both one-on-one as group sessions. Experts that have given information are working at grid companies (Tennet, Enexis, Stedin and Alliander), market parties (Jedlix and USEF) and research centers (TU Delft, University of Twente and ElaadNL). The literature review will answer the following context related questions:

- *What are the main developments in the power sector?*
- *What is the current EV system design and how is this related to the power system?*
- *Which parties in the power system have potential benefits from flexibility of EVs and what are their main business opportunities?*
- *What are possible market mechanisms for flexibility and how do they work?*

To be able to compare the different market mechanism, a simulation is built. Reason to work with a simulation is that many variables influencing the market mechanisms are not yet present today which makes pilots in a real-life setting difficult. The simulation makes it possible to model a future neighborhood and gives the potential to compare different market mechanisms with the exact same assumptions. Next to that, the simulation makes it achievable to model a complex system with a lot of different variables. Before the simulation was built, aspects are formulated for the comparison of the mechanisms. This comparison leads to a conclusion which mechanism has the highest potential for the DSO and energy system. The questions that are researched with the simulation are:

- *What is the effect of the market mechanisms on the load profile on the transformer?*
- *What is the effect of the market mechanism on the average charging price?*
- *Does the market mechanism influence the mobility behavior of the agents?*
- *What is the best market mechanism for the flexibility system design for electric vehicles?*

In the conclusion of this report a system design for flexibility of EVs is developed. This system design consists of a functional design which indicates the responsibilities in the system. A physical design which relates the functions to roles in the system and a technical design which shows the interfaces needed to communicate in the system. At the end of this report a conclusion of the PDeng will be presented.

1.4. Outline of this PDeng thesis

The following structure will be used in this PDeng thesis. In chapter 0, the developments in the electricity system are described. This starts with an explanation regarding the developments in the energy transition. This will be followed by a description of the structure of the power sector, EV market and the electricity network. Chapter 0 ends with a clarification of flexibility and the description of the different market mechanisms. Chapter 3 gives the aspects on which the results of the simulation will be compared. Chapter 0 presents the structure of the simulation and a description of the implementation of the market mechanisms in the simulation. This will be followed by the results of the simulation in chapter 5. The functional design of the system will be presented in chapter 6. Chapter 7 contains the discussion, conclusion and future work. In Figure 4 the outline of this PDeng thesis is schematically displayed. All chapters start with an introduction and outline what will be covered and finish with a conclusion of the main findings.

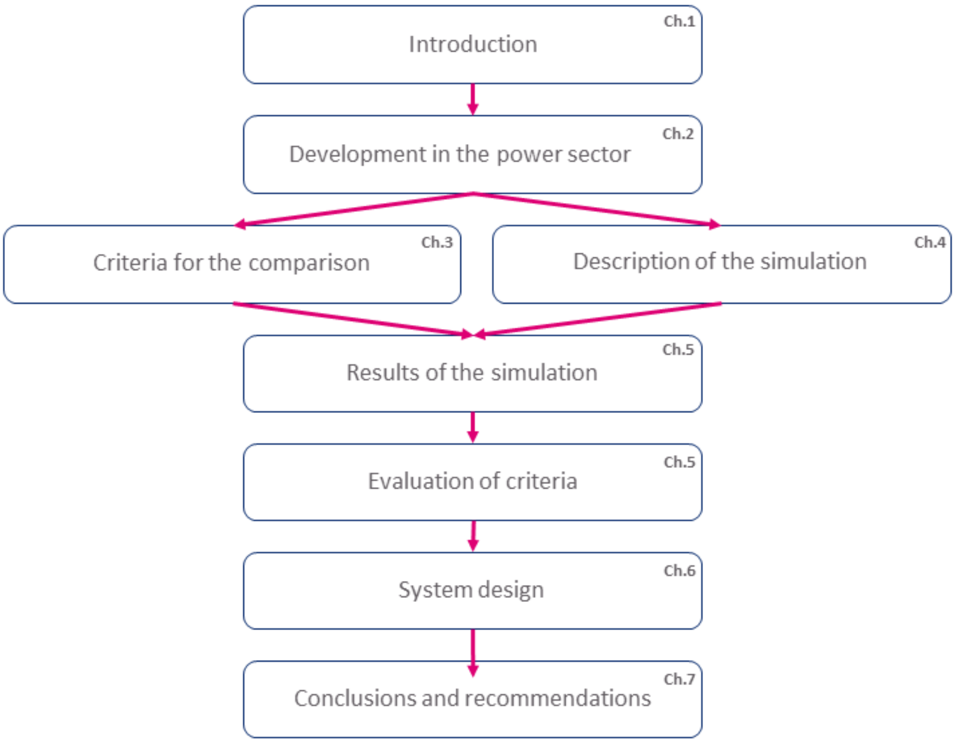

Figure 4, Schematic outline of this PDeng thesis

2. Developments in the power system

In this chapter the literature review will be presented. The literature review will give the needed context to the design issue. Section 2.1 will describe the energy transition and the challenges that are expected. Section 2.2 will elaborate on the electricity markets and its developments. In this section both the Dutch market, as the difference with the European market will be described. In addition, the need for flexibility in the electricity market will be covered. Section 2.3 discusses the EV developments and market design. To conclude this chapter, a description of the electricity network will be given. This section will give insights in de technical structure and the use of the coincidence factor. Next to this a definition of congestion is given.

2.1. Energy transition

The current society is based on the idea that there is an abundant amount of energy. However, as can be read in the introduction, a depletion of fossil fuels is expected. This, is next to the deteriorating air quality one of the main reasons that the world is facing an energy transition. The energy transition is the conversion from a fossil fuel-based energy system to a sustainable energy system. This means that for generation of heat and electricity renewable sources will be used, in the case of the Netherlands this is mainly wind and solar energy. Next to this, there needs to be a higher energy efficiency which gives opportunities for new technologies such as electric mobility.

Reliable, affordable and renewable energy is an important topic on the EU agenda after the continuing discussions about clean energy generation, climate change and a safe environment [14]. As described in the introduction of this report, the energy goals of the EU for 2020 are to reduce greenhouse gas emissions by at least 20%, have a 20% growth of renewable energy and 20% energy savings. For 2030 the targets at EU level are set on 40% greenhouse gas emissions compared to 1990 levels, 27% of renewable energy consumption and 27% of improved energy efficiency. Long-term goals are more challenging. For 2050, the target for the reduction of greenhouse gases is set at 80-95% compared to 1990 levels. Although the Netherlands has committed itself to these goals, the Dutch energy transition is lagging on the other EU countries. The share of renewable energy in the Dutch final energy consumption was 2.5% in 2005, 3.9 % in 2010 and has reached 6.0% in 2016 [8]. This is only a little increase compared to the EU average which was 9.0% in 2005, 12.9% in 2010 and 17% in 2014 [15]. This makes the Netherlands with Malta the lowest scoring country in the EU. Scholars explain this by the strong focus on the fossil fuel regime in which incumbents have an influential role [16].

Transport has a global CO_2 footprint of 28% [17]. This leads to a deterioration of air quality and affects the public health. Therefore, governments are searching for ways to lower these emissions by seeking for alternative fuels for transport. Two most important options for alternative fuels are hydrogen and electricity [18]. Looking at the different technologies it can be said that a full electric passenger vehicle is more efficient in energy use (tank-to-wheel) than a hydrogen fueled vehicle (83 % vs 48%) [19]. On the other hand, hydrogen cars have a bigger range which is one of the challenges of full electric cars. Currently, a growing number of manufacturers are developing EVs for commercial purposes. This leads to bigger investments in the development of EVs which leads to a higher maturity level and mass consumption. Therefore, it’s likely EVs will dominate the market for passenger vehicles.

2.2. Electricity market and its developments

This section describes the structure of the EU electricity market and which roles there are. This is a brief overview of the electricity market to understand the context of the design issue. More elaborated market descriptions can be found in [20]. After this a comparison of the Dutch electricity market to other EU electricity markets will be made and the most important differences will be described. A detailed description on the Dutch electricity market can be found [21] [22]. At the end of this chapter the most important developments of the electricity system regarding the energy transition will be explained.

2.2.1. Electricity market – Europe

Europe has implemented a liberalized electricity market to offer a level playing field in the international trade of electricity and broadening the market for generation of electricity [23] [24]. In a liberalized electricity market, organizations for generation and distribution of electricity are separated. The electricity network is operated by natural monopolies, which indicates that the network has high infrastructural costs which make barriers to entry high. Thence, the delivery of electricity is arranged, and long-term operation of the system is guaranteed. An electricity market operates well when price signals enable efficient short-term operation and offer enough incentives for investments in the required generation capacity [25].

The electricity market can be divided in two parts: the physical network and the trade markets. In the physical network electricity flows from production unit via the transmission network, for long distance transport, to the distribution network to end-customers. Two important fundamental principles exist in relation to electricity networks:

- Electricity demand and supply always need to be in a balance while electricity cannot be stored on a large scale [24]. This balance is indicated by the systems' frequency (50 Hz in Europe);
- Electricity flows cannot be controlled, it always takes the path of the least resistance.

The transmission system operator (TSO) is responsible for the transmission network (high voltage network), capacity of international network connections, frequency control and balancing services. Transmission networks are operated (sub)national and interconnections connect the different EU countries. The distribution system operator (DSO) is responsible for the low and medium voltage (MV) network. Where the boundary lies between de responsibilities regarding voltage levels of the DSO and TSO differ per country in the EU. While both the TSO as the DSO work in a natural monopoly, they are strictly regulated. In all EU countries the DSO landscape is different. In some countries there are hundreds of DSOs (Germany), and in some only one or two. All EU countries require at least a legal and functional unbundling for DSOs with an exception for small DSO (<100.000 connections) [26]. Functional unbundling implies that the management of the commercial activities like production and supply of energy are separated from the operation of gas and electricity networks.

The trade markets can be divided in different markets as can be seen in Figure 5. Forwards and futures are financial products that are traded from years before, to up to the day before delivery. These products arrange that a certain amount of electricity is supplied or used at a certain moment in the future for a price agreed upon today. Forwards are traded by over-the-counter (OTC) which are non-standardized bilateral agreements [27]. Futures are exchanges which are standardized options that are traded via the power exchange [28]. More customized options are traded bilateral [22]. The spot market is designed to trade a commodity which is delivered (almost) instantaneous [22]. It is divided in a day-ahead (DA) market, intraday (ID) market, a balancing market and the imbalance settlement [25]. In addition to this, a locational marginal pricing mechanism is in place to settle locational network constraints.

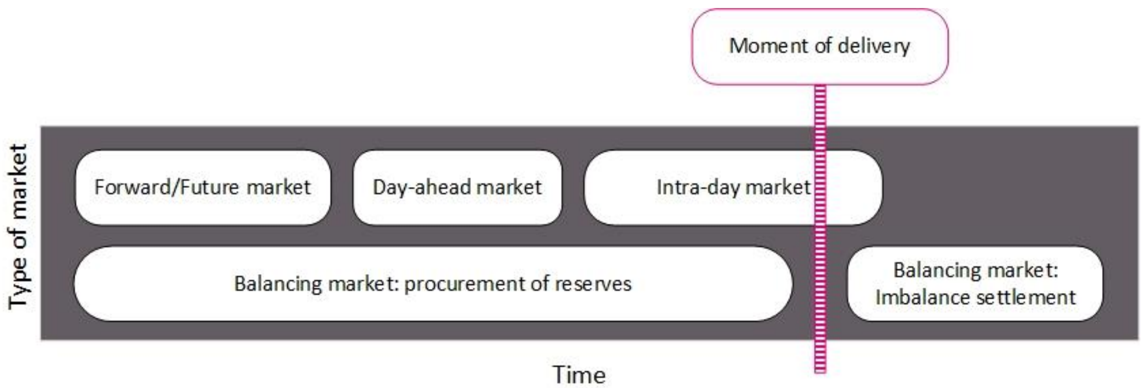

Figure 5, Outline of electricity markets in Europe

In the DA spot market hourly trades are made between seller and buyer for the delivery of power for the next day. Short-run marginal costs set the DA spot price. The DA market has the highest trading volumes and number of market players, and therefore the DA market price is often denoted as the “electricity price” [28]. The closure-time of the DA spot market is usually 12:00 pm DA and the closer the moment of delivery of electricity is approaching, the more accurate buyers and suppliers know their actual position in the market. Parties who have put in a winning bid need to schedule their power generation or consumption in advance. Depending on the country in the EU this is hourly (e.g. Spain) or half-hourly (e.g. France and Ireland) or quarterly (e.g. Netherlands and Belgium). In addition, they need to allocate their generation or consumption to a balance responsible party (BRP) which is financially responsible for the possible real-time net imbalance of their portfolio [25].

The ID market give BRPs the possibility to adjust their position by selling or buying power after closure time of the DA market [25]. This enables market parties to correct for trades made in the DA market based on more accurate renewable feed-in forecasts, demand changes etc. [28]. Depending on the country in the EU the ID market is based on discrete auctions (Same as DA market) or continuous trading (first come, first served principle). Discrete auctions are implemented in for example Spain, Portugal and Italy while in the northern countries of the EU continuous trading is the ID principle. Gate closure-times are for discrete auctions between 5 – 60 minutes before delivery and for continuous markets 135 – 690 minutes before delivery.

To keep the system in balance the TSOs have established a balancing market in which real-time balancing of power is arranged [25]. In this market balancing service providers (BSPs) have obligated themselves to be able to ramp-up or down their power output to provide balancing capacity when needed. This capacity is auctioned in advance by the TSO from BSPs by predefined requirements e.g. contract duration, activation time-frame etc.

Imbalance settlement is used to calculate the costs of the reserved and activated balancing services from the BSP to the BRPs that did not hold their position in their pre-arranged portfolio. In general, the costs are calculated regarding the difference between the day-ahead delivered portfolio and the real-time delivered power. In some countries (e.g. Spain and Germany) BRPs get an extra fine for being unbalanced to give an incentive to the BRP to reduce own imbalances.

2.2.2. Electricity market – Specifics of the Netherlands

The Netherlands has the strictest form of a liberalized electricity market in the EU [26]. Regulated by Dutch law, generation of electricity and the network operator are unbundled following the ownership unbundling [21] [26]. Tennet, the TSO, is responsible for the high voltage (>110kV) transmission network, capacity of international network connections, frequency control and balancing services [21]. Next to Tennet, there are seven DSOs which are responsible for the installation, operation and maintenance for all medium and low voltage (LV) networks (<110kV). Both TSO and all DSOs work in a full regulated market which is controlled by ACM (Authority Consumer and Market).

Figure 6, Dutch electricity trade markets.

The Dutch electricity market has many similarities with the EU market. The ambition of the EU to realize an international electricity trade platform has contributed to this. Figure 6 shows a more specific outline of the electricity market in the Netherlands. On the DA market electricity is traded for delivering the next day. Until 12:00 prior to the day of delivery providers can bid on the market [29]. After this moment demand and supply is matched and the market clearing price will be determined on an hourly basis. In the Intraday Market electricity can be traded until 5 minutes before the actual delivery. Next to this it is possible to trade OTC after the delivery. In the Netherlands the ID market accounts for 10% of the trades of the spot market, the other 90% is traded on the DA market.

In the balancing market there are three reserve markets: primary reserve, secondary reserve and tertiary reserve, which are all the responsibility of Tennet. The primary reserve is the first market which is activated when there is a deviation from the frequency. Activation of primary reserve is done automatically within 30 seconds [22] [30]. The primary reserve is a contracted amount which is procured on a weekly auction. In 2015 the total amount of contracted primary reserve was 96 MW of which 29 MW is procured on the Dutch auction [31]. The remaining part, 67 MW is procured on a Dutch- German auction [22]. Tennet determines on base of price which order will be activated first [29]. Participants of the primary reserve market receive a capacity price.

When the system is imbalanced for more than 15 minutes the secondary reserve is activated. Secondary reserve is both a contracted amount by Tennet, as it is possible to place a bid for offering reserve power. Tennet contracts 300 MW reserve power on a yearly basis. This voluntary balancing market closes 60 minutes before the moment of delivery [30]. The last reserve option is the tertiary reserve. This is activated when an unbalance occurs longer than 15 minutes. Offering tertiary reserve is only possible for (aggregated) parties who can offer big amounts of emergency power (minimal 20 MW) [30]. Tennet has contracted 550 MW in total for 2017 (taking together ramping up and down).

The market players in the electricity market in the Netherlands and relations between them can be seen in Figure 7. In this figure the pink lines indicate the physical electricity delivery and the green lines are the financial relations between the market players. When looking at the pink lines between TSO, DSO and Consumer the line is pictured with a bi-directional flow because of the implementation of decentral generation in the network. The aggregator is a new role which is often mentioned by scholars to have a big influence on the electricity market. The aggregator will aggregate flexibility appliances of consumers or industry to offer to the BRP, DSO or TSO for their flexibility needs. This role can be additional to one of the current market players or a complete new player therefore it is not yet pictured in the figure. In Table 1, an additional description of the characteristics of the market players can be found.

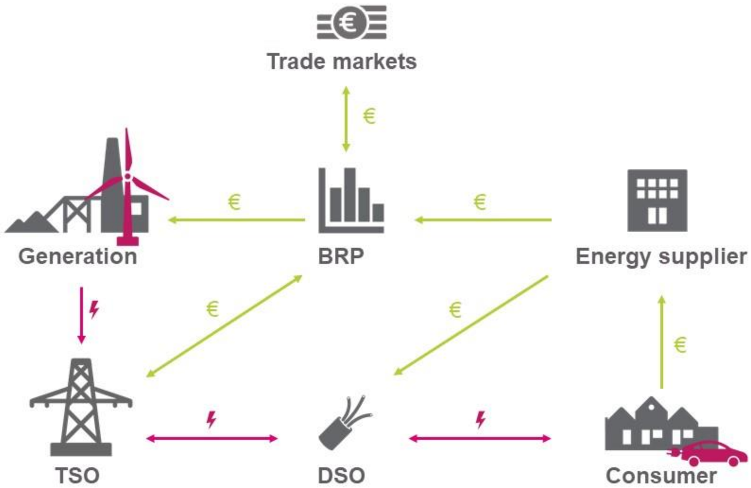

Figure 7, Market players in Energy Market.

Table 1, Description of the characteristics of the market players in the electricity market

Market player	**Characteristics**
Balance Responsible market (BRP)	Financially responsible for the possible real-time net imbalance of their portfolio.
Transmission system operator (TSO)	Responsible for the high voltage (>110kV) transmission network, capacity of international network connections, frequency control and balancing services.
Distribution system operator (DSO)	Responsible for the medium and low voltage network (<110kV), responsible for physical delivery of electricity.
Prosumer	Consumes and produces electricity
Energy supplier	Buys electricity from BRP and sells it to the consumer
Generation company	Generates electricity and sells it to the BRP
Trade markets	Market where electricity is traded financially

2.3. Renewable generation

An important dissimilarity between conventional generators, using fossil fuels and renewable energy supply (RES) based generators is controllability. RES extremely depends on weather conditions whereas fossil fuel generators mainly depend on the supply costs for fuel emission contributions and the availability of the generator [28]. This has had an important contribution to the price mechanism of the electricity market. The difference in short-run marginal costs between production units has led to units being deployed according to the merit order. The merit order determines the market clearing price. This is equal to the short-term variable costs of the last unit that produces electricity to meet the demand. The merit order will change when more renewable energy is generated while the short-run marginal costs of renewable generators is close to zero - see Figure 8 [32] [33]. This will lead to low energy prices when there is a lot of solar radiation or wind. However, when there is little renewable energy and demand is high, prices will be high. Hence, with a higher implementation of RES an increase in price volatility is expected.

This price volatility is related to three types of integration challenges of RES. The first is related to the higher need for back-up generation. This is related to the intermittent nature of RES. If there is a low supply of energy because of weather conditions, there needs to be a back-up in generation which leads to a higher need for installed capacity. Another refers to the need for controllability of the system. In the conventional situation flexibility on the supply side is used to keep the system in balance, while the supply follows the demand. When renewable energy is available, fossil fuel generation has a lower chance to be used. This leads to a lower utilization rate of fossil fuel generators and leads to a shift of fossil generators from a base-load generation (low operational costs) to a mid- or peak-load generation (high operational costs). These both challenges lead to a higher need for flexibility to lower the balancing costs of conventional generation.

Figure 8, Merit order, market clearing price is based on the short-term variable costs of the last unit that produces electricity.

The last integration challenge is the limited predictability of RES due to the uncertainty of weather conditions. As described in section 2.2.1 the BRP is financially responsible for their portfolio. Which means that the BRP needs to estimate the amount of demand and supply of their customers for the next day. This estimation becomes harder with the intermittent nature of RES, therefore the BRPs need flexibility to adjust their positions close to, or during the delivery.

2.4. EV market

In this section the EV market will be described in terms of current and expected developments. These numbers will be compared with other European countries. In addition to that the EV market design will be presented regarding the different roles and challenges.

Of the total 8 million passenger cars in the Netherlands there are currently about 130.000 electric passenger cars. These can be divided in 100.000 Plug-in Hybrid Electric Vehicles (PHEV) and 30.000 Battery Electric Vehicles (BEV) which makes the Netherlands one of the frontrunners in this field [12]. Figures show that the sales of PHEVs are declining because of abolition of incentives by the Dutch government while the goal of the government is to sell only zero-emission cars in 2030. The current sales of BEVs however, are growing exponentially - see Figure 9.

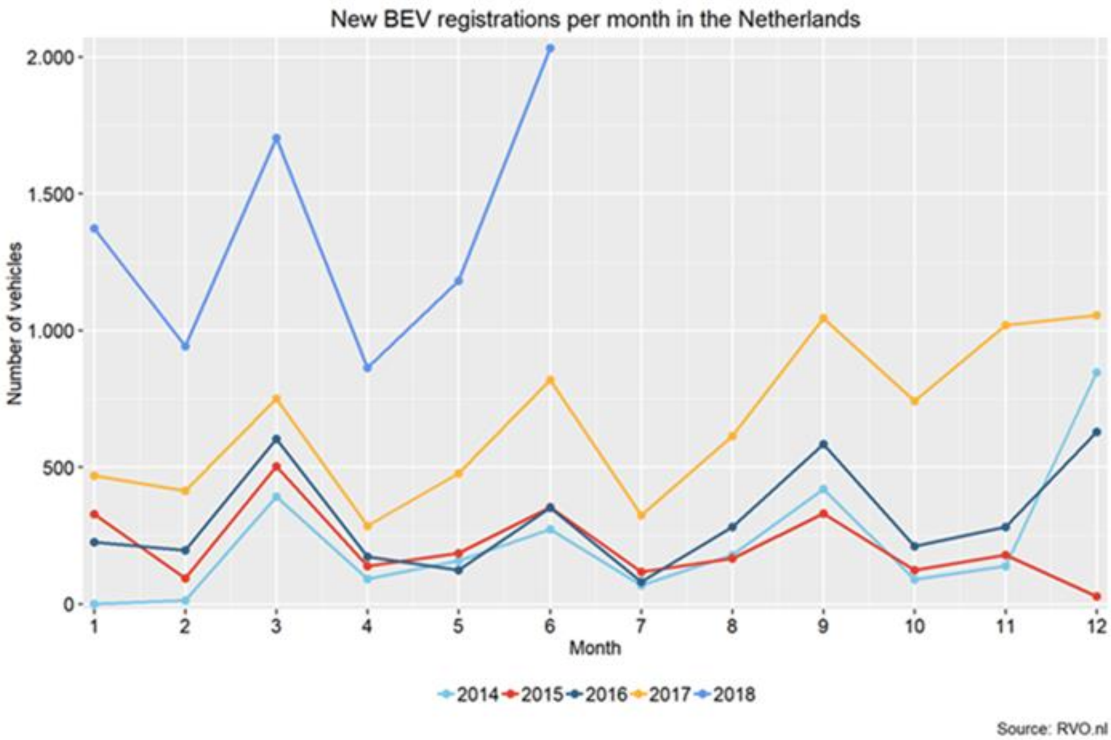

Figure 9, Exponential growth of adoption of electric cars by month, colours indicate the different years [34].

Expected is that BEVs result in a higher peak load, electricity and capacity demand [35]. In the paper [36] an estimation has been made about the additional peak load in the electricity grid with a 100% adoption of BEVs and uncontrolled charging (uncontrolled charging refers to the situation that the car will be immediately charged when the driver plugs-in). This results in an additional peak load of approximately 7 GW, which will according to [36], cause a significant higher peak load (+42%) and an increase in total electricity usage (+22%). Next to this it will result in a higher variability of the load profile. Although EVs have the potential to cause problems for both the grid as the installed capacity, they can also be a solution if managed efficiently.

The EV market in the Netherlands can be divided in three markets: private charging, public charging and fast charging. Private charging means that consumers charge their car at home and the charging station is connected behind the household connection. This means that charging speed is limited to the maximum capacity of the household connection. The current average charging speed for private charging is 3.6 kW. Public charging means that consumers use a charging station at public ground. The charging station has an own connection to the LV network. Public charging stations charge on average between 11 kW and 22 kW. The difference between private and public charging is that consumers who can charge privately, pay for their own charging station while public charging is mostly financed by the government and market. Therefore, this leads to different market designs. The last market is fast charging. Fast charging is developing rapidly. The current installed chargers have a maximum power output of 350 kW and are used for corridor charging. These chargers are installed at MV level and are used like the function of a fuel station next to the high way. This also means that fast charging is less interesting for performing a flexibility service. Therefore, this market is not included in the scope of this report.

In Figure 10, a current overview of the EV market is portrayed in the Netherlands. In this figure all roles are incorporated which are present in both the private as public market design. As can be seen the EV market has a physical (pink) and financial (green) relation to the electricity market (showed in picture only by DSO and Energy supplier but has more roles - see Figure 7). The blue lines indicate the data that is transferred between the parties. Data is needed for charging station operators (CSOs) to control charging stations remotely via OCPP (open protocol between charging station and CSO).

The CSO role and mobility service provider (MSP) role are separated to make maximum use of the installed base, while this makes it possible to charge at every charging station independently of the contracted MSP. This results in data communication about for example: authentication and billing of customers via a clearing house. An original equipment manufacturer (OEM) is the manufacturer of the electric car, this market player can as well offer charging services. A clearing house ensures interoperability by offering roaming services to MSP and CSO, this role is only present in the public charging market. The (home) energy management system ((H)EMS) controls the charging station in a bigger ecosystem which gives the option to control the charging of an EV within the capacity of a connection considering other appliances for example in a household, this is a role that is only present in the private EV market.

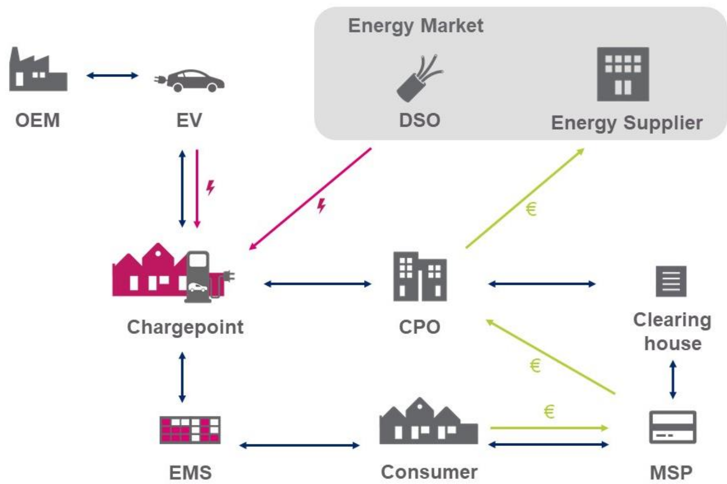

Figure 10, Current market players in the EV market in the Netherlands (public charging)

Table 2, Description of the characteristics of the market players of the EV market.

Market players	Characteristics
Charging station operator (CSO)	Is responsible for the maintenance and operation of the charging station. The DSO delivers the connection to the electricity network and the electricity supplier delivers electricity. Currently the CSO choses which supplier is delivering electricity to the charging station in the Netherlands.
Mobility Service Provider (MSP)	Is responsible for charging services to the customer. Currently, it hands out charge cards and arranges billing services of charging sessions.
Clearinghouse	Platform that enables the exchange of roaming authorization, charge transaction and charge point information data to ensure interoperability between charging stations national and international.
Charging station	Hardware device which delivers electricity to a car
Electric Vehicle (EV)	Electric passenger car
(Home) energy management system ((H)EMS)	Controls charging session within a bigger ecosystem. For example: controls charging speed to avoid overload on a connection when other appliances are needed in the household
Original equipment manufacturer (OEM)	Car manufacturer

2.5. Electricity network

This section describes the technical structure of the Dutch electricity network. It explains what a coincidence factor is and how the DSOs use it by calculating the needed network capacity. The relation of the energy transition and the electricity network will be described and at last the relation of the capacity tariff and flexible appliances is given.

2.5.1. Technical facts electricity network

In the Netherlands the total electricity network is 337.952 km long and has 8.2 million connections. The DSOs are responsible for the MV and LV network which is 288.000 km long. The MV network has 32.500 connections (medium sized industry) and the LV network (households, small commercial parties) 8.1 million [37].

Network operators have built a network that can be utilized at peak demand. Network operators use calculation methods to determine the peak load on a certain location [38]. Loads can be divided in a part that is relatively easy to estimate (medium term) and a part that behaves randomly. On an aggregated level, for example for a neighborhood it is relatively well known what the minimum and maximum amount of load is and when this will occur. On an individual level this is quite hard to predict [39]. However, the dimensioning of an electricity network is not based on the sum of the maximum connection capacity of all individual connections together, but on a lower capacity. While the individual maximum peak demand, will occur on different moments. Therefore, a coincidence factor is used to describe the affiliation of the peak demand of individuals to the peak demand of a group [38]. Hitherto, it was adequate to use an average daily load profile for all individual consumers, with an evening peak when consumers get home from work, in addition with a yearly growth factor to estimate the future demands.

These assumptions are not valid anymore with the arrival of new loads, like the EV which has a different load profile. Regulation states that it is obligatory for the network operator to connect and transport the electricity requested by a customer. On top of that DSOs are not allowed to discriminate one customer over another [40]. Up to date, this is managed by reinforcing the network when a higher capacity is needed, which is a solution with a high reliability. With the upcoming transition to renewables and the electrification of appliances it becomes harder for network operators to meet the obligations. Therefore, DSOs are looking for new solutions like flexibility to lower the increasing pressure on the electricity network. Important factor for DSOs is the reliability of the solution. The current network of the Netherlands has a reliability close to 100% which is one of the factors that the Dutch society is relying heavily on the electricity network.

New devices like, EVs and PV panels are expected to have a higher coincidence factor and will change the load on the network. The reason that PV panels have a different coincidence factor is that the sun will shine simultaneously on all panels on a cloudless day, which will make the coincidence factor close to 1 [39] [41]. Whereas the current used coincidence factor is 0.5[1] [39]. Another example is EVs: EV drivers return to their houses roughly concurrently in the evening. On top of that EVs have a high load demand (3.7 kW – 22kW compared to an average household load of 1-1.5 kW) for a long-time frame (1 to 8 hours) which is different from all other appliances in the household. This means that the existing electricity network in the Netherlands is expected to have a too little peak capacity for all new devices and planning methods need to be adjusted to respond to the developments in the energy transition [41]. This capacity problem is known as congestion. Congestion happens when the demanded distribution capacity surpasses the available capacity of the existing network [42]. Currently, the only solution for congestion is reinforcement of the electricity network. However, this is cost and labor intensive. Therefore, DSOs are developing new solutions to avoid network congestion. Flexibility on the demand side is one of these solutions. Benefit of the new devices like PV and EV, is that they are flexible and can be postponed or are able to buffer energy [43]. Non-flexible appliances are less interesting, they are used immediately after activation for example: television, lighting and cooking equipment. More in-depth information and a definition about flexibility will be given in the next section.

As of today, controlling flexible appliances with a (H)EMS in households can already be interesting for EV owners to avoid a need for a bigger household connection (3×25 A[2] to 3×35 A), while the price difference is high - see attachment I for the prices [44]. Reason for the price difference is that the costs of the connection is related to the computed capacity[3] (used in network planning) and not to the actual connected capacity. This means that an average household in the Netherlands (based on an electricity use 3400 kWh per year) with a connection of 3×25 A, has a connection capacity of 17.3 kW, an computed capacity of 4 kW and an actual average used peak capacity[4] of 0.8 kW [38]. The HEMS will lead to a better use of the available technical capacity (to maximum 17 kW) per household instead of 4 kW. This can result in a complete utilization of a household connection and if more households on a cable do this simultaneously this leads to congestion.

[1] The coincidence factor decreases depending on the number of households on a cable.
[2] Highest capacity connection within the connection tariff
[3] With computed capacity is meant the capacity that is calculated for net planning purposes including the coincidence factor, this calculated capacity is based on 70 households or more.
[4] Used peak capacity = the aggregated capacity used by households/ total number of households

2.6. Flexibility

This section will give a definition of flexibility and explain the need for flexibility for different market players. To conclude the differences between the market mechanisms will be described.

Flexibility is an subject that is researched extensively by both scholars and the market in various ways and for different solutions, examples of this are [38] [41] [45] [30] [46] [29]. This research topic knows many definitions, therefore in this report the definition that will be used for flexibility is: “a power adjustment sustained at a given moment for a given duration from a specific location within the network” [11]. This definition gives the essential parameters for congestion management by a DSO: possibility to adjust power consumption or production (kW), change the moment in time and duration (hours), and the location in the network.

Although in this report the DSO is the central party, as described above, other market players are looking for flexibility as well. The TSO and BRP are searching for flexibility for balancing and forecasting purposes. [46] has found that a power system solution in which both grid relating flexibility (capacity constraints) and energy related flexibility are combined in one market mechanism, will lead to the highest benefits. The consumer can get a direct incentive (financial incentives) or an indirect incentive (decrease energy prices) to provide flexibility. Below a summary of the challenges that are faced in the energy transition per organization can be found:

- *TSO: Large scale sustainable production, balancing capacity needs to increase on national level;*
- *BRP: The unpredictable nature of sustainable production leads to more problems in managing and predicting demand and supply;*
- *DSO: Large scale implementation of PV, EV and electric heating can result in deterioration of power quality and overloading of existing cables and transformers.*

The first two challenges are on national level, are interrelated and already have a system framework to cope with changing demand and supply (Reserve markets and trade markets). However, the needed amount of balancing capacity will increase with the growing sustainable production which could result in a need for a flexibility market. The third challenge is known for its local characteristics. Current national balancing markets are not effective in solving these problems. Grid congestion is a local problem which can only be managed locally. Therefore, solutions in the capillaries in the network need to be found.

By both academia and industry, it is widely recognized that demand-side flexibility is needed for effective competition, system efficiency and consumer enablement [47]. Demand-side flexibility can be unlocked in various ways, for example through demand/response (DR). DR distinguishes two classes namely implicit and explicit DR [47].

- *Explicit Demand-Side Flexibility* refers to consumers who receive an incentive for their willingness to change their energy behavior, regularly in response to a system operators’ request. This type of flexibility can be performed by the consumer of by an aggregator.
- *Implicit demand-side flexibility* is the reaction of the consumer to a price signal. These price signals are dependent on the prices of electricity markets and the capacity on the network. The consumer can adapt their energy use (automated or manual) to save on energy expenses.

The next sections will further elaborate on four flexibility market mechanisms. These includes two implicit DR and two explicit DR mechanisms. The implicit DR mechanisms are pricing based and variable connection capacity based. The explicit DR mechanisms are direct control and market-based flexibility. The market mechanisms are described from an DSO perspective, in the simulation a market-based approach will be added – see section 4.2.4.

2.6.1. Price-based mechanism

In literature, the abilities of price-based mechanisms to change consumption behavior have been broadly studied [48] [49]. The current used price structure in the Netherlands represents the total costs required to generate, transport and distribute electricity. The prices can be divided in four components: supply-, network-, metering costs, and taxes. Supply costs are the costs for the electricity demand and consist of a fixed tariff, determined by the supplier, and supply tariff per kWh. Network costs are costs that are related to the operation, use and maintenance of the electricity network and the connection to the network. These costs are determined every year by the regulator (ACM). The tariffs implemented by the DSO need to reflect the corresponding costs of the service offered. Metering costs are linked to the costs of recording the meter positions and installing, maintaining and managing of meters. There are two different types of taxes: a fixed tax per kWh and VAT levied on all costs [50].

In the Netherlands consumers can choose between a flat electricity tariff or day and night tariff. However, the current differentiation between day and night tariff are extremely low. The network tariff is based on the maximum technical capacity of a connection, without differentiation between time- or amount-of-use. This leaves the consumer with no incentive to change its electricity behavior from peak to off-peak periods. Changing the electricity behavior could lead to a reduction in costs for both supplier, network operator and consumer [51]. To give an incentive to the customer, dynamic price mechanisms have been proposed. Amongst others, examples of dynamic tariff mechanisms are [49]:

- Time-of-use (TOU): The price differs depending on the moment the electricity is used with high prices in peak periods and low prices in off-peak periods;
- Critical peak pricing (CPP): Is depending on the peak load of the network and can have therefore a locational difference. In peak periods there are additional charges and during off-peak periods the normal or lower network tariff is in place. CPP is an addition to either flat-rate or TOU tariff schemes.
- Real time pricing (RTP): The wholesale electricity market is leading which can be either determined real-time or day-ahead.

These tariffs are sent to the consumer who can manually or automatically respond to the prices. Regarding an EV automatic response, known as smart charging, seems most feasible because of technologic possibilities and lower behavioral dependence and result in highest costs savings [52].

This type of pricing can be complementary to other tariff schemes which can be seen in Figure 11. The DSO send its tariff scheme to the CSO as well as the energy supplier. To optimize the charge profile on the preferences of the consumer, the consumer sends it departure time to the CSO. The EV shares the state-of-charge (SoC) data and the charge point sends the connection time. The CSO will optimize the charge profile within the preferences of the consumer to become to a price optimized charge schedule.

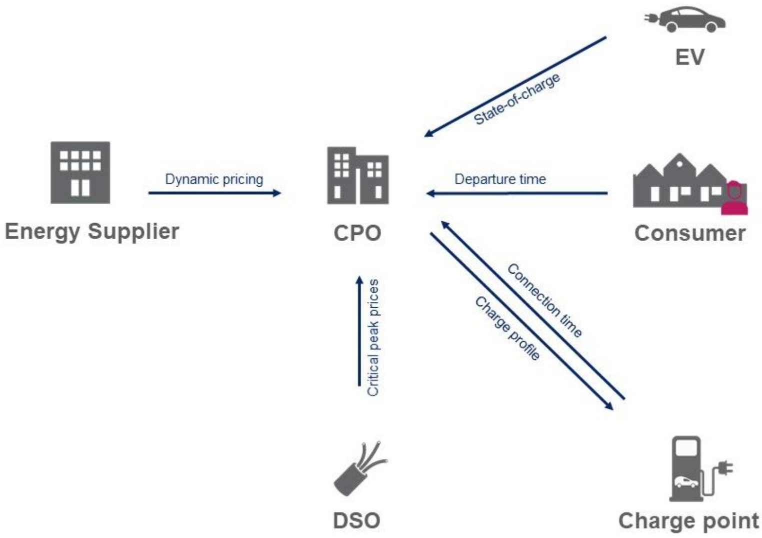

Figure 11, Roles in price-based charging market mechanism

2.6.2. Variable connection capacity

As described in section 22 the Netherlands has a liberalized energy market. DSOs operate in a regulated market, in which the distribution network is considered to be a natural monopoly. The DSO has capacity contracts with all end-users of the network. The technical capacity of the connection determines the tariff an end-user needs to pay. This is a fixed tariff which is not correlated to the amount of use, time or frequency. The variable connection capacity gives the possibility to implement a time-dependent capacity profile for a connection [50]. In this profile, see Figure 12, an on- and off-peak capacity is established. The compliance of the consumers is measured by using metering data of the smart meter.

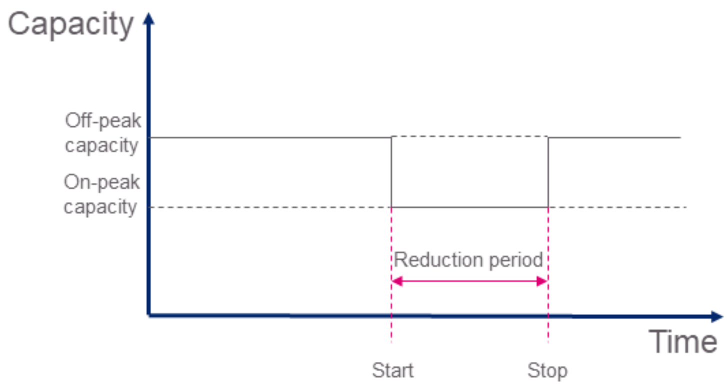

Figure 12, Variable connection capacity, with a restriction period which is connected to the peak moment in the network.

Variable connection capacity can be implemented in various ways: national or local level and can vary during the day in both time and capacity. This leads to the following options for capacity contracts:

- National fixed profile: The profile is based on the national aggregated demand profile;
- Local fixed profile: Local established profile which is based on historical measurement data of a specific transformer or cable;
- Local dynamic profile: The profile is based on the (real-time) measurement data for a specific transformer or cable. This profile has locational differences.

The needed interactions between the roles in the mechanism can be found in Figure 13. The DSO will conclude a variable capacity contract with the CSO in which the reduction period is stated. Within the contracted capacity the CSO can adjust the charge profile as agreed on with the EV driver. Within the threshold of the connection it is possible to optimize on costs, but it is not necessary.

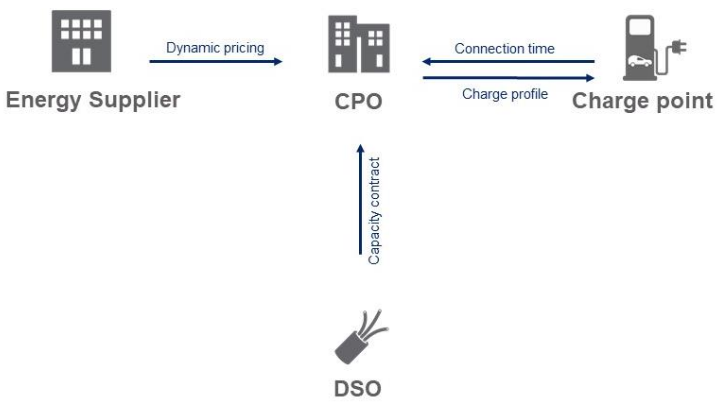

Figure 13, Roles in Variable connection capacity

2.6.3. Direct Control

Direct automated load control is a mechanism that is currently used in the energy market to restore the frequency by controlling the production directly. This is a locally installed mechanism to restore the (inter)national frequency by the TSO within 30 seconds. With the growth of renewable energy sources (more) flexibility is needed on the demand side. This type of mechanism could also give the DSO the possibility to use direct load control to shift load from peak hours to off-peak periods. When the DSO wants to implement direct control, it needs to have insight in the load of the cables and transformers. When an overload is expected a signal will be send to all flexible loads on that cable or transformer [53]. With direct load control the DSO has permission to actively switch on or off flexible devices of customers for which they receive an incentive based on their contract [54]. This will lead to a method that is implemented at device level to shift consumption depending on the grid condition.

The devices that can be managed by the DSO are for example the charge point for the EV, the heat pump or the PV panels. Next to these appliances, smart smaller appliances like washing machines, dryers or the electric boiler could potentially be interesting as well. Although a lot of these appliances need to be controlled to reach the same effect as the first named devices. This mechanism will be controlled by the DSO with a remote-control system. The consumer is therefore less involved and can even be duped by the utility while its preferences are not considered.

In Figure 14, the DSO has a capacity contract with the CSO. In this contract is agreed that the DSO can adjust the load when overload is detected in the electricity network. The adjustment, known as congestion management, will directly be controlled on the charging stations. Downside is that the CSO and customer are not in control over the charge profile in case of an overload situation.

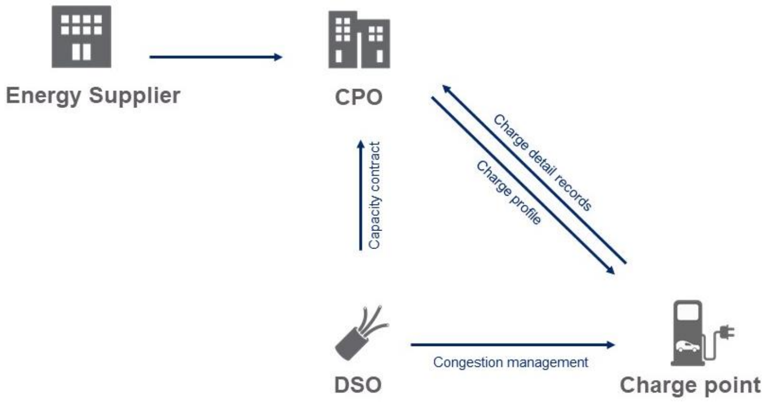

Figure 14, Roles in Direct control

The difference between direct control and variable connection capacity is sometimes difficult to notice. Especially when a dynamic local profile is implemented. The biggest difference is the controlling party. The controlling party for variable connection capacity is the CSO. The DSO concludes a contract with the CSO about the maximum load. Execution of the agreements in the contract are done by the CSO. For direct control the DSO has the lead. The DSO controls the network, if overload is detected on a cable or transformer direct control signals are directly send to the connected charging stations.

2.6.4. Flexibility market

Flexibility markets are a popular topic for researchers in the past years, and therefore are presented in many different setups. A DR exchange platform is presented by [55] on which flexibility is traded as a commodity by the DSO, TSO, and retailers. A few years later this is followed by [56] who proposes a flexibility clearing house, which can exist next to the wholesale markets. This last concept is later enlarged by [57], implementing several moments in time at which flexibility can be traded (e.g. year-ahead, day-ahead, hour-ahead). Next to researchers, the industry has also started contributing to the development of the flexibility markets. A consortium of partners has formed the universal smart energy framework (USEF) which provides in a (non-profit) market model for trading and comedizing energy flexibility [58]. USEF has developed an architecture, tools and rules to make the flexibility market work effectively and in parallel to the current electricity markets.

In the framework the aggregator has the central role to acquire flexibility from prosumers and offer it to different market players like for example: DSO, TSO and BRP on different markets like for example: day-ahead, intra-day or reserve markets. In return the aggregator can use the created value from the flexibility as an incentive for the prosumer to shift its load. Remuneration of flexibility can be implemented either based on a capacity fee, on an energy fee, or a combination of both. In the framework there is a separation of the flexibility supply chain and energy supply chain. This means that after trading flexibility between the prosumer, BRP and TSO the DSO need to actively monitor the network. When an overload is detected in the electricity network the DSO can obtain flexibility by bilateral contracts or a purchase on the flexibility market which can be both day-ahead or intraday, which results in a single-buyer market. Another possibility is to obtain flexibility from an open platform, where flexibility is offered and requested, and after gate closure, the market is cleared [50].

To safeguard the reliability of the energy system and enable trading of flexibility USEF has introduced operating regimes [58]. In the **green regime** there is a normal operation with optimization on the commodity value and without grid limitations. The DSO needs to actively monitor the network for congestion problems. In case an overload is detected by the DSO the **yellow regime** is activated. In this regime the DSO can actively buy flexibility for congestion management and peak load reduction. When there is not enough flexibility on the market the **orange regime** is triggered in which the DSO can autonomously make decisions to lower the load of flexible devices. If this is also not enough the congestion situation will lead to a **red regime** which indicates a power outage [58].

In Figure 15 a simplified overview of the roles within USEF are shown. It is not clear if the aggregator role will become a new market party in the system or that it will be incorporated in an already existing role. In USEF all parties are able trade flexibility as a commodity on the market. If possible, this is also the case for the DSO. The USEF model only allows trading flexibility if it is within the preferences of the customer who receives an incentive for offering flexibility.

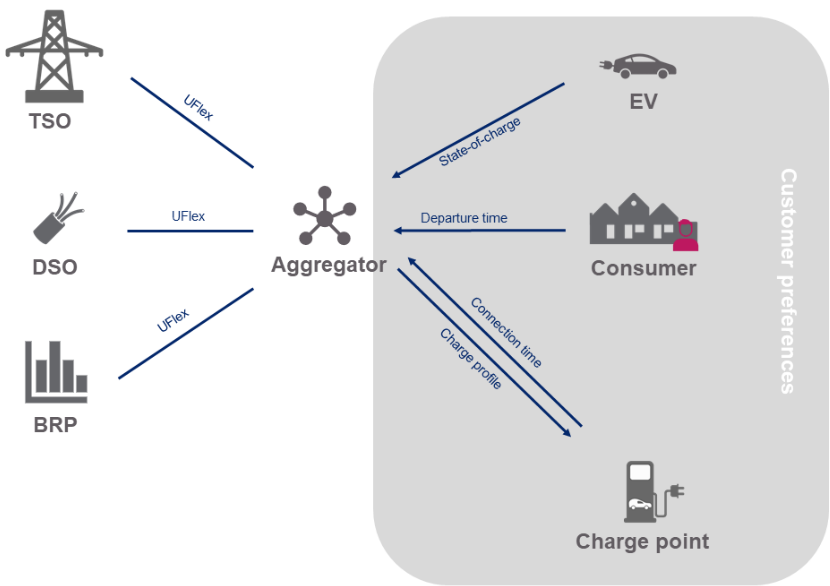

Figure 15, Roles in USEF flexibility market

2.7. Conclusions

The energy transition is an important topic on the EU agenda with ongoing discussions about sustainable energy generation, climate change and a safe environment. The current generation of electricity is almost entirely based on fossil power generation, although the percentage of renewable generation is growing. In the Netherlands renewable generation is mainly based on PV panels and wind turbines. RES is an intermittent form of generation which depends on weather conditions and therefore leads to a power system with a lower predictability and a higher volatility in electricity prices [28]. Balancing power is almost entirely based on natural gas fueled power plants. RES has very low marginal costs and be therefore first in the merit order, outcompeting fossil power plants [32] [33]. Therefore, the capacity utilization rates of fossil fueled generators has the potential to drop and this could lead to higher balancing power prices. Consequently, leading to a growing need for new control options on the demand-side of electricity.

With the electrification of household appliances, the DSOs are facing increasing pressure on the electricity network. Especially a high adoption of EVs can lead to a problem for the DSOs while they cause a high peak load in the LV network. In the conventional methods of network planning these high loads are not incorporated therefore, congestion is expected. The current solution is reinforcement of the network capacity, which has a high reliability factor but is expensive. Therefore, DSOs are searching for ways to use the current network more efficiently without lowering the reliability.

The number of BEVs is growing exponentially in the Netherlands. The current EV market design knows five market players: the CSO, Clearinghouse, MSP, OEM and EMS. The EV market is interrelated with the energy market through the DSO and energy supplier. At this moment the default method of charging is uncontrolled both for private as for public charging. Research has found that, with a 100% adoption of EVs, there will be an additional peak load of 42% and an increase of electricity usage of 22% with uncontrolled charging. This leads to an increase for grid and generation capacity. To make efficient use of the both flexibility in the charging schedule is needed.

The BRP, TSO and DSO can have potential benefits from using flexibility of EVs. The BRP can adjust their position with flexibility on the demand side close to real-time which will lower the amount of unbalance in their portfolio. This eventually leads to lower electricity prices for the consumers. The TSO can use flexibility for balance power. When the system is in unbalance the TSO can real-time adjust the charging schemas of the EV to readjust the system to 50 hz. At last, the DSO can have a benefit of EVs by spreading the load profiles to avoid congestion on the low voltage network. There is a difference in characteristics between the parties who can have benefits of flexibility. The BRP and TSO can make use of flexibility on a national level while the DSO can only make use of flexibility in the capillaries of the network.

There are four market mechanisms which are most mentioned in the literature and/ or researched by market parties for flexibility on the demand side. These are price-based mechanisms, variable connection capacity, direct control and the flexibility market. All these solutions have different characteristics. The price-based mechanism and flexibility market are seen as explicit flexibility mechanisms and price-based and variable capacity as implicit demand flexibility. These four mechanisms will be compared in a simulation to understand the effect on the electricity network.

3. List of aspects

To be able to propose a system solution for flexibility, a comparison on the different market mechanisms needs to be executed. This comparison is set up by using the Smart Grid Architecture Model (SGAM) [59]. The SGAM is developed to support the design of smart grid use cases, like the disclosure of flexibility. It consists of five layers: the business layer, function layer, information layer, communication layer, and component layer - see Figure 16. There are aspects appointed to all the layers of the SGAM. The link between the model and the aspects will be described in the next section. For some aspects it is needed to make a simulation to be able to make the comparison, for others literature or expert opinions are used. The results of the comparison can be found in Table 12.

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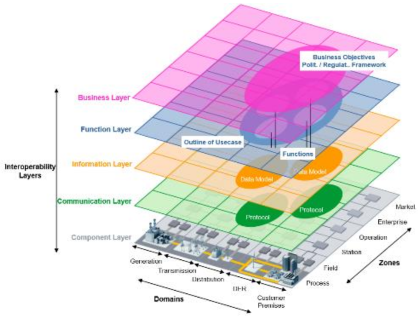

Figure 16, SGAM framework developed by the smart grid innovation group to support the design of smart grid use cases [59].

The **business layer** refers to the organizations, roles and responsibilities for the exchange of information between actors needed in smart grids. The first aspect that is related to this layer is the *number of different players* in the market mechanism. The higher the number of players the more interaction and coordination is needed in the exchange of information therefore a comparison on the number of players is interesting for the system design. Important in the system design is which role in the market mechanism is leading, while it shows the difference in responsibilities and the dependence between roles in the mechanism. Therefore, the aspect *leading role* is added. The last aspect that refers to the business layer is *nature of transactions*. In the mechanisms a different form or cooperation between roles is present. The aspect *nature of transactions*, refers to the relation between the roles involved and can be horizontal, hybrid or hierarchical [11]. If a single deciding role is involved, this naturally refers to a hierarchical nature. The central role will make decision for the end-user. When two or more roles are involved there are two options: hybrid or horizontal. Horizontal refers to a situation where all roles have equal influence on the management of flexibility. When the market mechanism has hybrid transactions the roles involved do not have equal influence, one role can be appointed to manage flexibility on behalf of others. This aspect gives an indication how alignment is executed. The more parties that are involved with a difference of interest, the harder coordination becomes. The BRP and DSO can experience a difference of interest when prices are low on a congestion moment in the network, which makes this aspect useful to describe.

The **function layer** refers to the functions and services that are needed for a smart grid. The function of the flexibility mechanism is solving congestion for the DSO and providing balancing services and portfolio optimization for BRP and TSO. Therefore, the aspects that are used for this layer are the *ability to resolve congestion* on the transformer for the DSO and *degree of free competition* in the market. The *ability to resolve congestion* is measured by looking in the simulation at the amount of overload after implementing a market mechanism. The higher the overload, the lower the ability to resolve congestion. In addition to this the aspect *level of reliability* is evaluated. This aspect refers to the degree of reliability for the DSO to resolve the overload. A low level refers to a low reliability and therewith a high uncertainty if the congestion is managed and a high level refers to a certain solution for overload control. The *degree of free competition* in the market is measured by the level of interference in the mechanism by the DSO. The DSO is, as described in section 2.5, a monopolist in the market. The aspect *degree of free competition* will look at the influence of the DSO on the competition in the market. Because the flexibility market mechanism can have an influence on the free competition in the market the actions related to flexibility executed by the DSO are strongly regulated [11]. The services in the flexibility mechanism are related to EVs and therewith the consumer. Therefore, the consumer is needs to be willing to provide flexibility. This leads to the last aspect which is *user involvement*. *User involveme*nt is interpreted as the level of influence of the consumer on the flexibility mechanism. The higher the level the more a user can put in its preferences. The last aspect to compare the mechanisms on the services that they offer is *cost-effectiveness*. *Cost-effectiveness* says something about the price of charging and is measured based on the average charging costs based on the spot market prices during the moment of charging. The lower the price accomplished the cheaper the charging price will be for the customer.

The **information layer** describes the exchange of information that is used between functions, services and components. In the flexibility mechanisms, transactions of information between functions can be executed with several interfaces and protocols. The information exchange need to be reliable to be able to implement flexibility as alternative for grid reinforcement. Research has found that it is very challenging to achieve secure and reliable power generation, in an economical manner, with the use of consumption functionalities and services [60]. The market mechanisms have a certain reliance on ICT to accomplish the mechanism to work. Therefore, the aspect that is used is the *degree of information transfer*. If a lot of information needs to be transferred, the reliance on ICT is high, which makes the system more expensive. This is measured by an estimation of experts.

The **communication layer** refers to the mechanism to exchange information. In the flexibility mechanisms, transactions of information between functions can be executed in different response and execution times. Therefore, the aspect that is used is *mode of communication*. The aspect analyses the timing of communication needed. This can be static in the form of a contract which is established for a fixed period. Day-ahead (DA) which refers to communication that is done one day before the delivery moment or real-time (RT) which indicates that response and execution are at the same moment. The outcome of this aspect gives an indication on the level of reliance on communication. If static communication is sufficient there is a low dependence, if real-time communication is needed the dependence is high.

The **component layer** describes the physical distribution of all components in the mechanisms. This includes the actors, hardware and software needed to execute the mechanism. The flexibility market mechanisms all have a different level of development. Therefore, the aspect that is used is *technology readiness*. This aspect looks at the Technology Readiness Level (TRL) to indicate the maturity of a mechanism. The TRL is developed by Nasa to measure the maturity level of a certain technology for being deployed in space. Currently, it is transformed to an official innovation policy tool for the EU [61]. A low TRL indicates that the mechanism still needs a lot of development before it can be implemented. At the highest level, TRL 9, the mechanism is operational - see Figure 17.

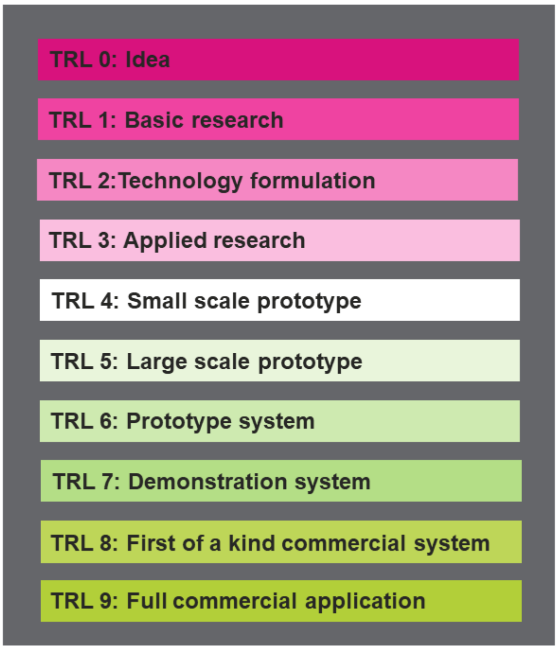

Figure 17, Technology readiness levels implemented by the European union to indicate the maturity level of technologies.

4. Simulation

In this chapter, a description about the choice for an agent-based simulation will be given. This is followed by the explanation of the Sparkcity model in section 4.2. This starts with an explanation of the method of modelling of the electricity network in section 4.2.1, followed by the household characteristics in section 4.2.2. The driving behavior is discussed in section 4.2.3 and electricity market in section 4.2.4. Added to this model in this PDeng are the market mechanisms, the method of implementation in the simulation is explained in section 4.2.5. This chapter will end with an elaboration on the scenarios tested in the simulation and a description of the sensitivity analyses that are used to assess the uncertainty of the output parameters to the uncertainty of the input parameters.

4.1. Agent-based modeling

This section will give the substantiation of working with an agent-based model. In section 1.3, a causal loop diagram is presented about the developments in the energy transition in relation to the developments in the mobility sector. Concluded is that EVs can be a problem for the energy system while they increase the need for flexibility supply. At the same time, they can be a potential solution for this problem since they could deliver flexibility to the electricity system. The causal loop diagram portrays the theoretical influences of the energy transition to the EV sector. However, what the consequences of the use of flexibility of EVs are in relation to different market mechanisms on the electricity network, cannot be concluded.

There are different possibilities for modeling the developments in the energy transition. Equilibrium and optimization-based models are the standard approach because they are relatively detailed and tested [62] [63]. However, [63] has found five shortcomings to this type of modeling:

1. They have a normative and optimization-based nature.
2. The models assume that agents will behave fully rationale.
3. They cannot cope with mutual influences between agents
4. They cannot support different solutions.
5. They do not support agent heterogeneity.

The lack of a causal relationship with human behavior, its diversity and multi-agent interactions make that these models only give a partial representation of real-life. In agent-based modelling it becomes possible to give a description of how agents interact and behave, which results in an evolution from optimization to simulation, where it is possible for analysts to work with “what if” approaches. This option makes it probable to model statistic substantiated driving behavior in relation to charging on spot market prices and combine this with the constraints of the electricity network. The combination of all influences related to these three topics make it a complex system which cannot be imagined without assistance of a computing model [62].

Agent-based modelling can represent actors and technology in a detailed and heterogeneous way. Agent-based models are developed in a bottom-up manner, which makes it easier to relate the assumption to real-life situations. Assumptions need to be configurable and the model should cover interactions between different levels in society like: global, national, local and individual levels [62]. Especially this last option is important when looking at market mechanisms for smart charging because of the different forces between international level (balancing) of the TSO, national (portfolio management and spot market prices) and local level (congestion management and households).

4.2. Structure of Sparkcity

Hoekstra and Hogeveen [62] [64] have designed an agent-based model called SparkCity. SparkCity is a virtual model for the adoption and impact of EVs in real neighborhoods. This model

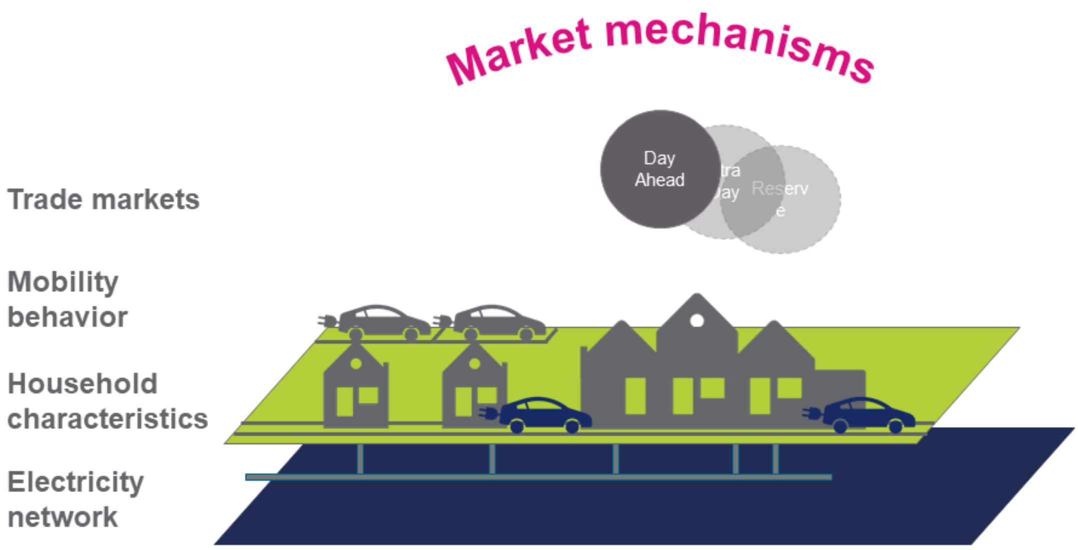

Figure 18, Representation of the implemented modules in Sparkcity is used as the basis of the simulation of market mechanisms for smart charging. SparkCity contains the following modules: local electricity network, household characteristics including energy demand and driving and charging behavior. This model has been extended by Lelyveld in 2017 [65] with a module of the electricity spot market in 2030. Added in this PDeng to this model are the different smart charging market mechanisms - see Figure 18. Due to limited time and the complexity of the electricity market, the simulation of the smart charging market mechanisms is focused on the forces of the national (spot market, day-ahead) and local level (local congestion). A summary of all basic characteristics of the simulated neighborhood can be found in Table 11.

4.2.1. Electricity network

This simulation is based on real network data of Enexis. It contains the location and capacity of the transformers and cables, and the number of households connected to the both. The transformer in the neighborhood is 630-kVA and has five outgoing cables. Spread over four cables there are 205 households connected. Two of these cables have a fuse with the maximum value of 145 A and two have a fuse with the maximum capacity of 220 A. One of these latter cables has 112 households connected which are all apartments. The fifth cable is connected to a big high school with a fuse with a maximum capacity of 260 A.

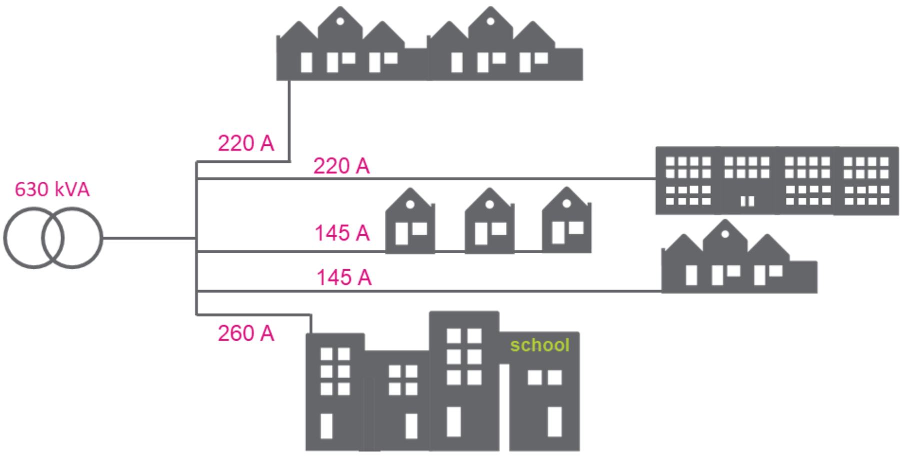

Figure 19, Representation of the electricity network in de Vliert in ‘s-Hertogenbosch.

A few assumptions are made in the simulation compared to the real-life situation. Four out of the five cables are included in the model. The cable to which the high school is connected is not taken into consideration while the electricity consumption of this high school is unknown. Because of this, the maximum capacity of the transformer is large compared to the number of connected households. In an average neighborhood with 205 households a 400-kVA transformer would be more frequently used. To set the threshold of the transformer, a power factor of 0.85 $(\cos\theta)$ is considered in the simulation. This power factor is based on an average power factor used in the market. A power factor represents the relationship between real power and apparent power in the electricity network. In the simulation, this power factor is taken on the transformer and not simulated per transaction.

This means that the maximum threshold of the 630-kVA transformer is 535 kW – see equation I. The threshold of 400-kVA is 340 kW – see equation II:

$$Apparent\ \times Power\ factor = Real\ power$$

$$630\ kVA\ \times 0.85 = 535{,}5\ kW \tag{I}$$

$$400\ kVA\ \times 0.85 = 340\ kW \tag{II}$$

4.2.2. Household characteristics and energy demand

The neighborhood which is simulated is “de Vliert” in ‘s-Hertogenbosch. Reason to choose for this neighborhood is that it has a diverse type of households and parking options. In this neighborhood both apartments (117), terraced houses (63), corner houses (19) and detached houses (6) are present. The detached houses and corner houses own a private parking lot.

Although many households have a smart meter in the Netherlands, the data cannot be used for simulation purposes because of privacy issues. Therefore, a calculation is made based on historical electricity demand of residents in the Netherlands [66], to simulate the electricity demand per household. The calculation is based on current household appliances. The additional demand which arises through the EV will be calculated based on mobility needs - see section 4.2.3. Consumers have a dissimilar electricity demand at different moments during the day. The demand for electricity depends on the individual activities of consumers in the household, the temperature and day cycle. Although the profiles of electricity demand are unique per household, for large numbers of consumers, individual peak demands are evened out because of random consumer behavior [38]. This means that the coincidence factor remains the same, based on load demand samples of 70 consumers or more. Therefore, in this simulation the aggregated electricity profiles are used.

As described in section 4.1, the simulation is a bottom-up approach. Therefore, a translation needs to be made from an aggregated load profile of all consumers to individual load profiles for individual households, known as agents in the simulation. The method used is based on the standard household profile multiplicated with a factor depending on the household type (apartment 0.6, terraced house 0.9, corner house 1.1 and detached house 1.4) and a random multiplication factor per quarter between 0.5 and 1.5. This last factor is used to represent the random use of an individual household. This results in electricity profiles per household type as can be seen in Figure 20. These profiles are not adjusted to weekend demand or seasonal differences. While these differences could have an influence on the total load on the transformer this is subject for further research.

In the simulation only EVs are considered as flexible appliance. Other flexible appliances like PV-panels or electric heating could have a different effect on the market mechanisms and could therewith make it hard to conclude what the effect is of the market mechanisms on EVs.

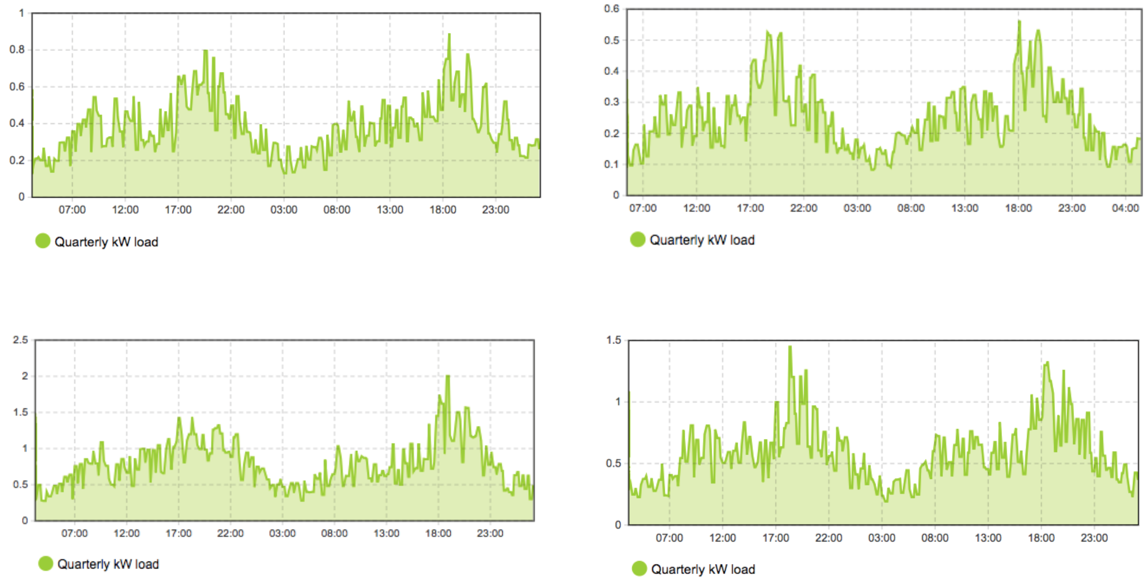

Figure 20, Electricity profiles of household types in the simulation in order: corner house, apartment, detached house and terraced house.

4.2.3. Driving behavior and charging demand

The neighborhood has different types of parking possibilities. The detached houses and corner houses have private parking options. All other households make use of public parking areas. Since, the real number of cars in the neighborhood is unknown, an assumption is made that 80% of the apartments, 80% of the terraced houses and that 100% of all corner houses and detached houses own a car. This lead to an average of 165 electric cars in the neighborhood. Consequently, there are households who do not own an EV and there are no households who own more than one EV. Reason for this is that household with two cars, use this second car differently compared to a first car which leads to different charging behavior. Currently there is little statistical charging data available because of the low adoption of EVs. To that end, the charging behavior is based on the mobility database OVin in which departure times, duration and distance of Dutch citizens are collected [67]. Mobility behavior and charging needs can be characterized as stochastic which means that traffic flows vary by the hour of the day, weekday, weekend, commute reasons and destination [68]. The battery capacity of all EVs in the neighborhood differ from 30 to 100 kWh. This is based on the expectation that battery sizes will continue to grow [69]. Current battery sizes are 22 kWh of the BMW i3 until 90 kWh of the Tesla model S. The fuel efficiency taken for all EVs in the model is 0.2 kWh/km.

The charging demand differs per individual and every agent is therefore modeled with its own personal mobility behavior. Four types of trips are simulated: work related, day trips, evening trips and weekend trips. All these trips have different characteristics which can be found in appendix B. Within the boundaries of the trip characteristics, the trips are randomized per agent. This mobility behavior results in connection times and amount of kWh to charge, portrayed in Figure 21. This figure shows that most EVs connect between 16:00 and 20:00 and few EVs charge between 02:00 and 10:00 which can also be seen in Figure 22. This can be explained by the residential nature of the neighborhood. Figure 21 also shows that most EVs charge up to 20 kWh, and only few charge more than 50 kWh. Next to this it shows the difference between connection moments of the type of trips: most EVs are connected between 10:00 in the morning and 2:00 in the evening. Work trips are the most common trip, of the total trips of 1212 in the figure, half are work related.

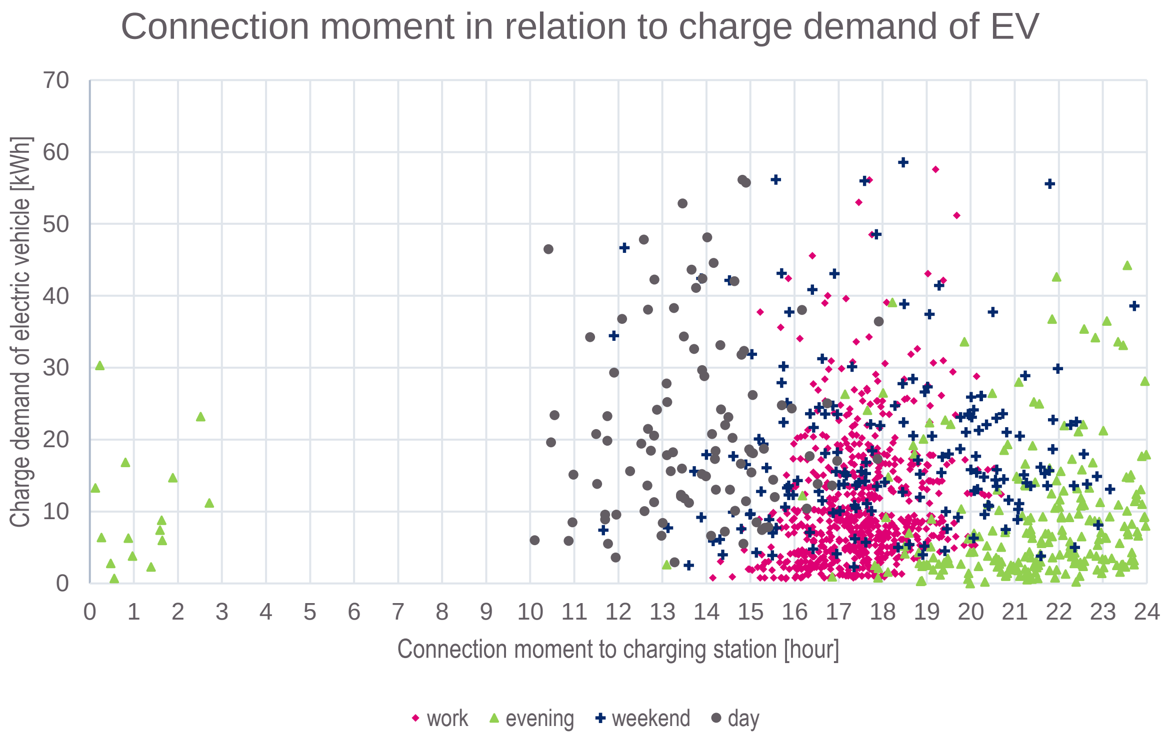

Figure 21, Plug-in time of EV drivers in the neighborhood compared to the demand of the EV in kWh based on 1212 EVs being connected in two weeks.

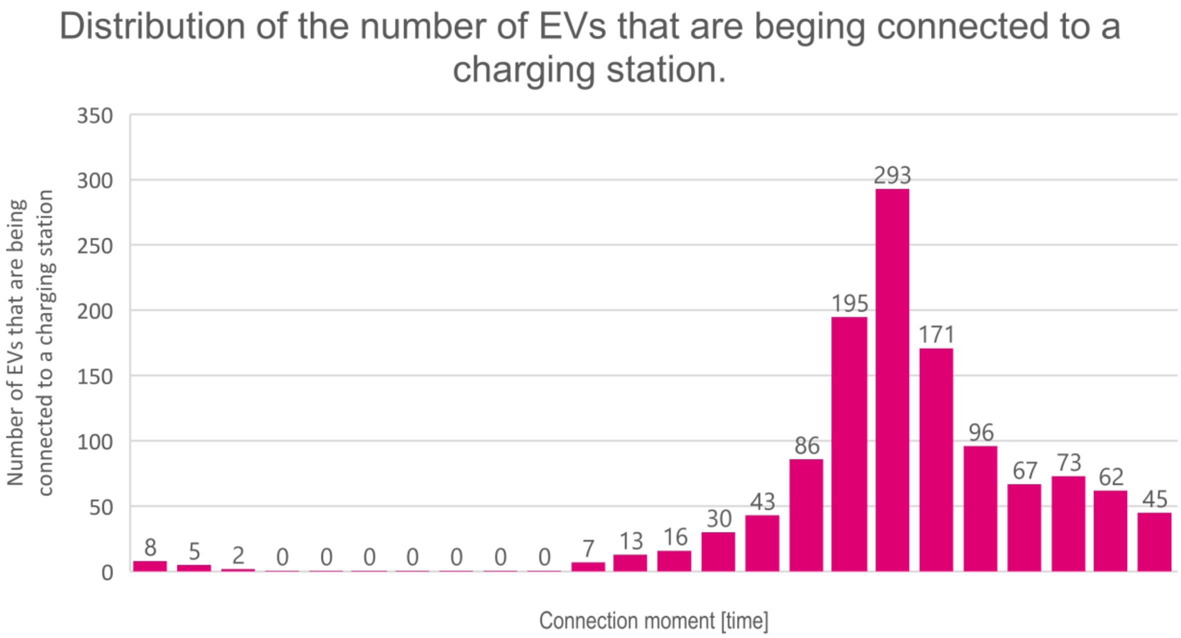

Figure 22, The amount of EVs in the neighborhood connecting their EV at a certain hour of the day. Based on 1212 EVs being connected in two weeks.

Connection times and load

In the simulation agents can charge privately and publicly. Private charging has a maximum load of 11 kW. Since households have a maximum connection capacity of 17 kW (based on a 3×25 A. connection) on which both the EV as other household appliances are connected. In the simulation the assumption is made that owners of an EV with a private parking lot always plug-in their EV after returning home. Public charging is only for agents who do not own a parking lot and therefore need to charge at public ground. Connecting the EV at a public charging station is based on the state of charge (SoC) of the EV, the SoC indicates if a EV driver will or will not plug-in its EV - see Table 3. When plugged-in the charge session has a maximum load of 22 kW.

Table 3, Opportunity that the EV driver will plug-in its EV

SoC	<100 km	100 – 200 km	200+
P (charging)	95%	60%	30%

All these assumptions result in a load profile that can be seen in Figure 23. The first two load profiles are the weekend and show a significantly lower peak demand than the third profile which is a Monday. The difference in peak load is about 100 kW that can be explained by the lower mobility need on weekend days compared to week days. Other conclusions that can be made from this figure are that when charging is not controlled there is little load demand during the night, and that the peak load of EVs are as expected simultaneously with the peak load of households.

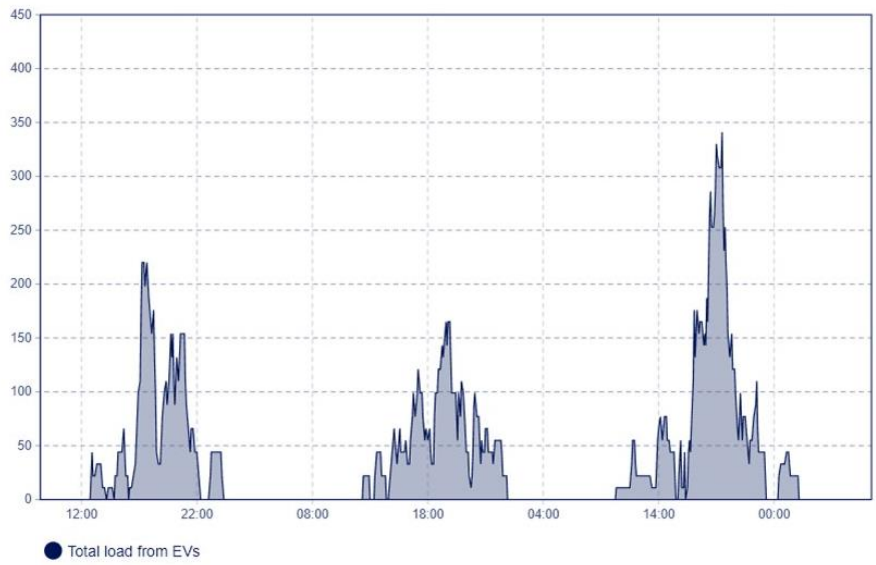

Figure 23, Uncontrolled load profile on transformer based on 165 EVs

4.2.4. Spot market

A spot market of the year 2030 is simulated in the model which is created by [65]. The simulated spot market assumes that all energy generation and consumption of the Netherlands is traded on this spot market. International trade is not considered. Next to this, all fossil generators (coal, gas, nuclear) are continuously available during the year for a fixed price. The spot market in the simulation is based on the amount and type of expected installed capacity of ECN[5] for 2030 will be met - the figures can be found in appendix C. This simulation does not concentrate on the correct prediction of future electricity prices, trends in weather, storage, conversion and other technologies but is only used as a basis for a cost optimization for smart charging.

In the electricity market module, a fitted supply curve is used to model the supply curve in 2030. This method is based on the correlation between spot market prices and hourly average electricity demand [65]. An analysis is made of the DA market in the Netherlands (EPEX) of 2016 to establish the electricity price. The reason to choose this market is that it is the most dominant market in the Netherlands [28]. In the analysis a plot is made to indicate the slope of the merit order for all hours of 2016 - see Figure 24.

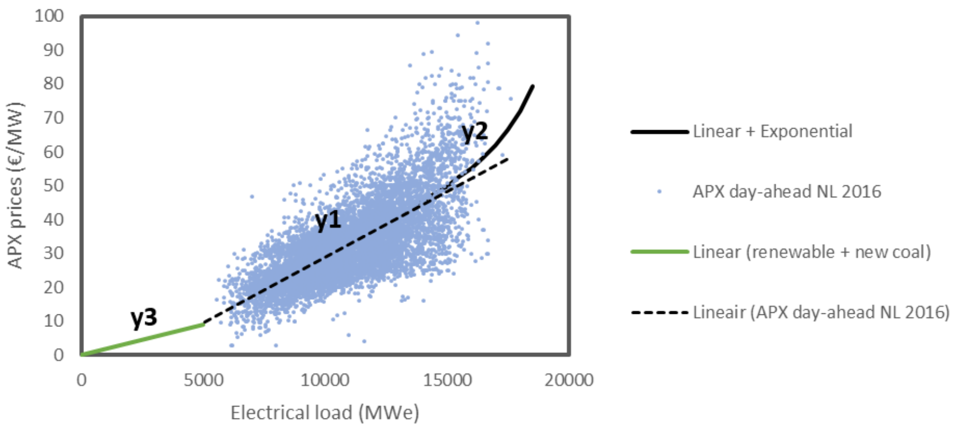

Figure 24, APX day-ahead prices fitted supply curve based on 2016 [65]

- y1 represents the fitted linear line which relates to prices of conventional generation (nuclear, new coal, CCGT and CHP) between 5000 MWe and 15000 MWe.
- y2 the exponential trend in prices from 15000 MWe that relates to older gas plants that mainly run for balancing purposes and therefore have a different price setting.
- y3 relates to renewable and coal supply.

Looking at the slope it can be said that the steepness is depending on the short-run marginal costs and the installed capacities of generators. When the slope is steeper it indicates that prices become more volatile. When more renewable generation is implemented the line will shift to the right which implies lower prices. If the demand would change this would have influence on the prices, a higher demand leads to higher prices, a lower demand for lower prices.

To predict future electricity prices an assumption need to be made about several variables. First, the amount of renewable electricity production needs to be established. In the model this is based on the renewable production in 2016 which is scaled to the expected installed capacity of 2030 and the national demand curve of the Netherlands. The assumption is made that the national demand curve of 2030 is the same as in 2016 and that only EVs cause an increase in electricity demand. To relate the local neighborhood to a national market a scaling factor is used between the number of EVs in the neighborhood to the number of cars on a national level. This means that

[5] Research organisation on sustainable energy in the Netherlands

the demand shift of EVs will directly influence the electricity price on a certain hour. Leading to an establishment of an hourly electricity price with and without EVs.

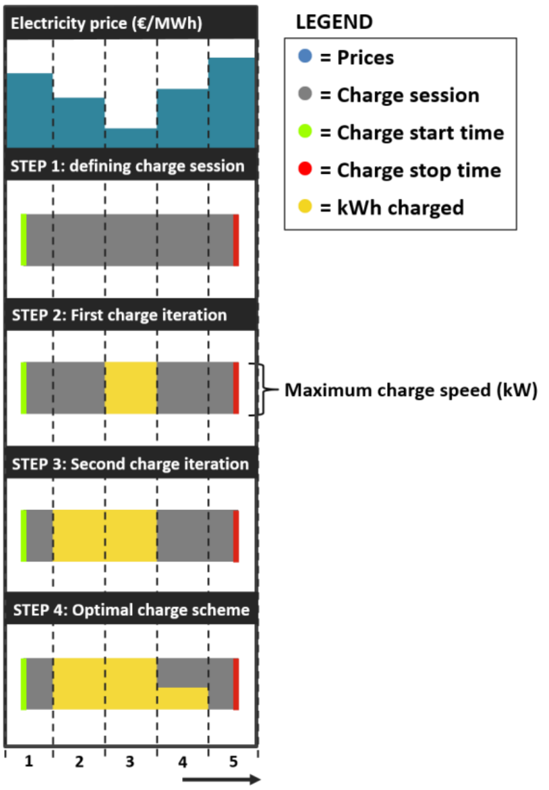

Figure 25, Example of spot market charging planning [65]

Spot market charging will directly influence the price by creating an increase in electricity demand on the spot market. Figure 25 shows an example of spot market charging. During every iteration the cheapest hour is chosen to charge the EV. The optimization of the charge schedule ends when the whole battery is charged, the car disconnects from the charging station or optimization is not possible because of the limited charging time [65]. The sport market price is adjusted depending on the load shift after every iteration. Result for the electricity market is a change in demand from expensive to cheaper hours. The shift in load is depending on two aspects. The load curve of the EVs in the neighborhood and a scaling factor which is depending on the ratio between the number of EVs in the neighborhood and the Netherlands. This relationship is stated by equation III [65].This scaling factor is calculated by relating the number of EVs in the neighborhood to the total number of cars in the Netherlands which results in equation IV. The neighborhood has 165 cars and in total the Netherlands has approximately 8 million which results in a scaling factor close to 15[4].

$$Demand\ shift = average\ load\ curve * scaling\ factor\ [65] \qquad \text{(III)}$$

$$Scaling\ factor = \frac{number\ of\ cars\ in\ NL}{number\ of\ cars\ in\ the\ neighbourhood}\ [65] \qquad \text{(IV)}$$

4.2.5. Market mechanisms

As described in section 2.6 there are various market mechanisms to unlock flexibility of EVs by the DSO. Four often mentioned mechanisms in literature and by the industry are price-based, variable connection capacity, direct control or a flexibility market [50]. In the next section the way of implementation in the simulation will be described. The simulation will give an identical environment which makes it possible to compare the effects on the transformer load of the different market mechanisms.

Price-based mechanism

For DSO purposes the CPP pricing is implemented in the simulation. DSOs are not allowed to discriminate between end-users which makes it impossible to implement a dynamic price signal differentiating on location and time in the current regulation. Hence, a static price profile is applied in the simulation. For the design of the tariff scheme the average household load profile of [66] is used. Based on this profile the tariff differs depending on the expected aggregated load on the network. The new differentiated prices are based on the current capacity tariff which was in 2018: €224,27. Based on an average household use of 3400 kWh per year this is equivalent to: €0,06 per kWh. In Table 4 the tariff scheme can be found that is implemented in the simulation as CPP.

Table 4, Critical peak prices in simulation

From		To	Price per kWh
00:00	-	06:00	€0,01
06:00	-	16:00	€0,06
16:00	-	21:00	€0,12
21:00	-	00:00	€0,07

Variable connection capacity

Variable connection capacity is a mechanism that is established in the contract with the consumer. In the case of public charging this contract is concluded with the CSO, in case of private charging with the consumer. There are different possibilities that need to be arranged in the contract. For example, the time that the peak starts and the amount of power that can be used in the peak by flexible loads. This mechanism is based on a capacity restriction; hence the price is static. In the simulation a fixed national profile is implemented, this is a profile that has a non-discriminator character which makes it possible to implement with current regulations. The static profile is implemented on the connections, but in the simulation only the flexible loads will react to the static profile. Reason for this is that some EV drivers charge at home, the charging station is therefore connected behind the connection of the DSO to the household. Implementation of a variable connection capacity with a low capacity during the restriction period is not feasible for the household while this would mean that during the restriction period the household cannot use non-flexible appliances. During the restriction period, between 17:00 and 20:00 three types of load restrictions will be implemented to show the different effects. These restrictions are set on a maximum of 0 kW, 4 kW and 10 kW of power demand for EVs.

Direct control

In the simulation a direct control mechanism is implemented on the charging stations of the EVs, all other appliances are not considered for load adjustments. Reason for this is that the electricity profile is aggregated per household and it is not known which appliance is using electricity. When overload is detected by the DSO the system will send a signal to the charging station connected to that cable or transformer. When there is overload on a cable all charging stations will lower their load evenly, no difference is made between public or private charging, although the maximum load of a public charging stations (22kW) is considerately higher than private charging stations (11kW). Reason for this is that the DSO does not want to discriminate between connections. In the simulation the household load is never adjusted if overload is detected. When overload is detected on the transformer all charging stations on the transformer will lower their load, as well when load is already adjusted because of an overload on the cable. This could mean that charging stations need to adjust their load twice, first for the overload on their cable, then for an overload on the transformer.

Flexibility market

To implement USEF in the simulation a few simplifications are made to the framework. The fundamentals of the framework are based on a free market operation. This means that the BRP and TSO can trade without constraints on the electricity and flexibility markets. In the simulation this is represented by spot market charging. The design of these schedules is following the principles which can be found in section 4.2.4. When an overload is detected (more than 100%) the DSO can obtain flexibility from the CSO, if there is still flexibility available within the preferences of the customers. This is seen as the yellow regime. The DSO will always buy all the possible flexibility on the market which can solve the congestion. When the overload cannot be resolved by buying flexibility the orange regime starts. This means that the DSO can directly control all flexible assets in the network. This is implemented in the same way as direct control, which is described in section 4.2.5 in direct control.

4.2.6. Scenarios

To compare the market mechanisms, ten scenarios of different market mechanisms are considered in the simulation. All DSO market mechanisms are tested separately even though the DSO is part of a bigger eco system while it gives more insights of the results of the DSO mechanism. This means that the first scenario for the mechanism is always modeled in combination with a flat fee. However, research has found that the highest societal value is obtained when flexibility is stacked for different parties [46]. Therefore, all market mechanisms for the DSO are combined with dynamic prices based on the spot market. The design of the spot market is described in section 4.2.4 and is used to optimize the charge profiles based on costs. This results in the scenarios as described in Table 5. To be able to make an equal comparison between the mechanisms the reaction of the EV driver is always 100%. This means that if a price incentive is applied, all the EV drivers will react to the price incentive within their mobility behavior and/or if a cost optimization is possible that all EV drivers are interested in it.

Table 5, Scenarios in simulation

DSO mechanism	**Uncontrolled charging**	**Critical Peak Pricing**	**Variable connection capacity**	**Direct control**	**USEF - Flexibility market**
Flat fee (DSO only)	Uncontrolled charging - flat fee	Critical Peak pricing - flat fee	Variable connection capacity - flat fee	Direct control - flat fee	Not possible
Combination with dynamic fees based on spot market	Uncontrolled - spot market charging	Critical Peak pricing - Spot market charging	Variable connection capacity - Spot market charging	Direct control - Spot market charging	USEF

Uncontrolled charging

- Flat fee: Both the DSO as the energy supplier do not give an incentive to the EV driver. Charging starts immediately after plugging in the EV. The electricity price is equal on every hour of the day. This scenario is similar with the current system in the Netherlands.
- Spot market charging: The DSO does not give an incentive for charging of the EV, but the energy supplier does. This means there is a cost optimization based on the prices of the spot market.

Critical Peak Pricing

- Flat fee: The DSO gives a price incentive depending on the charging time. On moments of high expected loads on the network there is a higher price than on moment of lower expected loads (based on a historical profile see section 4.2.5). The energy supplier does not give an incentive.
- Spot market charging: Both the DSO as the energy supplier give a price incentive to the EV driver. The incentive of the DSO is based on expected load on the network and the incentive of the energy supplier is based on spot market prices.

Variable connection capacity

- Flat fee: The DSO gives a capacity constraint on the connection when high loads are expected in the network. This results in a restriction period (0 kW, 4 kW or 10 kW) for charging between 17:00 and 20:00. The energy supplier does not give an incentive.
- Spot market charging: The DSO gives a capacity constraint on a connection when high loads are expected in the network resulting in the same restriction period as described before. Simultaneously the energy supplier offers dynamic energy prices. This gives an incentive to the EV driver to charge on the cheapest moments within the capacity constraint set by the DSO.

Direct control

- Flat fee: The DSO controls all charging stations actively. When an overload is detected in the network the DSO will adjust the charging speed real-time on the charging stations connected to that cable or transformer. The energy supplier does not give an incentive.
- Spot market charging: The energy supplier sends dynamic price signals, on which cost based charging is executed by the EV. When an overload is detected in the network the DSO controls all charging stations real-time by adjusting the load until the overload is solved.

USEF

- Flat fee: USEF is a framework which is based on free market competition. This framework is therefore not possible without the use of a flat fee.
- Spot market charging: USEF is based on a flexibility trade market. While this is hard to simulate it is decided that in the USEF scenario all EVs will charge on the most cost-efficient moment. If this causes an overload the DSO needs to buy all the flexibility available on the trade market to solve the congestion. If this is not possible direct control will be used to manage the overload directly.

Sensitivity analysis

The sensitivity analyses in this report study the relation between the uncertainty of the results of the mechanisms in the uncertainty in the input parameters used in the simulation. As stated earlier in this section, the assumption is that all EV drivers react on the market mechanisms implemented by the DSO and/or energy supplier. However, this is not the case in a real-life situation. Therefore, different sensitivity analyses are done to research the effect of the reaction of the EV driver to the effectiveness of the market mechanism.

The first sensitivity analysis that has been executed is the price sensitivity analysis in relation to overload. This analysis changes the behavior of the EV driver by differentiating the percentage of EV drivers that are reacting to price signals (between 0% – 100% price sensitivity). It shows the relation between the percentage of price sensitive EV drivers to the amount of overload on the transformer. This sensitivity analysis shows how solid the market mechanism works for the DSO if price sensitivity is reduced. The analysis is only performed on the scenarios were a price signal is send to the EV drivers, either by the DSO or energy supplier.

The second sensitivity analysis is the relation of price sensitivity to the average charging price. In this analysis different percentages of EV drivers that are reacting to price signals are implemented (between 0% – 100% price sensitivity). The analysis examines the relation of price sensitive people to the average charging price. Reason to perform this analysis, is the idea that if more EV drivers are price sensitive the lower the electricity price will be, while more demand can be shifted to the moment of high levels of supply, resulting in a lower price volatility. This sensitivity analysis is only performed in scenarios that give a price incentive.

The third and fourth sensitivity analyses are only applicable to variable connection capacity. In the analyses the threshold of the restriction period is adjusted between 0 kW and 10 kW. The third analysis relates the threshold to the average charging time. This results from the idea that if a lower threshold is implemented by the DSO the charge duration will increase.

The fourth sensitivity analysis relates the threshold of restriction period (kW) to the number of fast charging sessions and preliminary finished charging sessions. The supposition is that the lower the DSO will set the maximum power in the restriction period the higher the number of fast charging sessions and preliminary finished charging sessions.

The last two sensitivity analyses that are executed are like the third and fourth but instead of the threshold of the restriction period, the threshold of the transformer is differentiated. This sensitivity analysis only relates to the direct control scenarios. The assumption to perform these analyses are the same as the third and fourth.

5. Results

The results of the simulation are presented in this chapter. First, the qualitative results per scenario are specified. Followed by a detailed description of the results per mechanism. This is structured as follows: each section starts with a figure of the load profile of the mechanism on the transformer, followed by an elaboration on the sensitivity analyses as described in section 4.2.6 and it ends with an interpretation of the results. The structuring of the results is as depicted in Table 6.

Table 6, Scenarios tested in the simulation in order of the presentation of the results

Uncontrolled charging	**Critical Peak Pricing**	**Variable connection capacity**	**Direct control**	**USEF - Flexibility market**
1. Uncontrolled charging - flat fee	*3. Critical Peak pricing - flat fee*	*5. Variable connection capacity - flat fee*	*7. Direct control - flat fee*	
2. Uncontrolled - spot market charging	*4. Critical Peak pricing - Spot market charging*	*6. Variable connection capacity - Spot market charging*	*8. Direct control - Spot market charging*	*9. USEF*

After the results of the simulation, the evaluation of the aspects of the mechanisms will be described. This description is based on the layers of the SGAM framework which will be presented in the order of the SGAM layers as can be found in Figure 16, SGAM framework developed by the smart grid innovation group to support the design of smart grid use cases .Figure 16. The chapter ends with a conclusion and discussion of the simulation.

5.1. Qualitative results per scenario

In this section the qualitative results of the scenarios are presented. Table 12 in appendix - D shows the average of the 12 weeks per week. The runs are based on the weeks between 2nd of April (2030) until the 24th of May (2030). Reason to run more weeks of the simulation is because of the stochastic behavior which results in a difference in outcomes per week. Next to this the weather difference, especially related to sun radiation, accounts for a big difference is the prices on the spot market.

The chart in Figure 26 shows a comparison of the mechanisms on average charging costs. The colours are related to different price structures, see explanation in the figure. The figure shows that CPP with a flat fee has the highest overall prices. When looking at the pink bar it shows that SMC and a combination of direct control with SMC has the lowest prices on the spot market. The blue bar reveals that CPP with SMC has the lowest overall prices although, further research has found that this is mainly related to the prices implemented in this simulation see section 5.1.4.

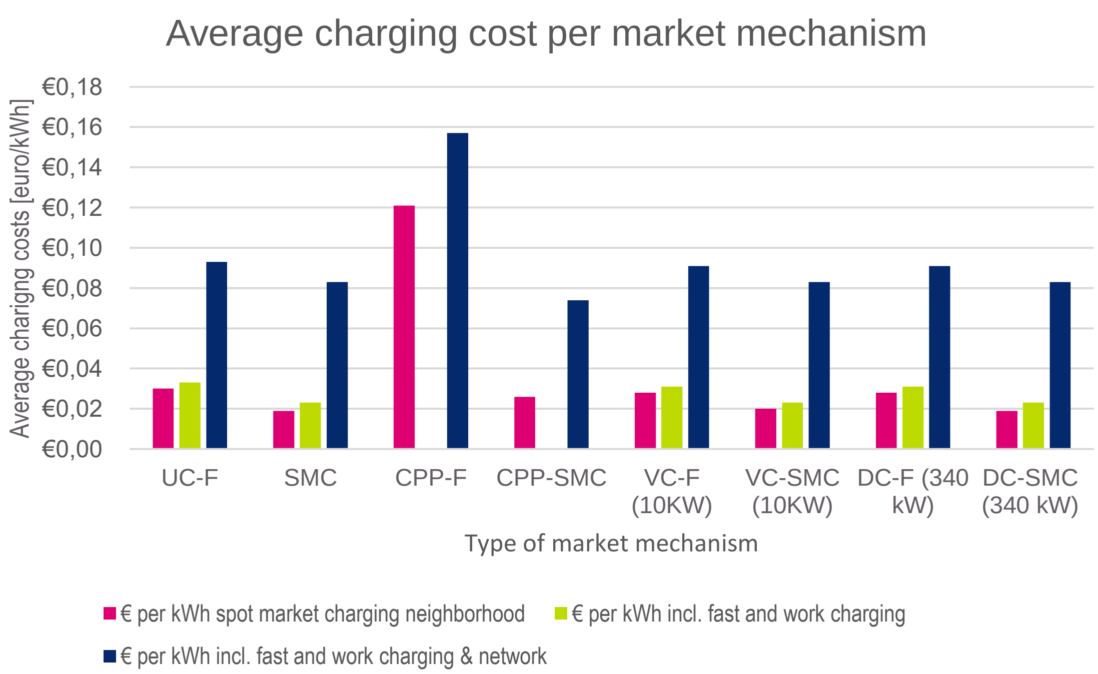

Figure 26, Comparison in the mechanisms in average charging price per mechanism. The prices portrayed in this chart are related to the simulated spot market.

Figure 27, shows the difference in the number of charging sessions per mechanism in relation to the unfinished and fast charging sessions. This chart gives a first impression how much the mechanisms is influencing the charging behavior of EV drivers. VCC with SMC has the highest amount of unfinished charging sessions which indicates that the EV is not fully charged when it is plugged-out. The level of fast charging sessions is stable, all mechanisms have approximately the same number of sessions. The total number of charging sessions is fluctuating between 614 and 632.

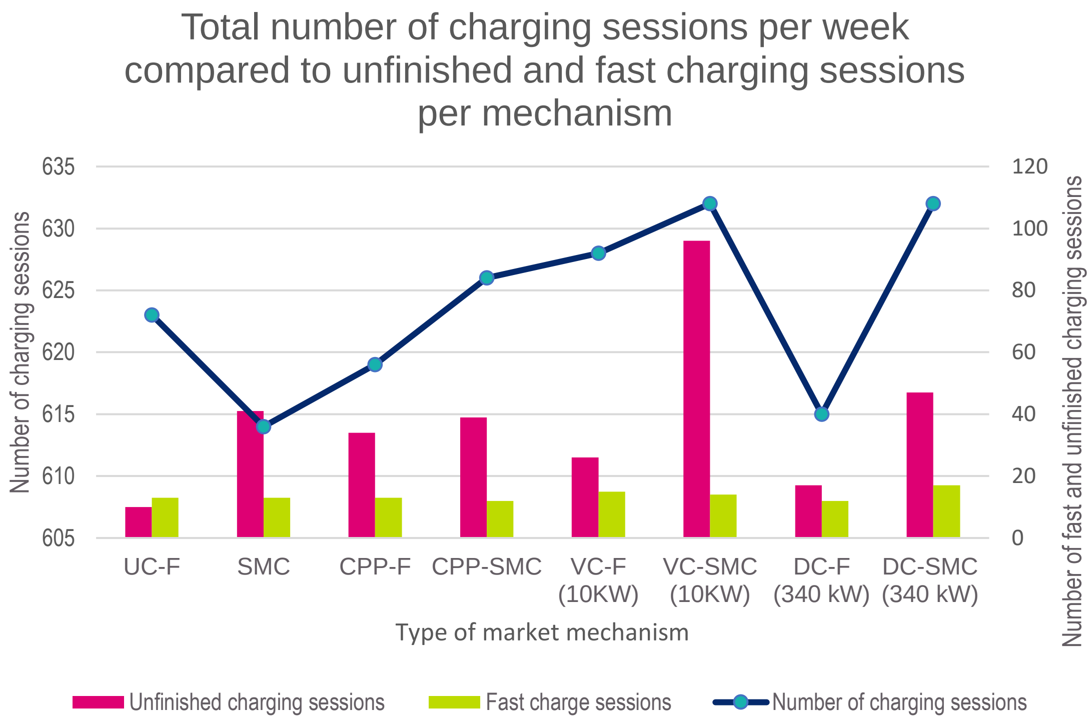

Figure 27, Comparison between the mechanisms of the total charging sessions per week to the number of unfinished charging sessions and fast charging sessions.

The mechanisms can be compared by the average charging demand. Figure 28 shows that the mechanisms with a flat fee result in the highest local charging power. Reason is that the EVs start charging immediately at the highest power possible, within the constraints of the mechanisms. The average charging time is higher with mechanisms based on prices, this is because these mechanisms will postpone the charge session until the cheapest moment. The average charging time is calculated by measuring the moment of connection of the EV until the moment of a fully charged battery.

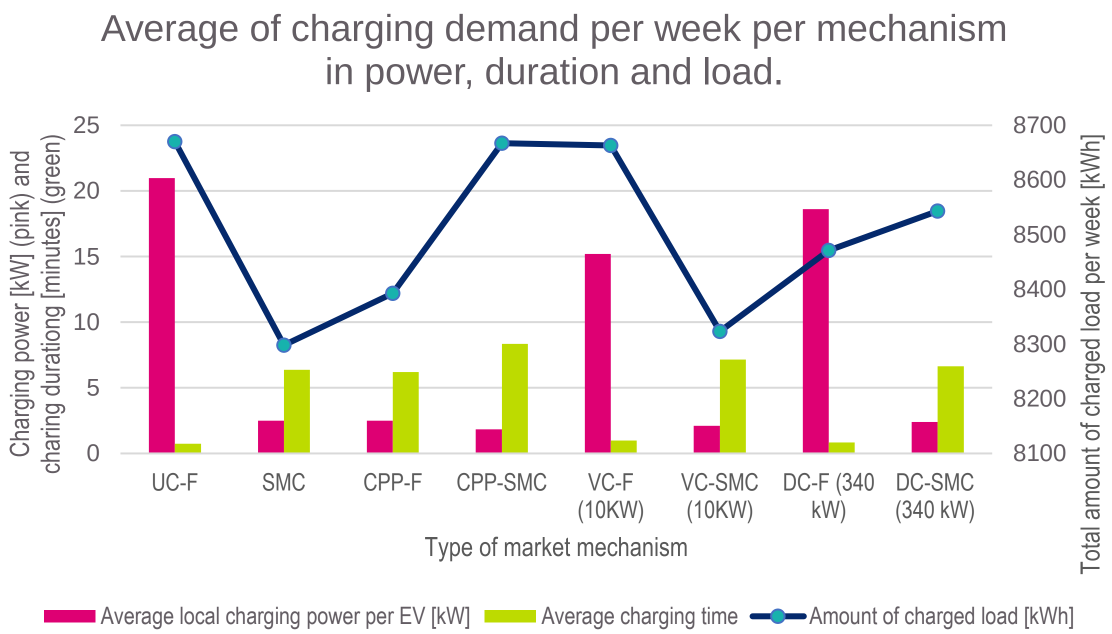

Figure 28, Comparison between the mechanism in charged load per week to charging power [kW] and charging duration [minutes]

5.1.1. Uncontrolled charging - flat fee (Base scenario)

Currently, Uncontrolled charging is the most common form of charging in the Netherlands and is therefore taken as the base scenario for this comparison. The impact of uncontrolled charging on the transformer in the neighborhood is shows in Figure 29. The figure reflects that uncontrolled charging leads to big peak loads between 16:00 and 20:00 which is simultaneous with conventual the household peak. During week days (first two days in the picture) an overload is detected between 17:00 and 19:00 on the 400-kVA transformer. This is caused by the simultaneous charging needs of the agents. The mobility behavior in the weekend results to less simultaneous behavior, hence the peak load is lower (last two days in the picture). When the 630-kVA transformer is considered, no overload is detected in this neighborhood in the portrayed week. However, the average of 12 weeks shows a 33.9-kWh overload per week with a duration of 9 minutes. The overload that is detected on a 400-kVA transformer is 542.5 kWh and the duration is 477 minutes per week.

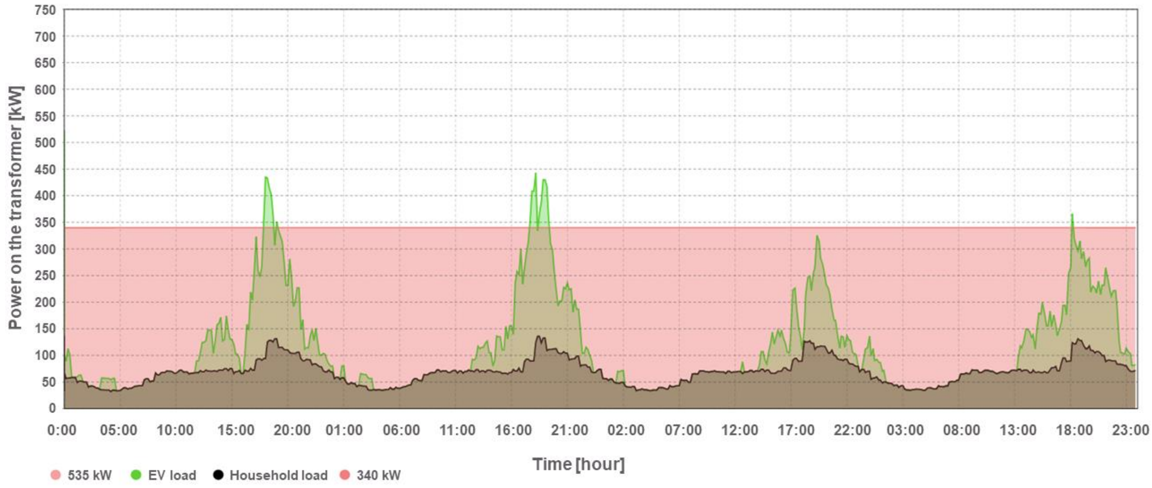

Figure 29, Uncontrolled charging effect on transformer at Thursday 21st of May until Sunday 24th of May.

The average charging time is low, a car needs to charge for 0.74 hours. The charging time is calculated by distracting the time that the EV is fully charged with the connection time. In the uncontrolled scenario the EV will always charge on full speed either 11 kW (private charging) or 22 kW (public charging). This explains the high average charging speed of almost 21 kW, see Table 12. However, the average charging price is high, a kWh costs on average €0,033. The simultaneous demand leads to higher prices on the spot market. This scenario leads to 10 unfinished charging sessions per week based on a total of 623 charging sessions. This means that EV owners have plugged-out their car before it was fully charged to make a new trip. At last, there are 13 fast charging sessions per week. Agents decide to stop for a fast charger when they can drive less than 10 km during their trip.

5.1.2. Uncontrolled charging - spot market charging

In this scenario the spot market prices are the leading variable for the planning of the charge schedules, on which the DSO has no influence. The charge schedules are adjusted to the most cost-efficient moment as is described in 4.2.4. Figure 30 shows the load profile of spot market charging on the transformer in the neighborhood. In the pictured week no overload is detected on both the 630-kVA as the 400-kVA transformer. Results of a run over three months reveals no overload for the 630-kVA transformer and 17.2 minutes per week with 9 kWh for a 400-kVA transformer – see Table 11. This market mechanism is based on a dynamic price signal which is optimized after every charge schedule. This means that there is a relation between the action (charging of the car) and reaction (price) which results in a damping effect on the variability of the aggregated load profile on the transformer.

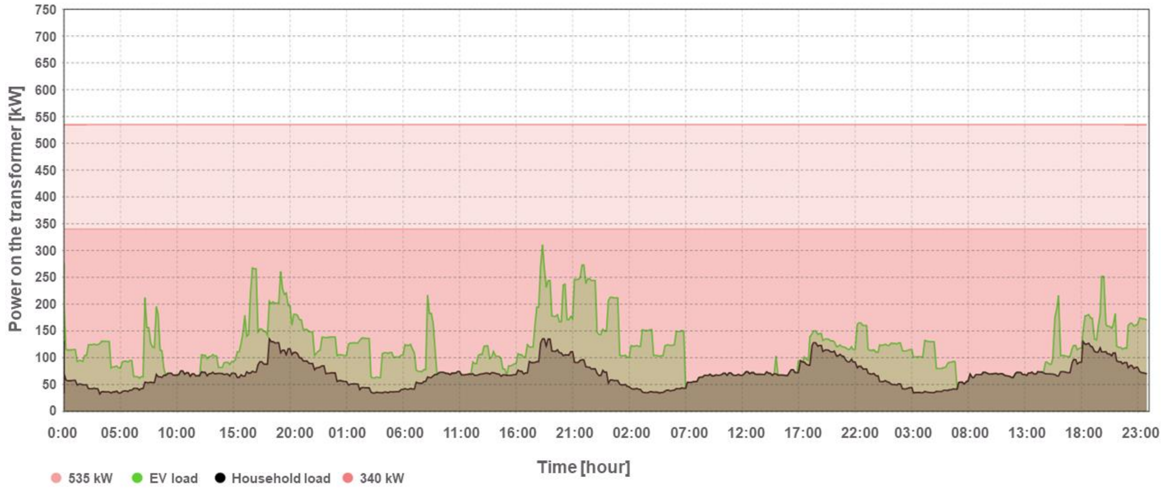

Figure 30, The load on the transformer resulting from spot market charging during at Thursday 21st of May until Sunday 24th of May.

The load profile depicted in Figure 30 is formed by assuming price sensitivity of 100%. Research does not define the level of price sensitivity of consumers; therefore, a sensitivity analysis is made on price sensitivity which can be found in Figure 31 and Figure 32. This analysis indicates that with a price sensitivity of 20% overload can be neglected regarding a 630-kVA transformer. When looking at the 400-kVA transformer, a price sensitivity of 80% is needed to avoid an overload. A price sensitivity of 50% results in 50 kWh overload spread over 100 minutes per week. From this section can be concluded that with spot market charging overload can be neglected for a 630-kVA transformer. However, 60% of EV drivers need to be price sensitive to avoid congestion on the 400-kVA transformer.

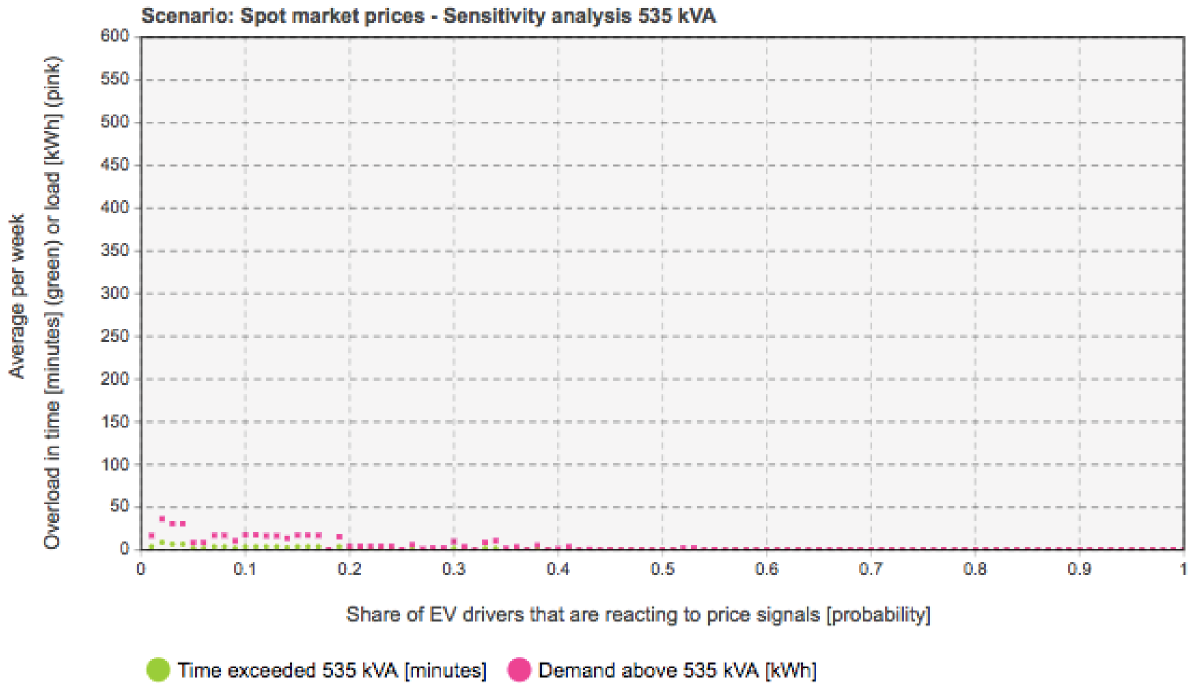

Figure 31, Percentage of EV drivers reacting to price signals related to minutes of overload on the transformer with a 535 kW threshold.

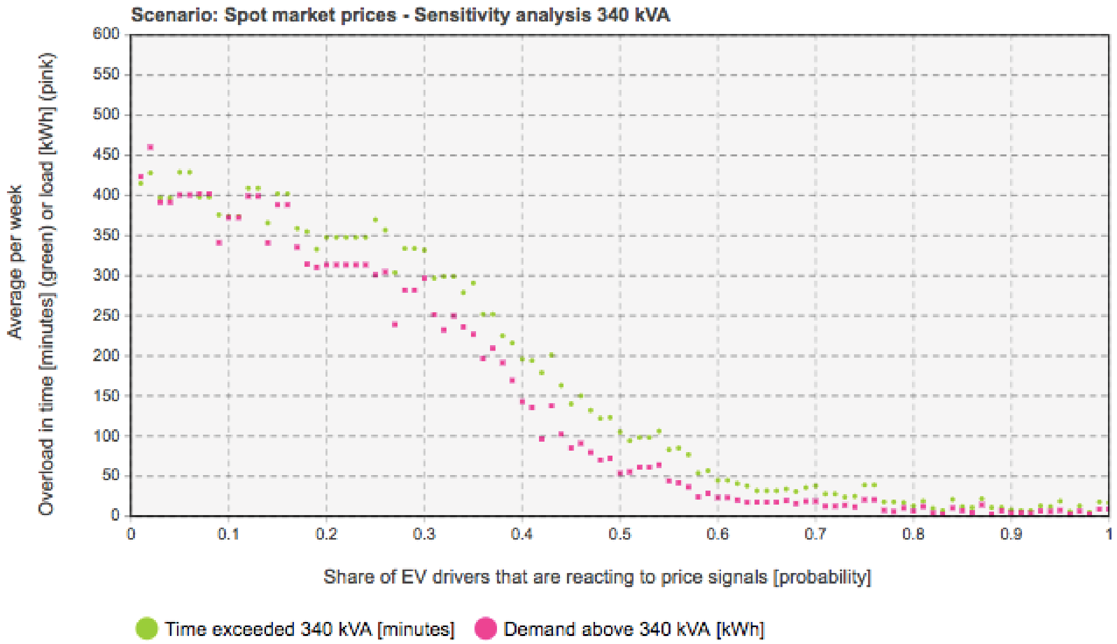

Figure 32, Percentage of EV drivers reacting to price signals related to minutes of overload on the transformer with 340 kW threshold.

The average charging session in this mechanism takes a long time: 6.37 hours. Charging does not start immediately after plugging-in, but a charge schedule is made based on the cheapest moment. While on average the prices are lower during the night than during the day many charging sessions are postponed, which makes the charging duration longer. Of the 614 charging sessions per week there are 41 unfinished, which is a bit higher than other scenarios. This results from a planning problem between agents who share a car within the household in the simulation. Next to this, less kWh are charged compared to uncontrolled charging although the mobility needs are the same. The number of fast charging sessions show no difference between the two scenarios which indicates that although not all batteries are fully charged when plugging-out, the agent is still able to fulfill its mobility need.

5.1.3. Critical Peak Pricing vs Flat fee

In this scenario critical peak prices are implemented – see section 4.2.5. The load profile that is related to this mechanism can be found in Figure 33. The static price signals send by the DSO, results in a daily overload on the transformer. This is due to the level of flexibility and price sensitivity of the agents, while all agents will respond to cheapest moment within their possibilities of their parking time. Since all agents are postponing their charging session for the cheapest moment, this leads to a high simultaneity in charging when this moment arrives. Triggering the cars to charge at their maximum power which results in enormous overload on the transformer.

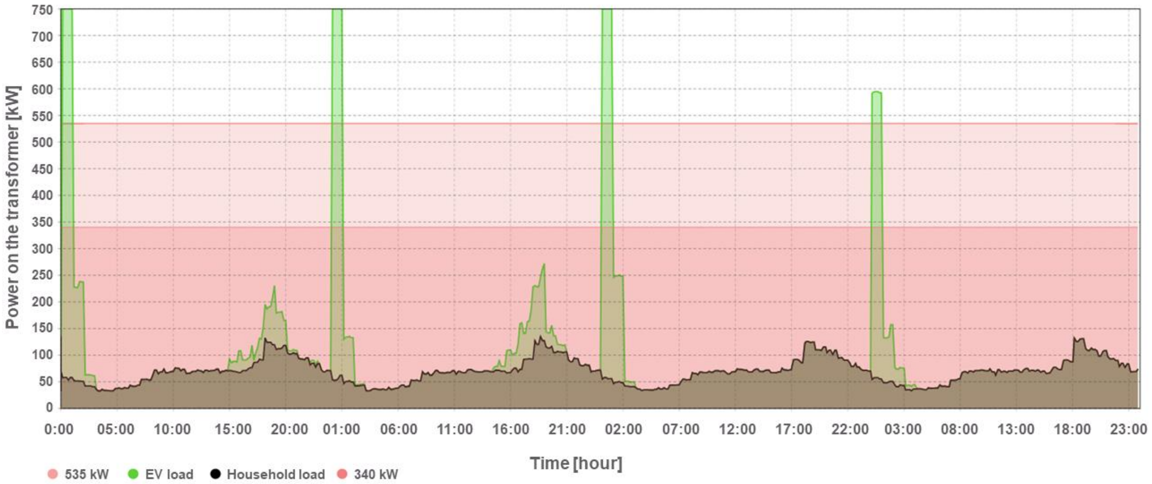

Figure 33, Load on the transformer with a critical peak price mechanism and a price sensitivity of 100% at Thursday 21st of May until Sunday 24th of May.

Figure 34 and Figure 35 show the price sensitivity analysis related to this mechanism. A price sensitivity of 40% leads to the lowest amount of congestion on the transformer. Although, this is still around 100 minutes and 900 kWh per week on the 630-kVA transformer and 750 minutes and 1500 kWh per week on the 400-kVA transformer which is higher than the other mechanisms. Next to this the congestion is increasing when the price sensitivity of the agents increases (from 45 – 100%), which indicates that this mechanism can magnify the problem for the DSO.

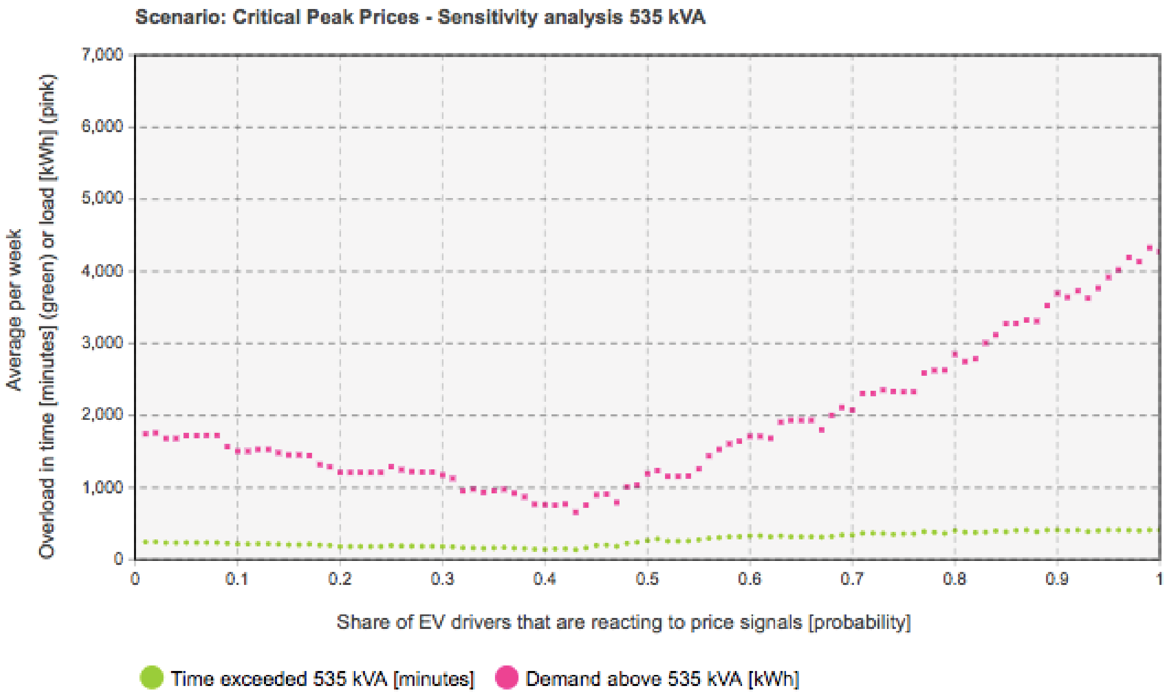

Figure 34, Sensitivity analysis of price sensitivity of EV drivers in comparison with the overload on the transformer with a critical peak price mechanism on a transformer with a treshold of 535 kW.

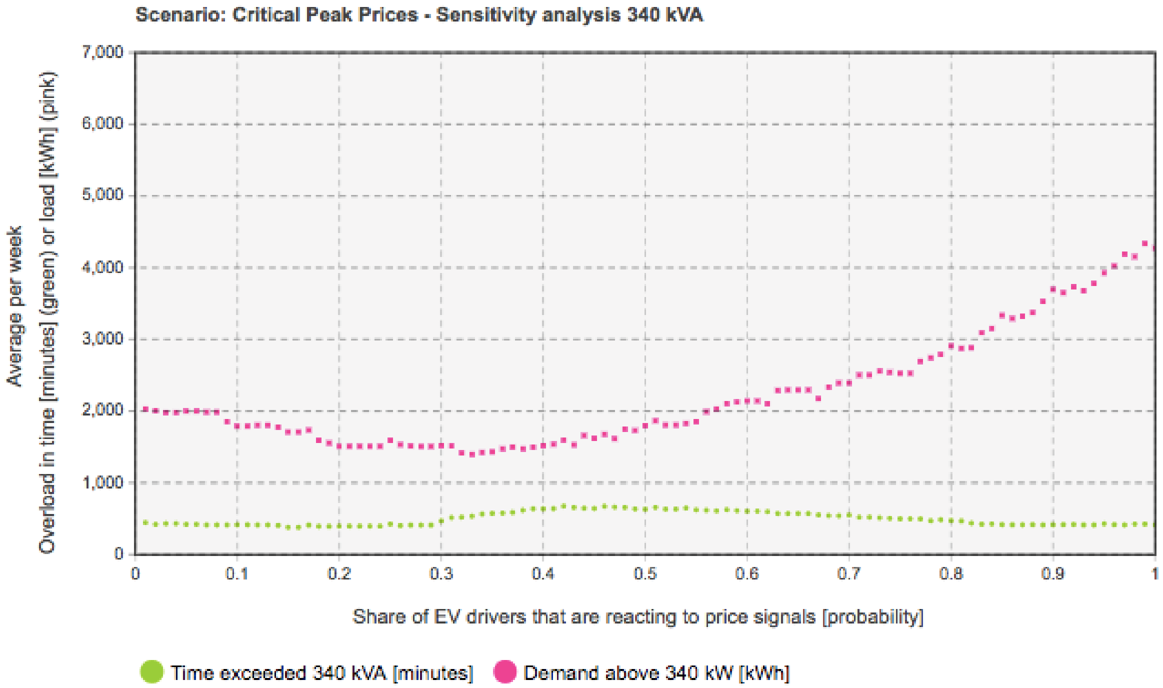

Figure 35, Sensitivity analysis of price sensitivity of EV drivers in comparison with the overload on the transformer with a critical peak price mechanism on a transformer with a threshold of 340 kW.

In Figure 36, the sensitivity analysis is portrayed which shows the effect of CPP with a static price profile to the spot market prices. The prices in this figure are calculated by taking the CPP in combination with the spot market prices during the moment of charging. In the figure can be seen that the lowest average charging price is when 50% of the EV drivers are price sensitive. More interesting is however, that if all EV drivers are price sensitive the average total price is increasing. This results from the fact that the EV drivers do not get an incentive related to the spot market (flat fee). This leads to an accumulation of charge sessions on the cheapest moment based on the CPP which creates a high demand on a particular moment on the day. In the worst-case scenario this can escalate to an imbalance on the national electricity system, which will trigger the activation of balance power. Balance power is expensive; hence electricity prices will increase if demand is scheduled simultaneous (on a large scale!). Therefore, the conclusion of this analysis is that static price profiles from the DSO can lead to congestion but as well to imbalance on a system level.

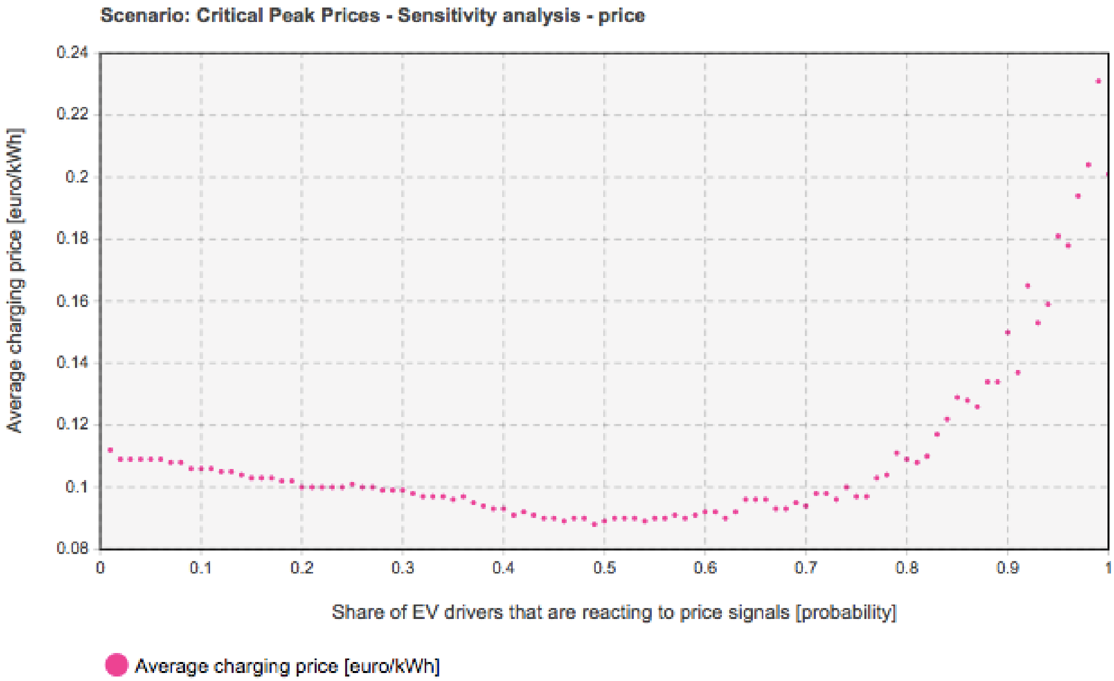

Figure 36, Sensitivity analysis of EV drivers reacting to price in relation to the average charging price with a critical peak pricing mechanism

The average charging time is 6.2 hours. In the last scenario, the increase of the duration of the charging session gave a financial incentive to the EV driver. However, in CPP with a flat tariff, the EV driver pays more than in any other mechanism in this simulation: €0,157 per kWh. The number of unfinished charging sessions are 34, which is a bit higher than other scenarios and the number of fast charging session are 13 which is equal to the other scenarios. Concluding from these findings, this mechanism is not useful for both DSO, BRP as EV driver.

5.1.4. Critical Peak Pricing - spot market charging

The mechanism of critical peak pricing can be combined with spot market charging. This means that both the BRP as the DSO will communicate a price signal. Although the prices of the BRP are dynamic and therefore reacting on the relation between supply and demand, the implemented prices of the DSO in the simulation are static. The load profile on the transformer can be seen in Figure 37. The profile is much more angular compared to the other profiles which is caused by the static prices of the DSO. Important with this mechanism is the ratio between the prices of the DSO and BRP. If the price level of the DSO is too guiding this can have negative consequences for the charge schedules.

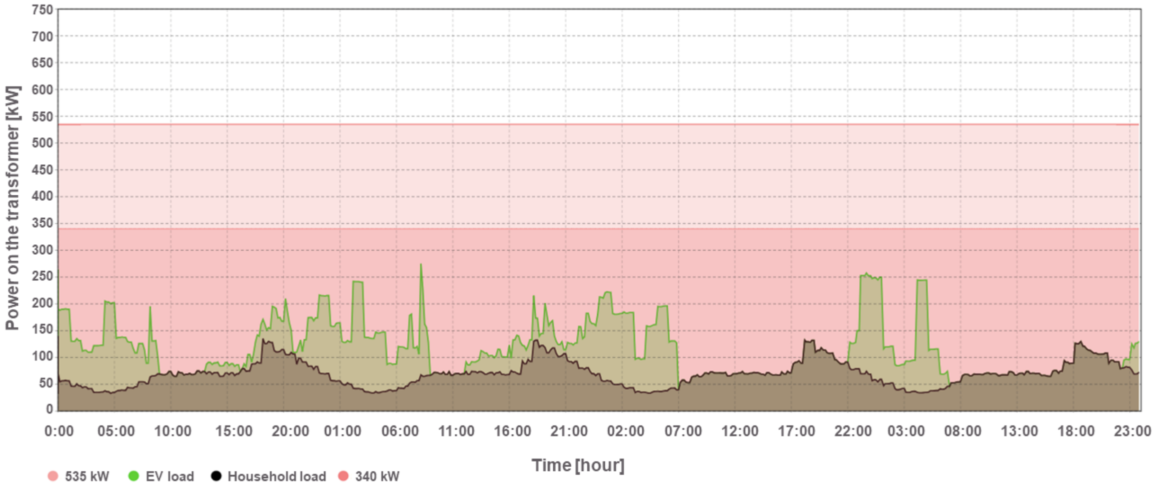

Figure 37, Load profile on the transformer with a combination of critical peak pricing and spot market charging at Thursday 21st of May until Sunday 24th of May.

The overload on the transformer is limited when a price sensitivity of a 100% is considered. However, this is not a realistic percentage to assume. Therefore, a sensitivity analysis is made on price versus overload in on the transformer. In Figure 38 and Figure 39 can be seen that at both transformers overload increases when the price sensitivity is lowered. For the 630-kVA transformer this is from 75% and for the 400-kVA transformer this is from 90% price sensitivity. This indicates that the mechanism leads to high risks while high percentages of price sensitivity are necessary to avoid overload and there is no direct control option for the DSO for congestion management.

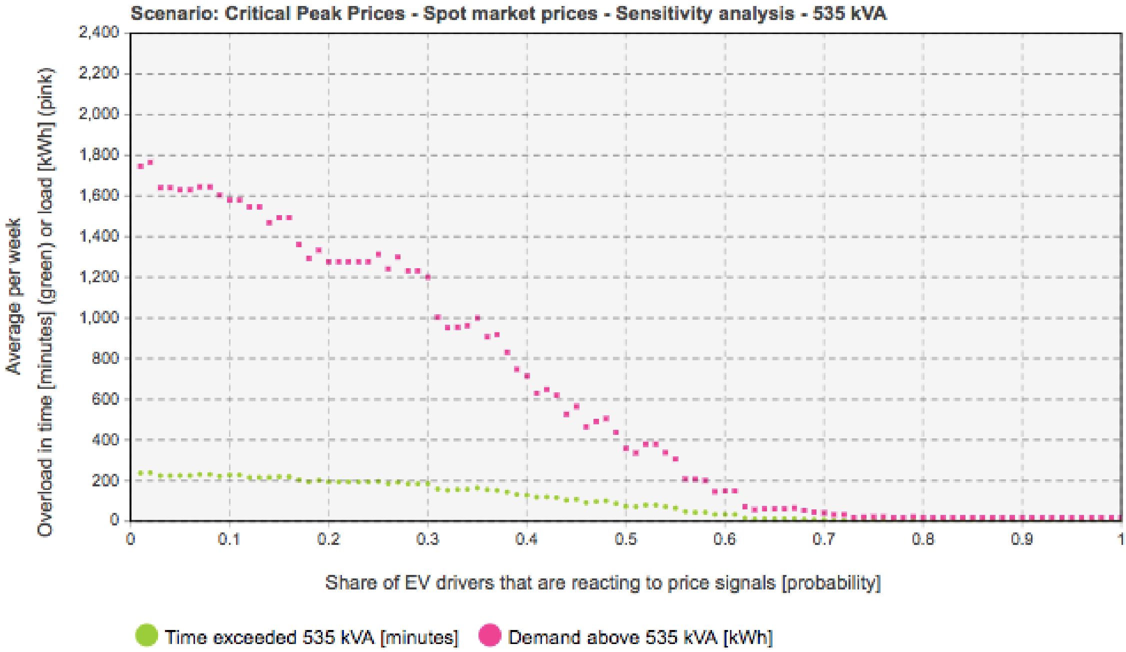

Figure 38, Sensitivity analysis on price in relation to overload on the transformer with a threshold of 535 kW with a critical peak pricing mechanism in combination with spot market charging.

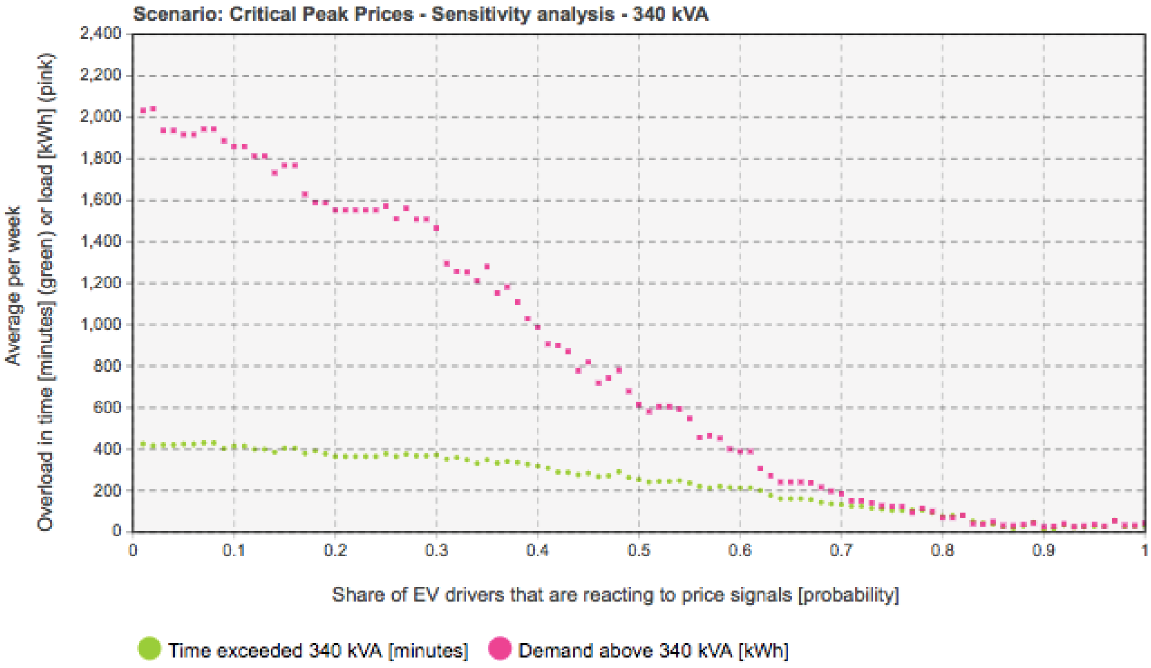

Figure 39, Sensitivity analysis on price in relation to overload on the transformer with a threshold of 340 kW with a critical peak pricing mechanism in combination with spot market charging.

The above charts have indicated that a high price sensitivity is needed, which leads to the influence of price sensitivity is on the average charging price. It is possible that EV drivers are interested in this mechanism because of low costs. Figure 40, shows that 0% price sensitivity leads to an average charging price of €0,11 per kWh and a 100% price sensitivity to an average charging price of €0,075 per kWh. The price with 100% price sensitivity is the lowest average charging price of all mechanisms when comparing the prices including the network tariffs. However, when only the spot market prices are considered this mechanism scores high compared to other mechanisms: CPP with SMC average charging price is €0,026 and with only SMC the average charging price is €0,019. This indicates that the positive effect of this mechanism is entirely depending on the price schema implemented by the DSO in the simulation.

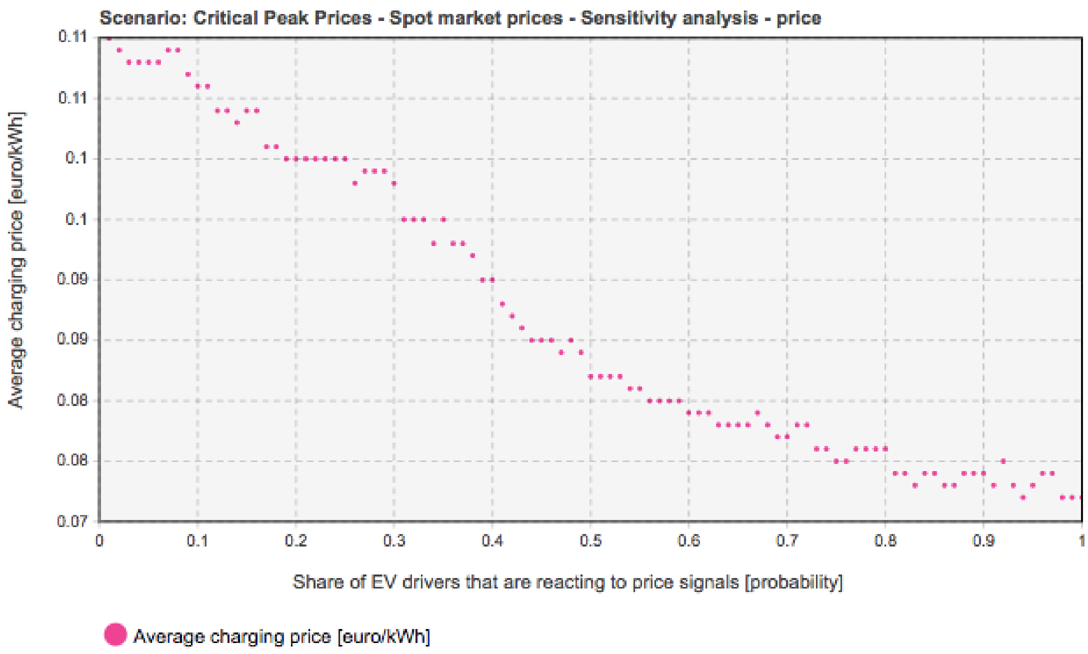

Figure 40, Sensitivity analysis on price sensitivity in relation to the average charging prices with a critical peak pricing and spot market pricing mechanism.

The average charging time is 8.3 hours, which is the lowest scoring scenario within this simulation. The unfinished charging sessions are 39, which is like other scenarios with a smart charging mechanism and the number of fast charging sessions are 12.

From the above analyzed results it can be concluded that price sensitivity needs to be extremely high to avoid congestion for the DSO. This results in a high uncertainty for the DSO while it is totally depending on the reaction of EV drivers on prices. Although prices seem to be low, this is mainly dependent on the price scheme of the DSO implemented in this simulation. When congestion is detected in the network there are no actions that can be taken by the DSO to control the situation.

5.1.5. Variable connection capacity - flat fee

Variable connection capacity is a contracted mechanism that is offered by the DSO to their customers. In the contract the maximum capacity of the flexible appliances used during the peak (e.g. between 17:00 and 20:00) is established. In Figure 41, Figure 42 and Figure 43, the effect of this mechanism on the load profile of transformer can be seen. There are three settings displayed: 0kW, 4 kW and 10kW maximum charging power during the restriction period, all with a timeframe between 17:00 and 20:00. In the figures can be seen that this mechanism will increase the overload depending on the maximum charging power during the restriction period. If the capacity in the peak is set on 0 kW or 4 kW the EVs are not finished charging when the peak period is over. Hence, the EVs start charging at full power (11 kW and 22 kW) which results in high simulations loads when the restriction period is over. If a higher load is given during the restriction period, for example 10 kW, this effect is averted, while EVs have had the opportunity to charge during the peak which has filled most of the batteries and only few need to charge after the restriction period, see Figure 42. Conclusion that can be made from this is that depending on the maximum load given during the peak period and the adoption of EVs, a static restriction in the peak period can lead to more congestion because of the accumulation of charge sessions.

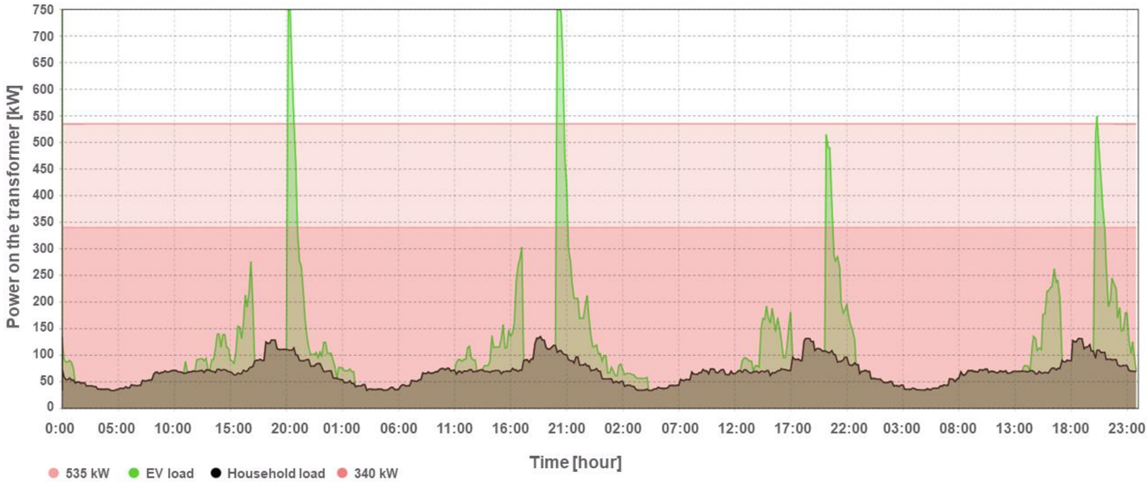

Figure 41, Load on the transformer by implementation of variable connection capacity with a flat fee for EVs, restriction to 0 kW during the peak between 17:00 and 20:00. At Thursday 21st of May until Sunday 24th of May.

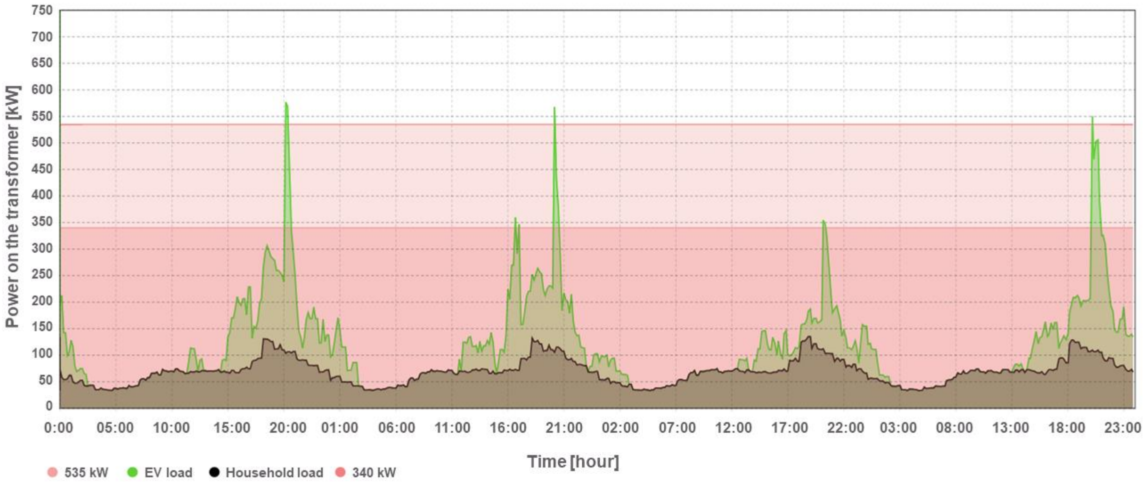

Figure 43, Load on the transformer by implementation of variable connection capacity with a flat fee for EVs, restriction to 4 kW during the peak between 17:00 and 20:00. At Thursday 21st of May until Sunday 24th of May.

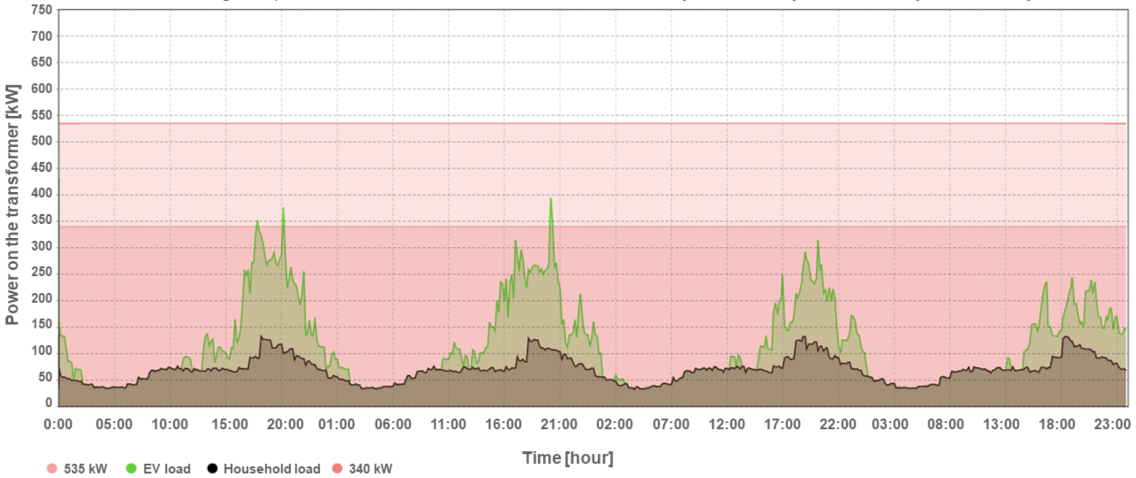

Figure 42, Load on the transformer by implementation of variable connection capacity with a flat fee for EVs, restriction to 10 kW during the peak between 17:00 and 20:00. At Thursday 21st of May until Sunday 24th of May.

A consequence of implementing a restriction period by the DSO is the possibility of a negative charging experience of the EV driver. Figure 44, shows that the level of restriction has an influence on the charging time, when the EV is restricted to 0 kW the average charging time is 1.65 hours and with a restriction of 12 kW the average charging time is 1 hour. Therefore taking 15 minutes longer than uncontrolled charging.

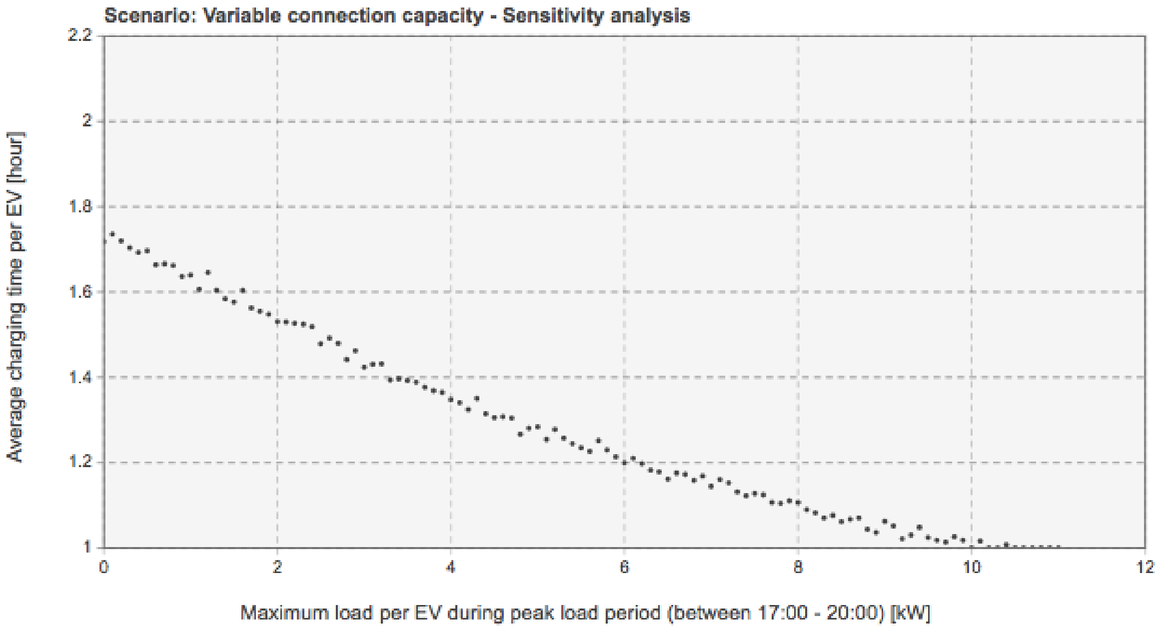

Figure 44, Sensitivity analysis for the relation between the maximum load during the peak period and the average charging time per EV

Although the average charging sessions are twice as long compared to uncontrolled charging this does not directly indicate that the EV driver experiences a negative effect. Therefore, another sensitivity analysis is made on the maximum load during the restriction period in relation to the number of prematurely finished charging sessions and fast charging sessions, the results can be found in Figure 45. This figure shows that a maximum load of 0 kW during the restriction period leads to twice as much prematurely finished charging sessions per week. On an average of 640 charging sessions of that week this is approximately 10% of all charging sessions. Although, these batteries are not entirely charged the number of fast charging sessions does not increase statistically: 15 compared to 13 with uncontrolled charging. From this it can be concluded that although the duration of charging session is taking more time and more prematurely finished charging session are taking place, this does not have a big influence on the EV driver while it is still able to reach its destination with a lower range.

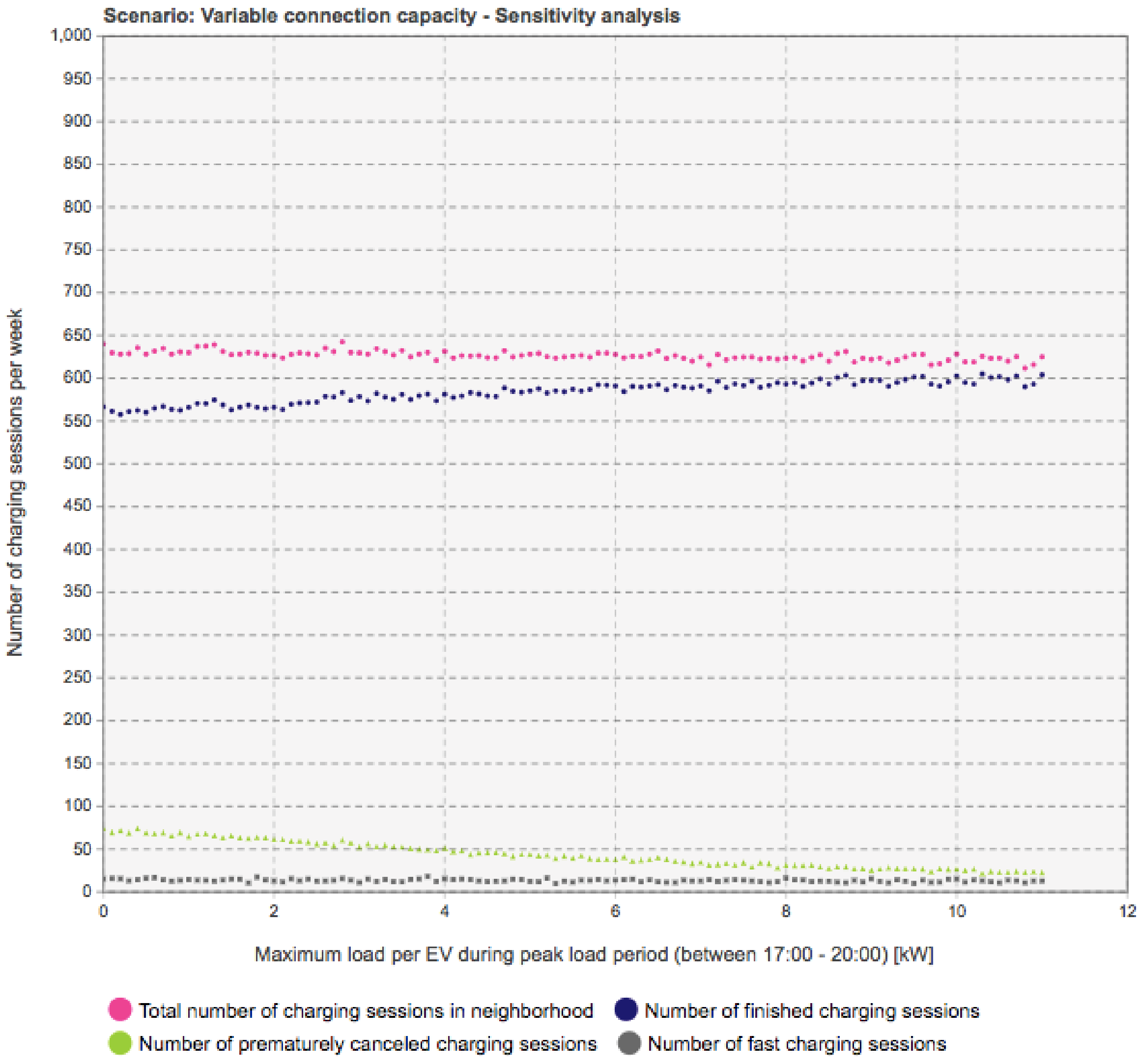

Figure 45, Sensitivity analysis between the maximum load during the restriction period and the number of charging sessions, number of fast charging sessions, number of prematurely cancelled charging sessions and the number of finished charging sessions.

5.1.6. Variable connection capacity - spot market pricing

Variable connection capacity with spot market charging is a mechanism in which the DSO can set constraints in the capacity contract and that within these constraints the market can perform freely. The timeframe and the constraints in load are as described in the last section. This mechanism results in a load profile on the transformer which can be seen in Figure 46, Figure 48 and Figure 47. In these three figures the first shows an overload on the transformer which is a result of the constraint set by the DSO. The figures of 4 kW and 10 kW do not show an overload.

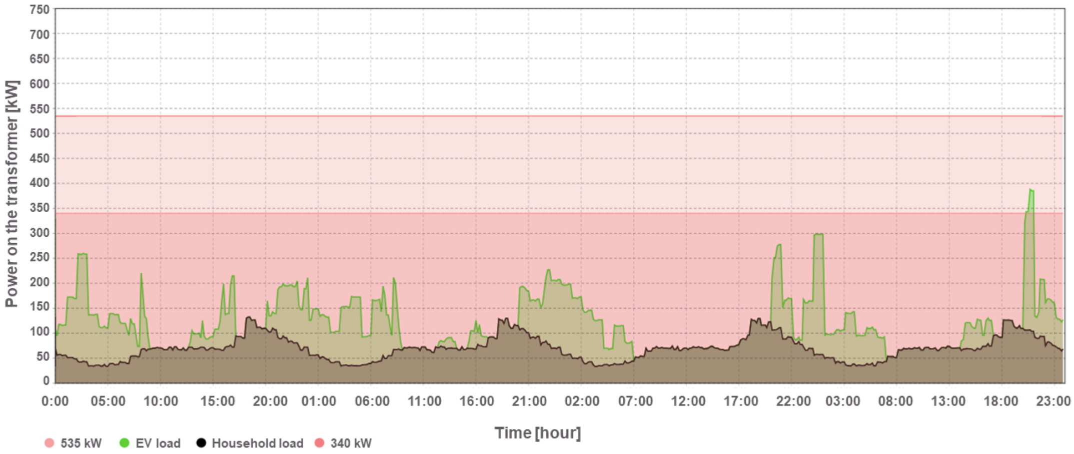

Figure 46, Load profile of the transformer with a variable connection capacity in combination with spot market charging with a maximum load during the restriction period from 17:00 to 20:00 of 0 kW. At Thursday 21st of May until Sunday 24th of May.

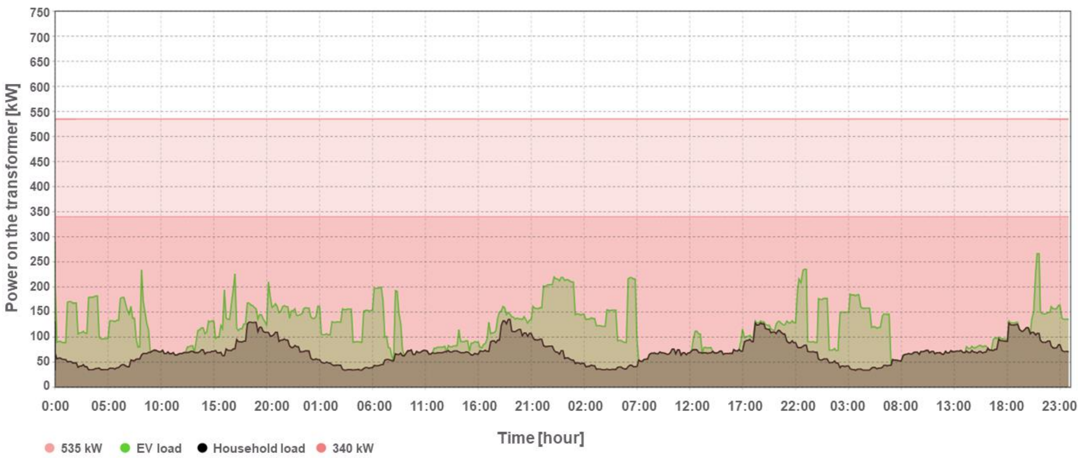

Figure 48, Load profile of the transformer with a variable connection capacity in combination with spot market charging with a maximum load during the restriction period from 17:00 to 20:00 of 4 kW. At Thursday 21st of May until Sunday 24th of May.

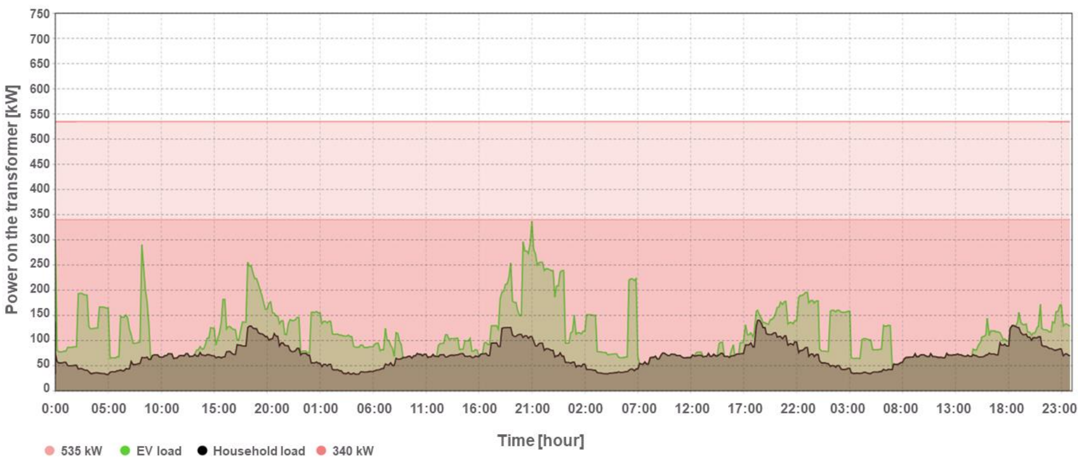

Figure 47, Load profile of the transformer with a variable connection capacity in combination with spot market charging with a maximum load during the restriction period from 17:00 to 20:00 of 10 kW. At Thursday 21st of May until Sunday 24th of May.

As described in the previous section, the variable connection capacity is causing more overload than uncontrolled charging with a high penetration of EVs. However, when this mechanism is supplemented with spot market charging this leads to a lower overload. Although, this is directly related to the price sensitivity of the EV drivers. Therefore, a sensitivity analysis is executed on price in relation to caused overload, see Figure 49 and Figure 50. A price sensitivity of at least 60% is needed to avoid congestion on the transformer of 630-kVA and 90% in case of a transformer of 400-kVA. This indicates that a high price sensitivity is needed to avoid congestion.

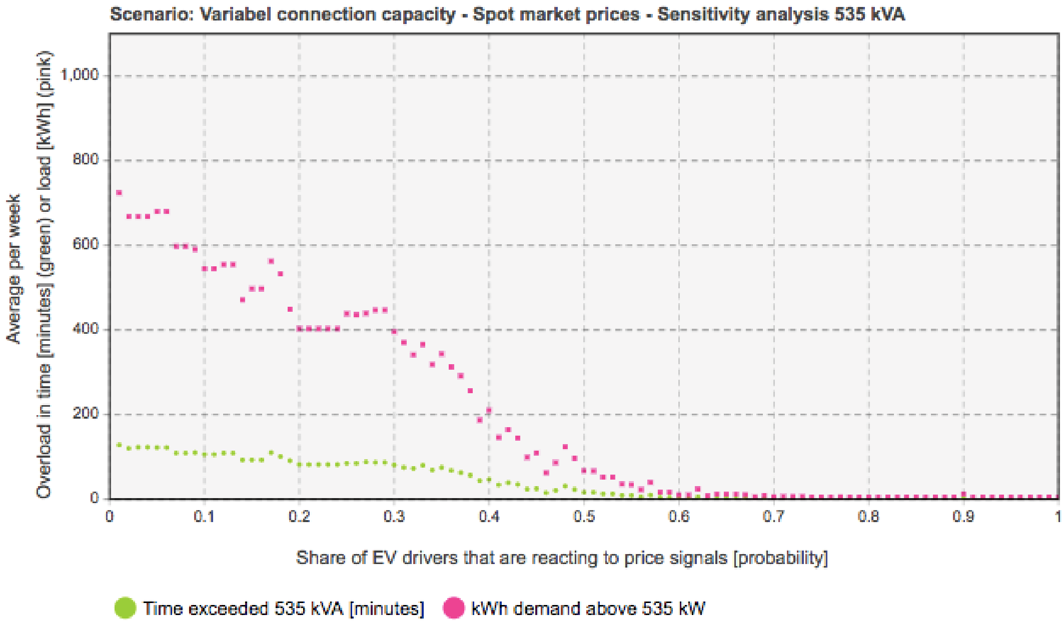

Figure 49, Sensitivity analysis comparing the level of price sensitivity to overload on the transformer with a threshold of 535 kW based on a maximum power in the restriction period of 4 kW.

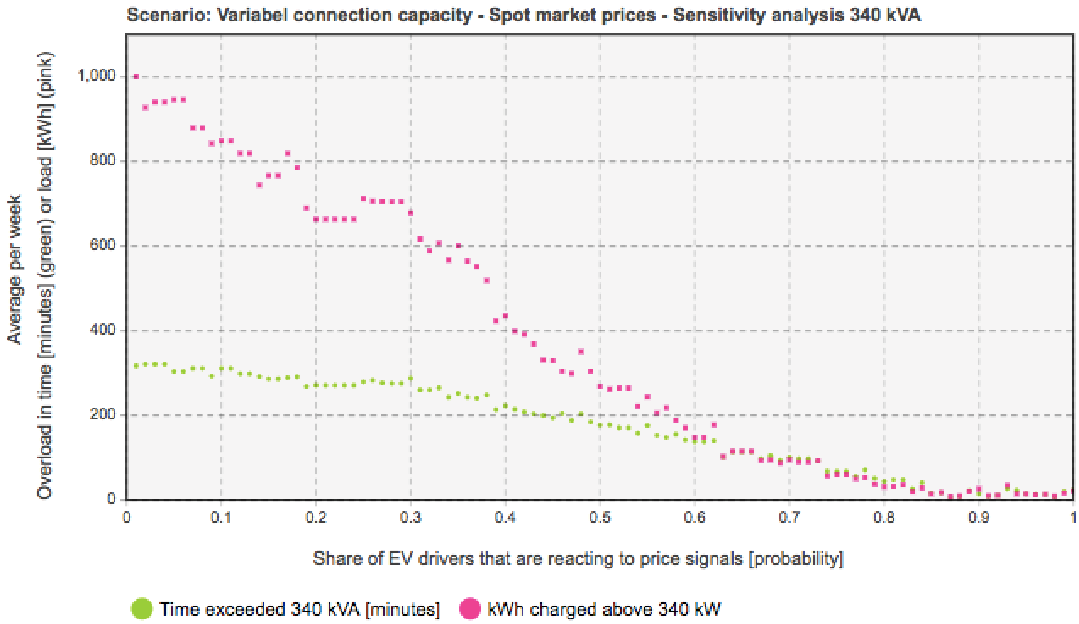

Figure 50, Sensitivity analysis comparing the level of price sensitivity to overload on the transformer with a threshold of 340 kW based on a maximum power in the restriction period of 4 kW.

Depending on the maximum power during the restriction period the numbers of unfinished charging sessions and fast charging sessions vary. A restriction period with a maximum power of 0 kW leads to 146 unfinished charging sessions, 4 kW to 125 and 10 kW to 96. All numbers are higher compared to uncontrolled charging and a clear relation can be seen between the amount of capacity during the restriction period and the number of unfinished charging sessions, the lower the maximum power the higher the number of unfinished charging sessions. For the number of fast charging sessions this relation cannot be found. A maximum power of 0 kW leads to 17 fast charging sessions, 4 kW to 15 and 10 kW to 14.

5.1.7. Direct control - flat fee

Direct control is a mechanism in which the DSO has direct control over the flexibility assets. In case of EVs the DSO will send direct messages to the smart meter in the charging station when an overload is detected in the network. This will lead to the load profile which is portrayed in Figure 51. The figure shows that charging profiles are similar to uncontrolled charging, but that on the days that an overload is detected the DSO will automatically lower the load. On the last two days portrayed in the figure no overload is detected therefore, the DSO had no need to control the charging of the EVs. In the figure can also be seen that the load profile is wider than the profile of uncontrolled charging, see Figure 29. This indicates that the charging sessions have a longer duration which is the result of the active control of the DSO. Which can only lower the charging speed or postpone the charging session on a specific congestion moment (real-time) and not reschedule a charging session to a different moment.

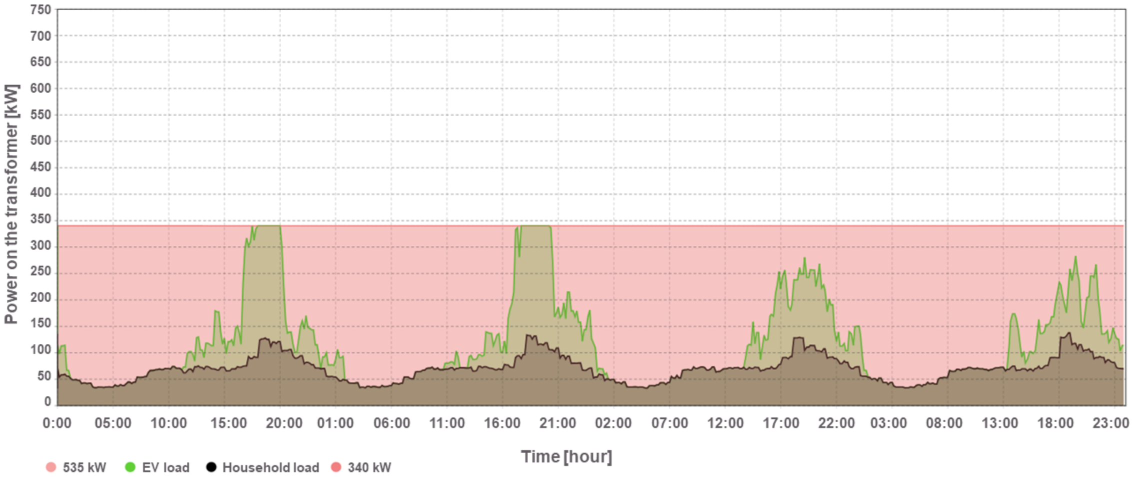

Figure 51, Load profile on the transformer with direct control from the DSO on the charging station. A threshold of 340 kW is applied. At Thursday 21st of May until Sunday 24th of May.

The EV driver will experience the effect of the control of the DSO during its charging session. This however depends on the amount of control the DSO takes during its charging session. Therefore, a sensitivity analysis is made which indicates how much a DSO can lower its threshold of the transformer without influencing the household demand and the mobility need of the EV driver, see Figure 52. The figure shows that the threshold of the transformer can be lowered to 160 kW without influencing the mobility needs of the EV driver. This indicates that the EV driver has a lot of flexibility during its charging session. This finding can be substantiated with the knowledge that the EV driver is parked for an average of 10 hours during the night [70].

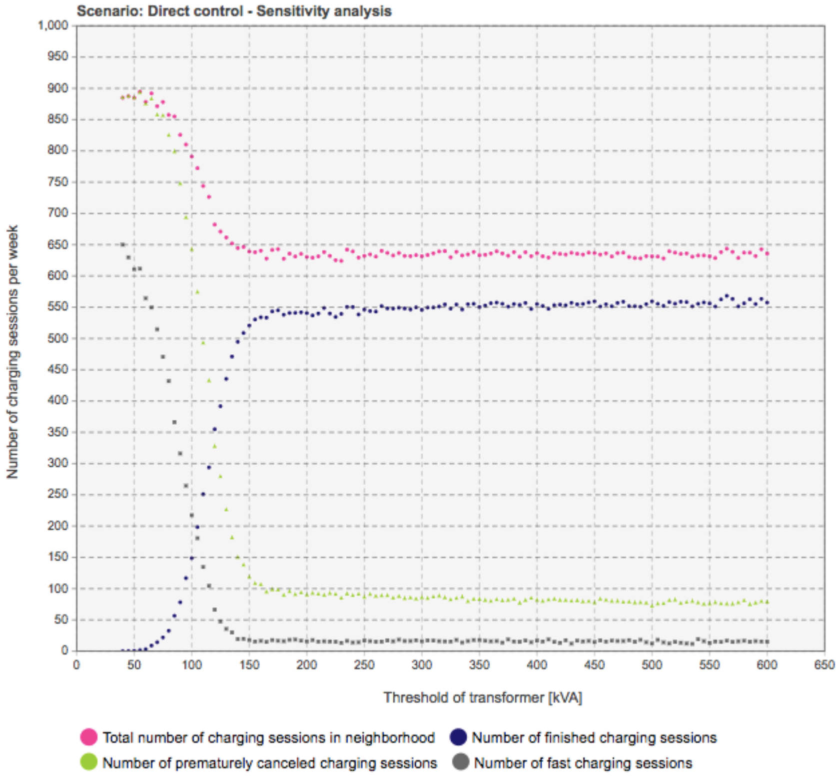

Figure 52, Sensitivity analysis on the threshold of the transformer in comparison with the number of charging sessions in the neighborhood, the number of prematurely finished charging sessions and fast charging sessions.

Although the sensitivity analysis on the number of charging sessions does not give an indication that the EV driver will experience problems in its mobility needs, it is interesting to know what the average duration will be of the charging sessions in relation to the threshold of the transformer. Figure 53 indicates that if the threshold of the transformer is set on 160 kVA the duration of the charging session will be more than twice as long compared to uncontrolled charging. From a threshold of 400 kVA until 630 kVA there is little difference in charging duration.

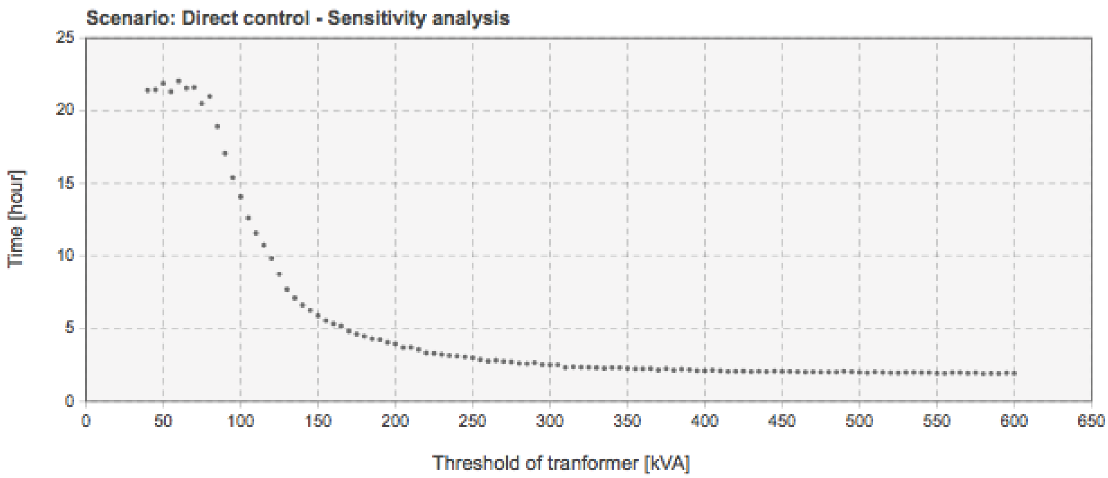

Figure 53, Sensitivity analysis on the threshold of the transformer in relation to the average charging time.

5.1.8. Direct control - spot market pricing

Direct control with spot market charging is a mechanism in which free competition is possible within the constraints of the electricity network. This means that only on occasions that overload is detected the DSO will control the charging stations in that congestion area. On all other moments the market is in control over the charging stations. This results in a load profile on the transformer that can be found in Figure 54. The figure shows that during the week of 21st of May until 24th of May no overload was detected. However, this does not guarantee that congestion is avoided for all times. Moments when congestion can happen is for example: when the amount of renewable generation is extremely high and therefore prices are extremely low or even negative. When this occurs during a peak load situation in the network it can lead to congestion while the low prices ensure that EVs will start charging on the same moment. With direct control this effect can be managed centrally by the DSO.
Figure 54

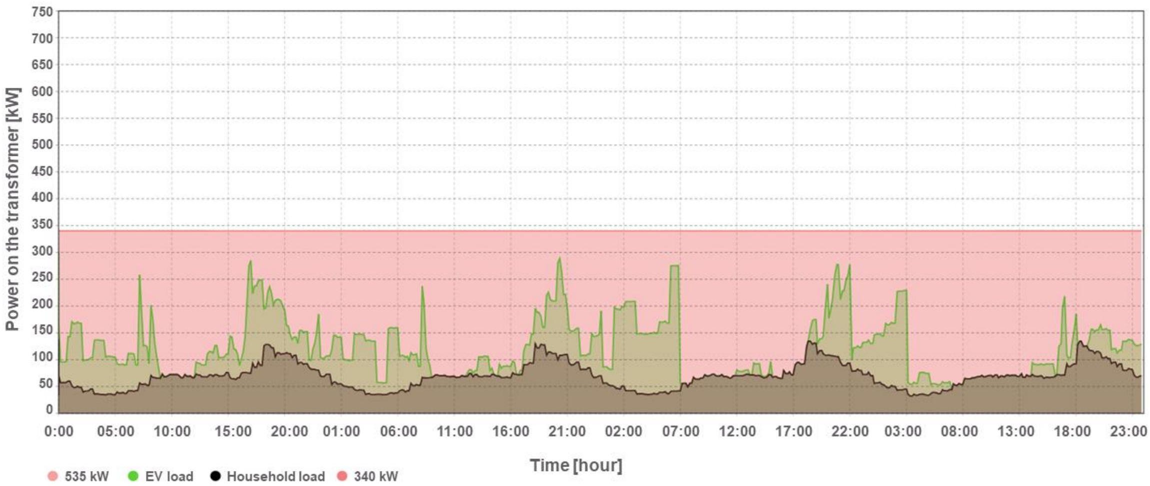

Figure 54, load profile on the transformer with a direct control and spot market charging mechanism with a threshold of 340-kW. At Thursday 21st of May until Sunday 24th of May.

While the DSO can regulate in this mechanism all flexibility devices centrally, all overload situation will be managed. Therefore, there will never be an overload situation, this can be seen in Figure 55. For the DSO this is a mechanism that gives a high reliance, but it does influence the charging profiles without considering the preferences of the EV driver. Therefore, it is interesting to know how much influence this mechanism has on the number of unfinished charging sessions which can indicate that the EV driver was not able to fulfill its mobility need. Looking at the 630-kVA transformer no difference can be found, with a 400-kVA transformer the number of unfinished charging sessions was 47, which is a bit higher compared to spot market charging without control of the DSO (7,4% of the sessions compared to 6,6% of the charging sessions).

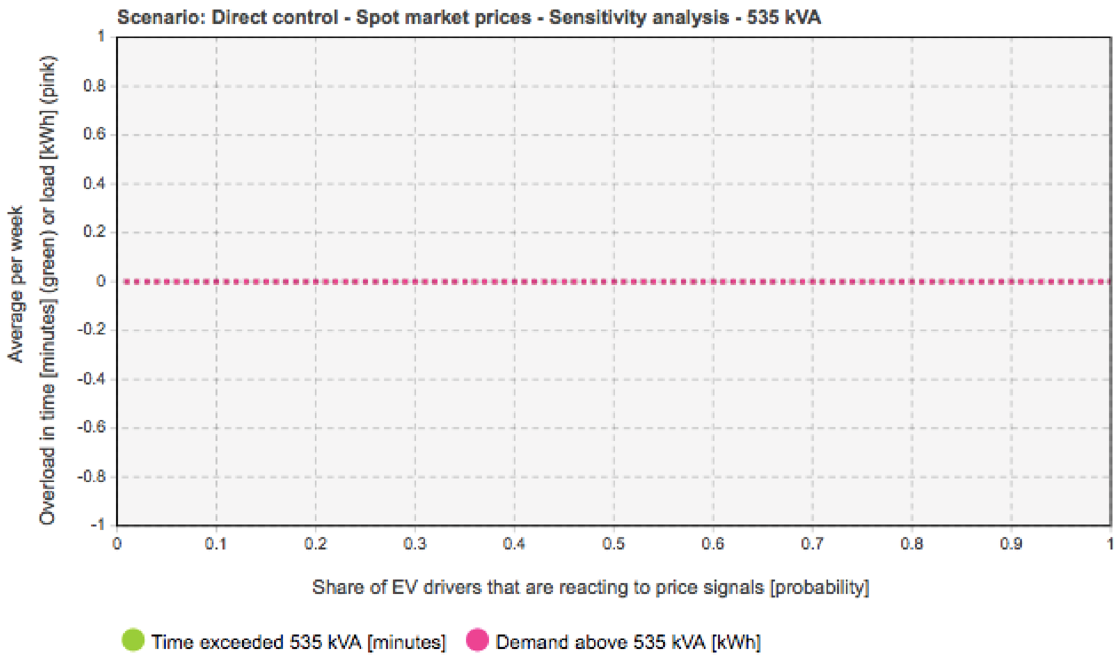

Figure 55, Price sensitivity analysis in relation to overload on the transformer

5.1.9. USEF

USEF is a framework in which free competition is leading. The mechanism is based on the implementation of a flexibility market in parallel to the existing electricity markets. All parties can obtain flexibility for their operation. The simplification of the mechanism in the simulation, as described in section 4.2.5, leads to an equal result as direct control with spot market charging on the profile of the transformer. Reason for this is that free competition is leading until the threshold of the network is reached. When all EV drivers are price sensitive this leads to hardly any overload situations in the current network as can be seen in Figure 54. In a real-life situation there would be a difference between direct control and USEF, while USEF has the option to reschedule the charging sessions DA in dialogue with the parties involved where direct control is a real-time adjustment of the charging session without considering the preferences of the EV driver. In the simulation this difference was hard to implement while a feedback loop is needed in the forecast of the expected network load and the scheduled charging sessions.

In direct control with spot market charging mechanism little overload is detected. However, this is based on a price sensitivity of 100%. The chance that all EV drivers will be price sensitive not a realistic. This leads in USEF to the situation that the DSO needs to buy flexibility in the case that there is overload detected in the network on a commercial trade market. The worst-case situation for the DSO will be that none of the EV drivers are price sensitive while this leads to the highest amount of overload. In

Figure 32, the amount of overload is pictured in relation to price sensitivity with spot market charging. From this picture can be concluded that with a transformer of 400-kVA the DSO needs to buy 425 kWh per week in this neighborhood, when the price sensitivity is zero and 50 kWh per week when the price sensitivity is 50%. This however gives no indication on the overload situation in other neighborhoods. To research this more neighborhoods, need to be simulated in future research.

5.2. Evaluation of aspects of the market mechanisms

In this section the evaluation of the aspects will be presented. Next to the influence of the market mechanisms on the load profile of the transformer, other influences are important as well, for example degree of free competition. If there is only limited degree of free competition possible in the market model it has a small opportunity to be adopted by the other parties in the electricity system. Therefore, evaluation aspects are introduced, in chapter 3, to be able to compare the mechanisms based on a broader range of aspects. To come to these aspects the SGAM framework is used. The results of the evaluation can be found in Table 7. The evaluation is based on the findings of the simulation, experts in the field and literature.

Table 7, Results of aspects of the market mechanisms: L = Low, M = Moderate, H = High

Scenario	UC-F	SMC	CPP-F	CPP-SMC	VC-F	VC-SMC	DC-F	DC-SMC	USEF
Number of active players	2	3	3	4	2/3	4	2	4	4+
Leading role	CSO	BRP	DSO	DSO/BRP	CSO	CSO/BRP	DSO	DSO	CSO
Nature of transactions	Hierarchical	Hybrid	Horizontal	Horizontal	Hierarchical	Hybrid	Hierarchical	Hybrid	Hybrid
Ability to solve congestion	L	M	L	M	L	M	H	H	M
Level of reliability of the DSO	L	L	L	L	M	M	H	H	H
Degree of free competition	L	H	L	M	L	M	L	M	H
User Involvement	L	H	H	H	M	M	L	M	H
Cost effectiveness	€ 0,03	€ 0,02	€ 0,12	€ 0,03	€ 0,03	€ 0,02	€ 0,03	€ 0,02	€ 0,02
Degree of data transactions	L	M	L	M	L	M	M	H	H
Mode of communication	Static	DA	Static	DA	Static	DA	RT	RT	DA/RT
Technology readiness level	TRL 9	TRL 8	TRL 9	TRL 8	TRL 7	TRL 6	TRL 5	TRL 5	TRL 5

5.2.1. Business layer

The comparison of the business layer is executed by evaluating three aspects. The first aspect is the number of active players in the mechanism. The second is the leading role of one of more of the active parties, and the third is the nature of transactions. These aspects indicate how the parties in the mechanism work together, which role has the highest power and how much coordination is needed between the parties.

Uncontrolled charging	<u>Flat fee</u>	<u>Spot market charging</u>
Number of active players	*2*	*3*
Leading role	*CSO*	*BRP/CSO*
Nature of transactions	*Hierarchical*	*Hybrid*

Uncontrolled charging has two players of which the CSO is leading in the market. The CSO controls the charging stations, sessions and authorization of the EV driver. The CSO has the possibility to change the duration or load of the transaction. The nature of transaction is hierarchical. There is an interaction between EV driver and CSO. When the EV driver decides to plug-in its car the CSO will check the RFID of the charge card of the EV driver and decide to authorize the transaction or not.

In a spot market charging scenario there are three active players: the EV driver, CSO and BRP. These players can all control the charging profile. The EV driver can control it by giving in its preferences, the CSO can control it by planning the charge schedule and the BRP can control it by sending dynamic price profiles. The BRP and CSO have the leading role, these parties have control over the prices and can control the optimization of the charging profiles. The nature of transactions is hybrid, the BRP has the same amount of power as the CSO.

Critical peak pricing	Flat fee	Spot market charging
Number of active players	*3*	*4*
Leading role	*DSO*	*DSO/BRP*
Nature of transactions	*Horizontal*	*Horizontal*

Critical peak pricing with a flat fee has three active players. The DSO, CSO and EV driver. The DSO sets the prices which makes it in this mechanism the leading role. Based on this price the CSO schedules the charge sessions. The nature between the parties is horizontal. All players have the same amount of power in the market.

Critical peak pricing in combination with spot market charging has four active players. These are the BRP, DSO, CSO and EV driver. The BRP sends dynamic prices to the CSO. Next to this the DSO sets the critical peak prices. The CSO receives the preferences of the EV driver and adjusts the charging schema according to both the prices as the preferences. The transaction nature is horizontal all parties have the same amount of influence on the charging session.

Variable connection capacity	Flat fee	Spot market charging
Number of active players	*2*	*4*
Leading role	*CSO*	*CSO*
Nature of transactions	*Hierarchical*	*Hybrid*

Variable connection capacity has two active players the CSO and the DSO, in which the CSO is leading. The CSO will decide if it, according to the variable capacity contract with the DSO, limits the charging sessions according to the maximum amount of kW during the agreed-on timeframe. How and if the EV driver is notified is the responsibility of the CSO. The nature of the transactions is hierarchical. The DSO controls the reduction period and the CSO needs to follow the restriction. The same is the relation from the CSO to the EV driver. The CSO controls the charging session in a way that it will stay within the contract limits.

Variable connection capacity with spot market charging has four active players which are the DSO, BRP, CSO and EV driver. The CSO has the leading role. The DSO concludes a contract with the CSO about the capacity. In this contract the restriction period and maximum load are defined. The BRP sends dynamic prices to the CSO and the EV driver its preferences. On base of these three input variables the CSO defines a charge profile. The nature of transactions is hybrid. The DSO defines the constraints which is the leading factor in the transaction. Within these constraints the charging profile is scheduled.

Direct control	Flat fee	Spot market charging
Number of active players	*4*	4
Leading role	*CSO*	DSO
Nature of transactions	*Hybrid*	Hybrid

Direct control is a mechanism in which the DSO has all the control. Even if the CSO knows the preferences of the EV driver the DSO can overrule these directly. This however results in zero overloads which leads to a high reliability for the DSO. This means that there are two active players of which the DSO has the leading role. The nature of transaction is hierarchical. The DSO has the end-decision if there is an overload in the network. The consequence of this is that the EV driver is not involved and that on occasions this can lead to a lower satisfaction.

This mechanism has four active players which are the DSO, BRP, CSO and EV driver. The DSO sends a capacity constraint when overload is detected to the charging stations. The BRP sends the dynamic prices to the CSO and the CSO schedules the charging profile according to the preferences of the EV driver. The leading role is for the DSO while the DSO can overrule all other control signals. What makes the nature of the transaction hybrid. The DSO can send constraints when it is necessary.

USEF	Spot market charging
Number of active players	5+
Leading role	aggregator
Nature of transactions	Hybrid

USEF is a mechanism with five or more active players. These are the aggregator, CSO, EV driver, DSO and BRP. An additional role that is possible to add to this framework is for example the TSO. USEF is a framework in which the aggregator had the central role. In the EV landscape this role could be incorporated in the CSO but as well an independent aggregator could perform this role. The aggregator will receive all flexibility requests from DSO, BRP and TSO and will try to match them with the available flexibility in its portfolio of EV drivers. Important is that the DSO has a locational constraint in the flexibility request which means that flexibility can only be delivered from the EVs connected to the congestion point. The nature of transaction is hybrid. The CSO has the central role which coordinates all flexibility requests in its portfolio.

Conclusion

All mechanisms have 2 to 5 active parties involved. Most of the mechanisms with 4+ active players involved have a hybrid mechanism, this indicates that one market player is taking responsibility for business operations of another market players, to make coordination between the parties easier. However, when a difference of interest arises between the players, clear agreements need to be set. When the nature of transactions is hierarchical this relates to a static solution in which either the price or capacity follow a static profile.

5.2.2. Function layer

The function layer looks at the functions the mechanisms need to perform. The mechanism needs to be able to solve congestion therefore the aspect ability to solve congestion is evaluated. It needs to be able to perform portfolio management and other business-related services therefore the degree of free competition is incorporated. The EV driver needs to be willing to offer its flexibility for congestion and commercial services therefore it is important how much involvement it has in the system. This is evaluated by looking at the customer involvement level. At last the cost effectiveness is analyzed of every mechanism by comparing the average price per kWh.

Uncontrolled charging	Flat fee	Spot market charging
Ability to solve congestion	Low	Moderate
Level of reliability of the DSO	Low	Low
Degree of free competition	Low	High
User Involvement	None	High
Cost effectiveness	€0,030	€0,019

In the uncontrolled mechanism an overload is detected of 477 minutes with 542,5 kWh per week on a 400-kVA transformer. The overload on a bigger transformer is negligible. While a high overload is detected on the 400-kVA transformer this mechanism scores low on the ability to solve congestion. This mechanism leads to problems for DSO and electricity market. When no control is possible on the charging sessions there is a daily risk off congestion, as can be seen in Figure 29. Therefore, the aspect level of reliability of the DSO is set on low. Next to this, the electricity market will experience a few hours of high peak demand daily, on which the installed capacity needs to be adjusted. This will lead to an in-efficient use of the installed capacity and therewith higher prices. Users have little involvement in this mechanism. The only option to change the charging schedule is to physically plug and un-plug the EV. This gives very little possibilities for the EV driver to change their charging behavior according to their preferences. When looking at the costs of uncontrolled charging the average price is €0,030 per kWh and €0,093 per kWh including the price for fast charging and work charging and the network costs. These costs are calculated based on the electricity prices on the spot market, added with the price for fast charging (€0,50 per kWh) and the average costs of the capacity tariff per kWh.

In the SMC mechanism the damping effect of the dynamic prices result in more efficient use of the electricity network which is positive for the DSO. However, it does not guarantee that there will be no congestion while the DSO cannot control the charging session. There are scenarios imaginable that electricity prices are low on the same moment that the local network has little capacity. This would result in congestion, while network constraints are not considered. This makes that SMC scores moderate on the ability to solve congestion. Next to this the level of reliance the DSO is set on low, while the DSO has no option to intervene when a congestion situation occurs. On the contrary this mechanism gives no limitation to free competition which makes the score on this aspect high. In SMC the user involvement is high. The user can indicate their preferences relating e.g. leaving time and the minimum load it wants to have in their battery. The optimization of costs on SMC leads to lower prices compared to uncontrolled charging. The price of an average kWh is €0,019. This makes this scenario together with direct control and SMC the cheapest scenario in the simulation.

Critical peak pricing	Flat fee	Spot market charging
Ability to solve congestion	Low	Moderate
Level of reliability	Low	Low
Degree of free competition	Low	Moderate
User Involvement	High	High
Cost effectiveness	€0,121	€0,026

With the implementation of CPP the ability to solve congestion is low. Especially, if all EV drivers are price sensitive. Next to this the level of reliance is set on low, since the DSO cannot actively control the load if necessary. As well it will have an enormous influence on the market as it only gives an incentive for EV drivers based on network congestion and not on the availability of electricity. Which can lead to a peak demand for generation capacity and high prices. Therefore, the degree of free competition is low. User involvement in this mechanism is high. The user can put in its preferences and charge schedules will be adjusted to it. Unfortunately, the costs effectiveness is low, while this mechanism is the most expensive system compared to all other mechanism tested in this simulation: €0,121 per kWh based on spot market prices and €0,157 based all additional prices included.

For the CPP in combination with a SMC mechanism the ability to solve congestion is moderate, while the price sensitivity needs to be high to avoid overload. There is no direct control option to manage congestion therefore, the level of reliability is low. The degree of free competition is moderate, CPP costs are influencing the market prices, which influences the moment of charging. This can be seen in the relatively high average price for a kWh which is €0,026. The customer involvement is high, consumers can give-in their preferences for the charging schedule. The cost effectiveness seams high when comparing the total costs €0,074 (including fast and work charging and network tariffs) to the other total prices of the other mechanisms. However, this is entirely based on the price schedule implemented in the simulation, looking at the prices on the spot market this mechanism scores moderate.

Variable connection capacity	Flat fee	Spot market charging
Ability to solve congestion	Low	Moderate
Level of reliability	Moderate	Moderate
Degree of free competition	Low	Moderate
User Involvement	None	Moderate
Cost effectiveness	€0,028	€0,020

As is stated earlier VCC will not solve congestion, it can even make the congestion worse. However, the amount of overload depends on the amount of power aloud in the restriction period. The level of reliability is set on moderate. Although, the static implementation leads to big problems with a high adoption rate of EVs, the DSO can assume that the contracted party will use the agreed-on capacity constraints. The same accounts for the degree of free competition. This mechanism does not have a relation to the electricity market which results in simultaneous loads because of the static profile that is used by the DSO. This will result in less market competition and high prices during the moment the restriction period is over. There is no user involvement in this mechanism. However, the sensitivity analysis shows that there is limited effect on the mobility behavior of the EV driver. The cost effectiveness of this mechanism is on the same level as that of uncontrolled charging: €0,028 per kWh.

The VCC with SMC has a moderate ability to solve congestion while it needs a high price sensitivity to avoid overload. The price sensitivity needs to be 60% with a 630-kVA transformer and 90% with a 400-kVA transformer. If this is not met congestion will be a problem for the DSO. The level of reliability however is moderate while this mechanism is fixed in a contract with the connected party. If the connected party is not working according to the contract it will receive a fine. The degree of free competition is moderate as well. The DSO actively limits the amount of capacity which influences the market. Next to this, the static profile gives not only a limitation on moments of congestion but as well when no congestion is detected. This leads to less capacity for free competition. This mechanism focusses on the contracted user of the connection which can be the CSO (public charging) or the home owner (private charging). The EV driver is not involved in the concluded contract which means that it has limited influence on the agreements of the restriction period. The cost effectiveness is moderate compared to other mechanisms in the simulation. The average price of a kWh is €0,020.

Direct control	Flat fee	Spot market charging
Ability to solve congestion	High	High
Level of reliability		
Degree of free competition	Low	Moderate
User Involvement	Low	Moderate
Cost effectiveness	€0,028	€0,019

Direct control has a high ability to solve congestion, while the DSO can control the charging stations directly when overload is detected. This gives the mechanism the highest reliability of all mechanisms that are simulated. However, the degree of free competition is moderate. Although direct control will only be used as a last resort solution the mechanism does not consider any communication with the other parties involved. This can influence the free competition, when the control of the DSO effects the other parties. There is no user involvement in this mechanism other than chose a contract with direct control possibilities\. Although the outcomes in the simulation suggest that this is rarely a problem it can have an enormous influence, if for example someone was not charged enough to drive to a hospital. The cost effectiveness of this mechanism is on the high side compared to other mechanisms: €0,028.

In the mechanism with direct control in combination with SMC the ability to solve congestion is high. If overload is detected by the DSO it can directly intervene with the charging transactions. This also leads to a high reliability. The degree of free competition is a bit lower than without capacity constraints although with a high price sensitivity, limited amount of control is needed: 10 minutes and 6 kWh per week. While there is no communication between the DSO and BRP about the moment of control the degree of free competition is evaluated as moderate. The user can send in its preferences to the CSO who will schedule a charging profile accordingly. It is possible that the DSO will overrule this charging profile without noticing the EV driver therefore the user involvement is moderate. The cost effectiveness is high, this mechanism is together with SMC the cheapest of the mechanisms in the simulation.

USEF	Spot market charging
Ability to solve congestion	High
Level of reliability	High
Degree of free competition	High
User Involvement	High
Cost effectiveness	€0,019

In the USEF framework flexibility is seen a commodity which is sold on a trade market. This is the case both for the DSO as other players who are interested in flexibility. The DSO can buy flexibility when overload is detected in the forecasted load profile of the CSO and BRP. The DSO sends in a flexibility request for a certain moment of the day. This continues until the moment of delivery. The degree of free competition is high, USEF knows no restrictions for free competition. Only when the market players fail to offer enough flexibility to solve congestion an orange regime is started. In this regime the DSO can directly control assets to solve the congestion. Which makes the level of reliability high. Next to this, the customer involvement is high as well, the customer preferences are leading in the amount of flexibility in the market. This means that customers need to actively communicate their preferences to the aggregator. For offering flexibility the EV driver will get an incentive from the aggregator. It is hard to say something about the cost effectiveness of USEF. Reason for this is that flexibility is seen as a commodity which needs to be obtained from a commercial market. What the costs for flexibility will be is uncertain, especially for the DSO.

USEF is based on ideal market circumstances, e.g. a lot of requesters and suppliers need to be available in the market to reach a sufficient level of liquidity. Expected is that this will be the case for national problems such as: frequency challenges for the TSO and portfolio management for the BRP with the arrival of renewable generation and EVs. The challenge of local congestion is interrelated but different. The EV can provide flexibility for its own overload, see section 1.3. but only on the cable or transformer that it is connected to, while congestion is a local problem that needs to be solved locally. The impact differs from cable to cable and therefore, the grid topology needs to be considered, this makes the execution tremendously complex. Besides this, one of the criteria for a market approach is that there are enough buyers and sellers. Fact is, that the DSO has very limited market power while it is restricted to the amount of flexibility and market players on a certain location.

Conclusion

The aspects in this layer lead to the conclusion that all mechanisms with a static construction either based on price or capacity can lead to contrary effects than anticipated if the adoption of EVs becomes high. Mechanisms with a dynamic pricing system have a positive effect on all aspects evaluated in this layer. Most positive in this layer is USEF which scores high on most aspects however, it is unclear what the costs will be for this mechanism while there are a lot of discussion about the price of flexibility. SMC and direct control with SMC have the same average price per kWh. The main disadvantage of SMC is that it needs a high price sensitivity to be reliable for the DSO. Direct control in combination with SMC however influences the degree of free competition and user involvement. This can be improved by implementing a feedback loop from the DSO to BRP and user.

5.2.3. Information layer

The information layer refers to the amount of information that needs to be transferred between the parties in the flexibility mechanism. This gives an indication of the reliance on ICT. If this is high this leads to higher costs.

Uncontrolled charging	<u>Flat fee</u>	<u>Spot market charging</u>
Degree of data transactions	Low	Moderate

The uncontrolled mechanism has a low reliance on ICT, the charging station could also work without any data transfer. This would mean that if the consumer plugs-in their car, charging will start immediately similar with the use of other household appliances.

In the SMC mechanism there is a moderate amount of data that needs to be shared. There is a data flow between customer and CSO in which the preferences of the EV driver are communicated. Next to this the BRP indicates their dynamic prices to the CSO. This will be processed by the CSO into a charge schedule which is send to the charging station.

Critical peak pricing	Flat fee	Spot market charging
Degree of data transactions	Low	Moderate

The reliance on ICT in the CPP mechanism is low. The DSO communicates the static prices to the CSO on a yearly basis. Based on these price schedules the CSO plans the charging schedules. This can also be implemented directly in the charging station, which would lead to less need for data transactions.

The reliance on ICT in the CPP mechanism in combination with SMC is moderate. There is a data flow between customer and CSO for sharing its preferences and BRP and CSO for the communication of the dynamic prices. On basis of these two inputs the CSO will schedule a charge profile which will be send to the charging station.

Variable connection capacity	Flat fee	Spot market charging
Degree of data transactions	Low	Moderate

The degree of data transactions with variable connection capacity with a flat fee is low. Static prices are concurred in a contract. If changes are needed these can be adjusted on a yearly basis by the DSO. The CSO is responsible of following the contract and will adjust their charging profiles according to it. This can also be implemented in the charging station directly, which leads to less data transactions.

Variable connection capacity with SMC has more data transactions. This is mainly based on the communication of the dynamic prices to the CSO by the BRP. Next to this the customer can put in its preferences for the adjustments of the charging profiles. The profile will be made by the CSO and send to the charging station.

Direct control	Flat fee	Spot market charging
Degree of data transactions	Moderate	High

Direct control with a flat fee has moderate amount of data flows. The DSO needs to control its network real-time and communicate congestion constraints if overload is detected directly to the charging station.

Direct control with SMC has more data transactions while both the DSO as the BRP can send in dynamic signals. Next to this the customer can give input about its preferences.

USEF	Spot market charging
Degree of data transactions	High

Of all mechanisms USEF has the highest degree of data transactions. The customer has a contract with the aggregator for the flexibility services. To execute these, the customer needs to communicate its preferences. Based on this information the aggregator knows how much flexibility it has in its portfolio. USEF has different moments on which flexibility can be traded. For all traded transactions data needs to be transferred. Next to this, if the flexibility is delivered a settlement needs to be made about the costs of the flexibility. The settlement is based on the actual delivered flexibility which means that a forecast need to be made for all flexibility devices or at least flexibility providing customers. These forecasts need to be compared to the actual delivery of flexibility. On base of this, the calculation can be made who should receive an incentive for the delivered flexibility, and who should receive a fine for not keeping the agreement. However, this also leads to possibilities of gaming while it is hard to predict and prove who as actively changed their charge profile for solving the congestion. Especially because of the predictability of the moment of congestion.

Conclusion

The evaluation of the degree of data transactions shows that the more dynamic the price profiles are the higher the degree of data transactions is. All mechanisms with a static profile use a contract-based system which leads to a low level of data transactions between the parties. USEF and direct control with SMC have both a lot of parties involved and a high level of data transactions which asks for the use of open protocols between parties. This will lead in less implementation costs in the system and to a limited degree of a vendor lock-in risk.

5.2.4. Communication layer

The communication layer refers to the type of communication. Flexibility mechanisms know different modes of communication. This can be day-ahead, intra-day or real-time. The closer communication is needed to the moment of delivery the higher the reliance on the communication in the mechanism.

Uncontrolled charging	Flat fee	Spot market charging
Mode of communication	Static	Day-ahead

The mode of communication for uncontrolled charging with a flat fee is static. The DSO has a fixed capacity contract with the CSO and the energy supplier a flat fee contract with the EV driver. There is no incentive to change charging behavior.

The spot market charging scenario works with a DA price schedule but can as well work with more real-time communication. This could be interesting for the BRP while it can re-adjust their position in the market when needed.

Critical peak pricing	Flat fee	Spot market charging
Mode of communication	Static	Day-ahead

The mode of communication is static for CPP with a flat fee, this makes it easy to implement. Little communication is needed between market players. The DSO can update its prices on a yearly basis and communicate this to the contracted users.

CPP in combination with spot market charging has at least a DA communication for a forecast of the spot market prices for the next day. The DSO prices will remain static.

Variable connection capacity	Flat fee	Spot market charging
Mode of communication	Static	Day-ahead

The mode of communication in variable connection capacity with a flat fee is static. The DSO has a contract with the CSO or consumer. Yearly, the DSO can update the restriction period parameters. For example: the duration, starting time and maximum allowed power.

Variable connection capacity in combination with a spot market charging mechanism needs a DA mode of communication. The dynamic prices need to be forecasted for the next day to be able to schedule the charge profiles according to the most cost-efficient moment. The communication from the DSO remains static.

Direct control	Flat fee	Spot market charging
Mode of communication	Real-time	Day-ahead, Intra-day and Real-time

The communication mode for direct control with a flat fee is real-time. The DSO detects the overload and sends a direct signal to the charging stations which are connected to the congestion point. This implies the need for a secure method of communication, while a hack in a big number of charging stations could potentially lead to a black-out situation [71].

Direct control in combination with spot market charging also needs a real-time communication. As can be read in the previous paragraph of direct control, this asks for secured communication methods. In addition to this, the dynamic prices of the spot market ask for at least a DA mode of communication to be able to send the forecast to the aggregator for the planning of the charge schedules.

USEF	Spot market charging
Mode of communication	Day-ahead, Intra-day and Real-time

USEF has different modes of communication. Both DA, ID as real-time communication is needed. The DA is for the first flexibility negotiations between the parties. During this process the BRP can request flexibility for an adjustment of their portfolio. When the negotiations are settled, the DSO can check if it needs flexibility for a congestion management. The closer the moment of delivery the better the BRP knows the needed demand and supply in their portfolio. Therefor the same flexibility request can be done ID and even real-time. When an orange regime is proclaimed the DSO has the option to directly control the flexibility assets to prevent for a grid outage.

Conclusion

Real-time communication is needed when direct control signals are send. This is the case for direct control flat fee, direct control with SMC and USEF. Secured communication is needed to avoid hacking in the energy system. With the growing amount of charging stations, a hack can potentially lead to a black-out of the network. All other mechanisms rely less on communication which leads to lower implementation costs and a lower risk in case of a loss of telecommunication.

5.2.5. Component layer

The component layer refers to physical distribution of components in the mechanisms. To measure this the aspect technology readiness is evaluated. This indicates if a mechanism is operational or that a lot of development is needed before the system can be implemented.

Uncontrolled charging	Flat fee	Spot market charging
Technology readiness level	9	8

For uncontrolled charging with a flat fee the technology readiness level is determined at 9, this mechanism is the currently operational in the field.

The technology readiness level of spot market charging is indicated on 8. Reason for this number is that this mechanism is recently launched in the market and the first commercial system are arising. For this mechanism households need to have installed a smart meter and in addition to this need an app or (H)EMS. It is operational but needs to proof itself to reach the highest TRL level.

Critical peak pricing	Flat fee	Spot market charging
Technology readiness level	9	8

The technology readiness level of critical peak pricing is set on 9. This mechanism is operational and can be implemented directly, although in case of a conventional meter the number of tariff schemes is limited to the amount of measuring discs in the electricity meter, which is two. Regulation needs to be adjusted as well, while currently the DSO in the Netherlands cannot decide to change from capacity contracts to kWh-based contracts. This needs to be coordinated with the regulator.

CPP with spot market charging is set on a TRL of 8. This is mainly because of the TRL of the SMC which is described in the last paragraph.

Variable connection capacity	Flat fee	Spot market charging
Technology readiness level	7	6

The technology readiness level for variable connection capacity in combination with a flat fee is set on 7, which is lower compared to the mechanisms described before. Reason for this is that it is still tested in experimental environments and that the method of validation and verification for the mechanism is not operational. On the other hand, this mechanism has proved itself in an experimental environment and all communication protocols, software and hardware are implemented

Variable connection capacity is currently only tested with a flat fee. Therefore, the TRL of VCC with SMC is set on TRL 6.

Direct control	Flat fee	Spot market charging
Technology readiness level	4	4

The technology readiness for direct control with a flat fee is set on 4. Although direct control is not a new technique the current hardware and software in the electricity sector is not sufficient to execute this type of control. For example: new smart meters need to be installed in all charging stations while the current smart meters in the Netherlands are not equipped with a direct control option for the DSO. Currently, this mechanism is only used in little pilots in test environments in the Netherlands. Reason for this is that this mechanism has politically little support in the Netherlands. The political opinion suggests that this has too much impact on free competition.

Direct control with SMC has been set in the same TRL level of direct control with a flat fee. Separately, SMC is already in much higher TRL, but in combination with direct control it still needs to prove itself in pilot situations.

USEF	Spot market charging
Technology readiness level	6

The TRL of USEF is set on 6. The large-scale prototypes of the system are finished, and the demonstration of the system is being executed. To work with USEF a high level of connectivity and sensors is needed. Smart meters are currently being installed even as distribution automation.

Conclusion

The implementation of direct control and USEF still asks for a lot of development. These mechanisms are currently not operational. Direct control needs a lot of hardware modifications in the field which is expensive. USEF needs a high level of connectivity for validation and verification which is not present today. Therefore, these two mechanisms are not an option for current implementation. The other mechanisms have a significant higher level of development which could lead to a faster implementation.

5.3. Discussion results

In this chapter the discussion of the results will be presented. It will start with a description of the validation of the simulation. This will be followed by the results and the interpretations of the results. After this the limitations of the simulation will be given, and a suggestion will be done for future research.

The simulation that is developed is based on a real neighborhood in the Netherlands with real network data and statistic mobility data. Although this neighborhood is not directly representative for all other neighborhoods and different type of networks could give a different result, it does indicate what the effect of market mechanisms is on the transformer loads. Goal of this simulation is to compare the different market mechanisms in an equal environment. Due to the complexity in the sociotechnical system that is simulated and the uncertainty in the developments in the energy transition, there are several variables on which assumptions had to be made. For example, the amount of installed capacity of 2030. In the simulation the assumption is made that this is equal to the prediction of ECN. Implementing different amounts of installed capacity could show if this would influence the cost-based pricing mechanism. Another assumption that could influence the results it the fact the only one spot market is simulated. In real life there are several trade markets which influence each other. These trade markets are day-ahead, intra-day and the reserve markets. Next to this the position of the BRP which is connected to the energy supplier who is delivering the electricity is influencing the request for flexibility. Because of the complexity of these influences this has been left out of the simulation.

The results have indicated that dynamic tariffs have a positive damping effect on the charge schedules of the EV. However, this is strongly related to the level of price sensitivity. At least 80% of price sensitive EV drivers are needed to avoid overload on the transformer with a SMC mechanism, see Figure 32. If dynamic prices are communicated directly to the EV driver, the consumer needs to decide to either start charging immediately based on a certain price or to postpone their charging to a later moment without knowing for sure what the future prices will be. Research has found that at this moment most EV drivers tend to be risk-averse which indicates that most EV drivers rather charge immediately for a certain price than postpone their charge session [72]. This indicates that to implement dynamic prices new services need to be developed which take over the decision making of the consumer to reach high levels of price sensitivity.

This simulation has a few shortcomings, in the current implementation of the mobility data in the simulation an assumption is made about the number of pleasure trips in the neighborhood.

These trips can have a big impact on the moment of the EV start charging. There are situations thinkable that although the car has less than 100 km in its battery when arriving after its work, the EV driver decides to charge their car on a different moment while it has planned a trip in the evening. This will result in a lower peak demand during the evening peak than currently simulated. This can be improved in a next version of the simulation by validating the change of charging in between these trips.

The spot market charging scenario makes use of the relation between action and reaction. This means that if a charge schedule is planned the next schedule will be receiving a new updated price schedule. Although this iteration is modeled in the simulation for the scheduling of charge profiles, this is not implemented for the negative effect of uncontrolled charging. This results in lower average charging prices for uncontrolled charging than there would be if the mechanism was used with the level of adoption in the simulation.

In the market there is the assumption that EVs can be a solution for the decentral electricity generated by PV panels in neighborhoods. Since the simulation is based on a neighborhood with only residential activities, this leads to a situation that most of the EVs are not home during the day. When PV panels would be added to this simulation there will be a mismatch with the moment that PV panels are delivering electricity and the moment the EV needs energy. However, EVs that can be charged at a work location could have the potential to deliver the solution, while they have a long duration of parking during the day [70]. Therefore, other types of neighborhoods, for example: work related and city centers, should be subject for future research.

This simulation is based on four market mechanisms which are combined with SMC. These mechanisms are implemented in a certain way in the simulation. There are however, options to have more static or dynamic versions of these mechanisms. For example, the VCC mechanism is modeled as a static profile, this can also be implemented in a dynamic version, which would have an impact on the outcomes therefore future research should focus on dynamic implementations of the mechanisms.

The current mechanisms implemented in the simulation are mainly monitored on a costs basis. However, this could also be evaluated based on the amount of CO_2 emissions or other variables. Next to this the amount of EVs is now set on 80% which leads to the outcomes described in this thesis. The current adoption of EVs is much lower. Sensitivity analysis on the adoption of EVs in relation to the market mechanisms is a recommendation for research. Also, other flexibility appliances are not considered. These new appliances can have a big impact on the load profile of the households as well on the load profile of the transformer. Combinations of different flexibility appliances and market mechanisms are recommended to simulate in future research.

5.4. Conclusions

A few important conclusions can be derived from the simulation. First, a static profile, capacity based, or price-based solution will not result in a satisfactory solution for the DSO. A static profile will often result more simultaneous loads on the network which results in (new) peak loads in the profile on the transformer see Figure 33 and Figure 41. When there is a high penetration of EVs in a neighborhood this can lead to more congestion than without interference of the DSO. Next to this, it influences the degree of free competition while both solutions interferer with the mechanism of the market. When the DSO implements a static profile and EVs start charging simultaneous this leads to higher prices on the electricity market. The high simultaneous demand influences the electricity market in such a way that on moments high amounts of expensive balancing power is needed to keep the system stable. This means that the price increases for the EV driver, which can be seen in Figure 36. In addition to this, if the static price schedule set by the DSO is too guiding this could also lead to more simulations charging cars, which would influence the charging schedule in a negative way.

Another conclusion that can be made is that dynamic prices give a positive damping effect on the load profile of the transformer. This indicates that allowing market parties the possibility to use EVs for their business opportunities will lead to a positive effect for the expected congestion of the DSO, see Figure 30. It also leads to a lower average charging price and better utilization of the renewable installed capacity which is positive for the total electricity system. The simulation shows that EVs are flexible enough to change the demand to moments that there is a surplus of electricity, which is at moments the prices are low. This however is not the ultimate solution while it is still possible that prices are low on a peak moment in the network. Or that (too) little EV drivers are price sensitive. In this situation the DSO wants to have a possibility to actively use congestion management on certain locations in the network. Although dynamic prices lead to positive results in relation to cheap and renewable charging for the electricity system, the duration of the charge sessions takes more time. Which indicates the importance of a flexibility system design in which services are delivering enough additional benefits for the EV driver.

The simulation has shown that EV drivers have a lot of flexibility in their charging schedules. Figure 56, shows that even if the DSO sets its threshold of the transformer on a maximum of 160 kW, which is more than twice as low as the threshold would normally be in this neighborhood, the EV driver has no noticeable effect on the number of prematurely finished charging sessions or fast charging sessions. This indicates that the EV driver has a big flexibility potential. This also indicates that although the DSO or BRP make active adjustments to the charge schedule this hardly ever leads to problems for the EV driver. However, to get a high adoption of smart charging it is important to consider the preferences of the EV driver and give real-time feedback to the EV driver to enable them to link their behavior to consequences [13]. Next to this the service offered to the EV driver needs to improve the experience of the EV driver and on the same moment yield substantial profits for the service operator [73].

When looking at all aspects in Table 7, it can be said that a lot of mechanisms are not useful to implement either for DSO or electricity market while it does not solve their problems. Reason to implement a flexibility market mechanism is to lower congestion and use flexibility for balancing services or portfolio management for which free competition is needed. Therefore, CPP with a flat fee and CPP with SMC, VCC with a flat fee and direct control with a flat fee will not be considered for the development of the system design. As is concluded from the results of the simulation dynamic prices have a damping effect on the load profile of the transformer, however the reliability of dynamic prices is too low for a DSO to only rely on for congestion management therefore this is also eliminated. The three mechanisms that are left over are VCC with SMC, direct control with SMC and USEF. As direct control has little political support in the Netherlands, this has resulted in the implementation of smart meters which are not controllable by the DSO. To implement direct control with spot market charging a lot of adjustments, hardware and software need to be made to the current system. Therefore, this mechanism is also eliminated. As can be read in section 5.2, USEF is a market mechanism that is built on two assumptions, there needs to be enough flexibility to have a liquid market on local scale and communication needs to be established between all actors involved. These two assumptions ask for a mature market with a high EV penetration. Currently there are less than 1% BEVs in the Netherlands. Therefore, in this maturity stage of the EV market a control signal from the DSO which is incorporated in the capacity contract seems the best solution for congestion. This is supported by the fact that if the spot market charging works effectively only a few moments of overload are expected. Next to this the control possibilities from the CSO to charging station are developed.

6. System design for EVs

In this chapter the system design for flexibility from EVs will be described. It will start with the functional design in which an overview of the functions needed in the system will be given. This will be followed by a physical design which will describe which actions will be executed by which role. The chapter will end with a qualification of all interaction in the system.

The conclusion of the simulation has indicated that a dynamic pricing system with an interaction between the demand of EVs and the price level is a solution that will be beneficial for congestion. This solution supports free competition which leads to lower prices for the charging of EVs. Although it is beneficial for both the market as the DSO it does not guarantee that congestion is avoided. There are scenarios imaginable with low prices during a peak moment in the network could result in congestion. Therefore, the DSO needs to have an extra control mechanism to stay within network constraints at a similar amount of reliability of grid reinforcement. The evaluation of the mechanisms in section 5.2 has indicated that this control signal cannot be send directly to the charging station by the DSO, while hardware and software are insufficient. However, the connectivity of the CSO to the charging station is implemented with a high degree of connectivity leading to the possibility to send the overload signal via the CSO.

A flexible capacity contract needs to be offered by the DSO to the connected parties with flexibility. This is possible by offering a product by the DSO which has for example a base load capacity of 4 kW and a variable capacity of 13 kW. The 4 kW is based on the current household load which is normally within 1 to 4 kW simultaneous demand. The additional flexible appliances like heat pumps and EVs can be controlled on moments that overload is detected by the DSO but only until the base load capacity of 4 kW. This overload signal will be send either directly to the

(H)ems or aggregator which will control the EV and other appliances. The overload signal will contain a request to lower the capacity in kW.

The aggregator has the responsibility to procure flexibility in the market and to know the technical possibilities of the different flexible appliances. For example: a heat pump needs to be controlled differently from an EV while the heat pump has different input variables. A heat pump is controlled by temperature levels while the EV has variables as leaving time and energy need of the battery. When the aggregator has a flexibility portfolio it can offer the flexibility to the market. The BRP has the option to procure the flexibility of the aggregator. This start in a DA process in which the BRP can buy a certain amount of flexibility for adjustment of its portfolio and/or reserve flexibility for operational reserves during the day of delivery. The BRP and aggregator will both be responsible for the imbalance settlement after the day of delivery. This means that the BRP and aggregator need to plan supply and demand of their portfolio for the next day. It is possible that for the balance of the portfolio, the both parties want to procure flexibility DA or that it is needed to change its position in the market real-time.

6.1. Functional design private and public charging

The functional design will describe the tasks of the system for private and public smart charging. The goal of the system is to charge the battery of the electric car in an economically and environmental friendly manner. This means that it is possible to adjust the timing of the charge session and the amount of power. This means that when the EV driver plugs-in its EV, it will not start to charge automatically but that the aggregator checks when the cheapest or greenest moments are for charging within the total connection time of the EV driver. This optimization will lead to lower costs for BRP and DSO which will result in lower costs for the EV driver.

The system needs to be designed to meet the needs of the EV driver while the EV driver is the owner of the flexibility. This means that the system needs to be easy to use for the EV driver and deliver additional benefits than without using the system. Therefore, the system is designed in a way that the EV driver does not need to change its charge behavior. The simulation has indicated that the EV driver has enough flexibility during its current parking time which implies that behavioral changes are not necessary, which is also supported by [70]. To optimize the charge schema the only variable the EV driver needs implement in is its leaving time. In the future it is possible to automate this variable by either using an algorithm that calculates the leaving time or by having direct insights in for example the agenda of the EV driver.

The functions the system needs to perform can be found in Figure 57. The system needs to be able to optimize the charging schema based on the input of the EV driver, BRP and DSO. The role that performs this task is the flexibility aggregator for public charging or (H)ems for private charging. This role is not yet connected to a party which means that both the OEM, MPS, BRP/energy provider, CSO or independent party can take this new role. All these parties have a connection to the EV market and can offer an added value by providing this service. For example, the OEM is the car manufacturer which has the connection to the EV and can therefore deliver the SoC of the car. On the other hand, the BRP is responsible for trading of electricity and can deliver the dynamic prices for the optimization of the charge schedule. The BRP can use the flexibility of the EVs to adjust its portfolio. For the description of the system design the aggregator is seen as a separate role from the other parties.

When the EV driver decides to offer its flexibility to the market it chooses a contract which matches its optimization preferences. This can be for example: most cost efficient, renewable optimization or home optimization.

6.1.1. Description day-ahead functional design flexibility process

In Figure 57 the functional design can be found of the DA flexibility process. The DA process is needed to be able to identify, forecast and negotiate flexibility. In the DA process the BRP buys flexibility for the change of their portfolio or it can reserve an amount of flexibility as operational reserve for real-time adjustments of their position in the market during the moment op delivery. The aggregator therefore needs to know how much flexibility it can offer from its portfolio.

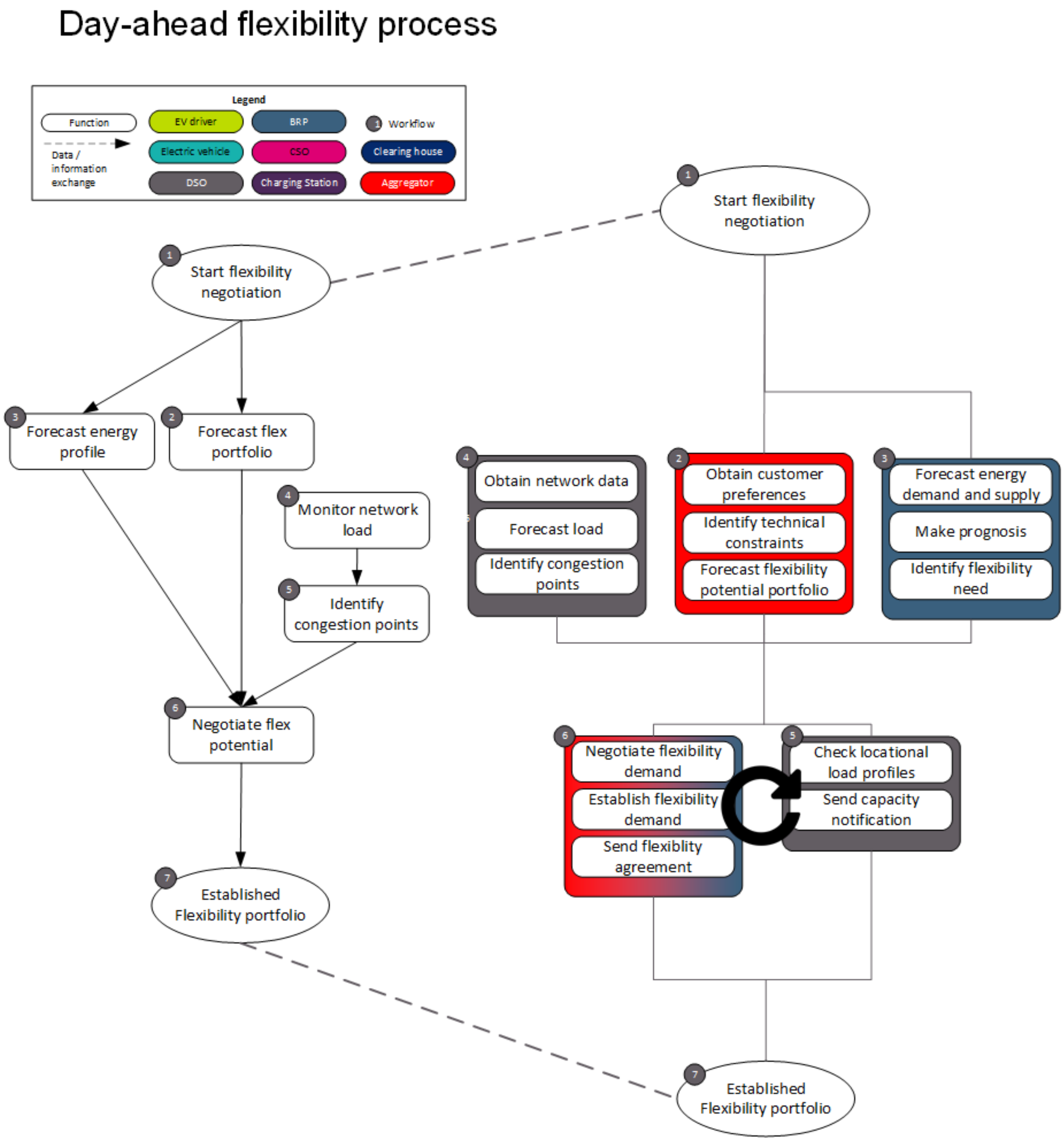

Figure 57, DA functional design to charge in an economically and environmentally way for private and public smart charging

The DA process start with a flexibility negotiation. First the aggregator needs to obtain all the customer preferences. These preferences are the leaving time and optimization preferences. This is followed by an identification of the technical constraints of the flexibility appliances. The preferences and technical constraints together form the foundation for the forecast of the portfolio.

Other data that can be used is for example: weather information, when the outside temperature is below zero the battery of the EV has different characteristics then when it is hot and sunny.

Parallel to this process, the BRP is calculating its portfolio. This portfolio is based on the total demand and supply in its portfolio. The BRP will continue to look for the possibilities in the trade markets and in the flexibility market for the adjustment of its portfolio. If flexibility is interesting to procure for the DA portfolio it will contact the aggregator. This can be on a trade market but can as well by bilateral contracts.

In addition to this the DSO obtains the load details out of the sensors in its network and will make a forecast of the capacity utilization of the cables and transformers. This forecast is enriched by weather data and historical load profiles of the network. This together results in an identification of the congestion points in the network.

At the start of the negotiation of the flexibility agreement, the aggregator and the BRP will negotiate the flexibility demand. If possible the BRP will procure flexibility for its adjustment of the portfolio and reserves flexibility for operational reserve. When both parties agree on the level and moment of delivery of the flexibility, the agreement will be settled and the portfolios including locational parameters of both aggregator and BRP will be send to the DSO. The DSO will check the portfolio of both aggregators and BRPs for congestion problems. If the settlements cause congestion problems, the DSO will send a notification to the aggregators and BRPs who are responsible for the congestion. This is a notification to indicate an adjustment needs to be made to the portfolios on a certain moment of the day. However, it is voluntary if the aggregators and BRPs do or do not adjust their portfolios. If adjustments are made the negotiation will continue. This process can have several iterations before the portfolios are established.

6.1.2. Description real-time functional design flexibility process

The real-time flexibility process of electric vehicles starts when an EV driver, which is contracted to a flexibility service, decides to charge its car. The EV driver starts a charge session by scanning its charge card. The charging station receives the RFiD details of the EV driver from its charge card and checks at the clearing house if the EV driver can be identified and if it is connected to an aggregator. When this is the case the aggregator gets a message of the clearing house that one of its customers is starting a charging session.

The EV driver will give in its leaving time on an app or at the control panel in its EV to the aggregator. The aggregator will inform from the EV, the energy need and the maximum power settings. Next to this the aggregator asks the charging station for the connection time and the local constraints. A possible local constraint can be that a charging station has two connectors and that two cars are connected. If the charging station has a lower capacity connection to the grid than the two cars need the charging station will start a local balancing service. The aggregator needs this to adjust the charging schedule according the local possibilities. When the aggregator has all the input, it will check the dynamic prices within the charging period of the EV driver. The aggregator will process all the charge details and calculates a charge schedule, next to this it will also check the flexibility potential of the EV. The level of flexibility potential is related to the amount of time the EV will be parked, the demand of electricity and the technical constraints of the charging station and EV. Based on these two parameters and the agreement with the BRP, the aggregator schedules a charging session.

This leads to the start of the charging session. The EV will start charging and during this, actively monitors the battery level. Both the DSO and BRP start an active monitoring. The DSO monitors its network, if an overload is detected at a certain point in the network an overload signal will be send. The BRP looks at its portfolio, if an imbalance is detected the BRP sends a flexibility request to the aggregator. The aggregator looks at the possibilities in its portfolio and adjust the active charging sessions if possible within the preferences of the EV drivers. Important difference between the overload signal of the DSO and flexibility request of the BRP is that the signal of the DSO has a location parameter. This means that the DSO will ask one or more aggregators on a certain cable of transformer to lower their load. This lowering is contracted by the DSO in the capacity contracts with the CSO and is obligatory for the aggregator to respond to. The flexibility request of the BRP however is a national request and has therefore a bigger pool of EVs which can deliver the flexibility.

The charging session ends when the battery is fully charged. When the EV driver is ready to use the EV again the EV driver will plug-out the charge cable by scanning its charge card. This triggers the payment to the aggregator.

Real-time flexibility process

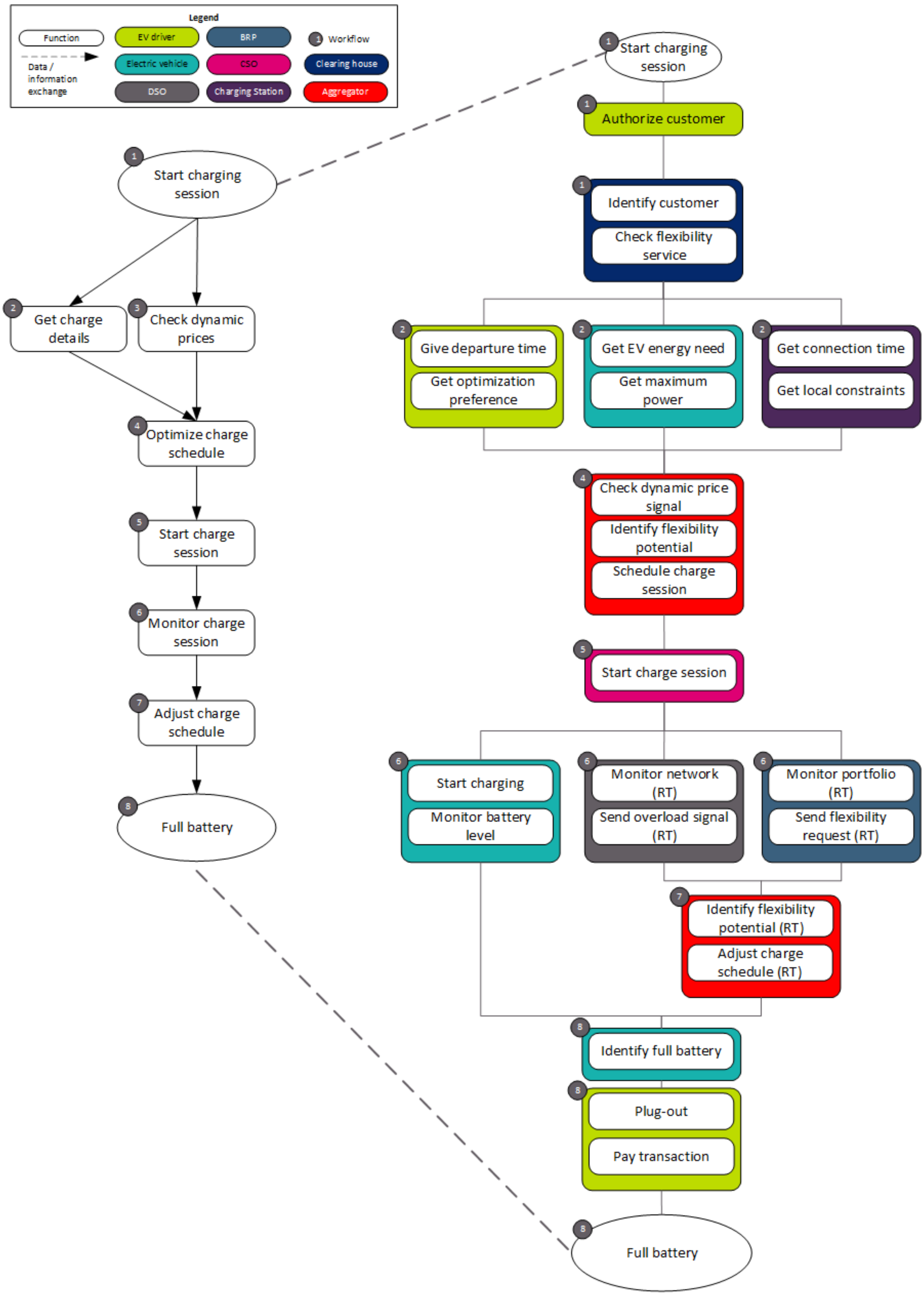

Figure 58, Real-time functional design to charge in an economically and environmentally way for private and public smart charging

6.2. Physical design private and public charging

As described in section 2.4, there are two different types of market designs in the Netherlands. These are a private charging and a public charging market design. The biggest difference is that in the private charging market the charging station is connected behind the household connection and smart meter while the public charging station is directly connected to the LV network with an own connection and smart meter. This has also influences on the physical flexibility market design which can be seen in Figure 59 and Figure 60.

6.2.1. Private smart charging market design

The private market design for smart charging can be found in Figure 59. The functions that are necessary for private smart charging can be found in Table 8. The charging station in a private situation is part of a bigger environment with other smart appliances. This is controlled by a (H)ems which operates the energy demand of the household based on the preferences of the consumer. The consumer implements its preferences like for example cost optimization and/or optimization of the connection capacity in the (H)ems to indicate the variables on which the (H)ems can control the household appliances.

In Figure 59, both the actions (blue), physical (pink lines) and financial (green lines) interactions are displayed. In the private market design the consumer can choose its own energy supplier. This energy supplier can also function as the role of EMS but other parties like the CSO and MSP can also offer these services. The EMS will optimize the charging schedule to the given preferences of the customer. Although in this picture the EV is the only flexible load, other loads like the heat pumps and PV-panels can also be part of the optimization. Next to this, the EMS can work central as an aggregator or decentral as an appliance in the household.

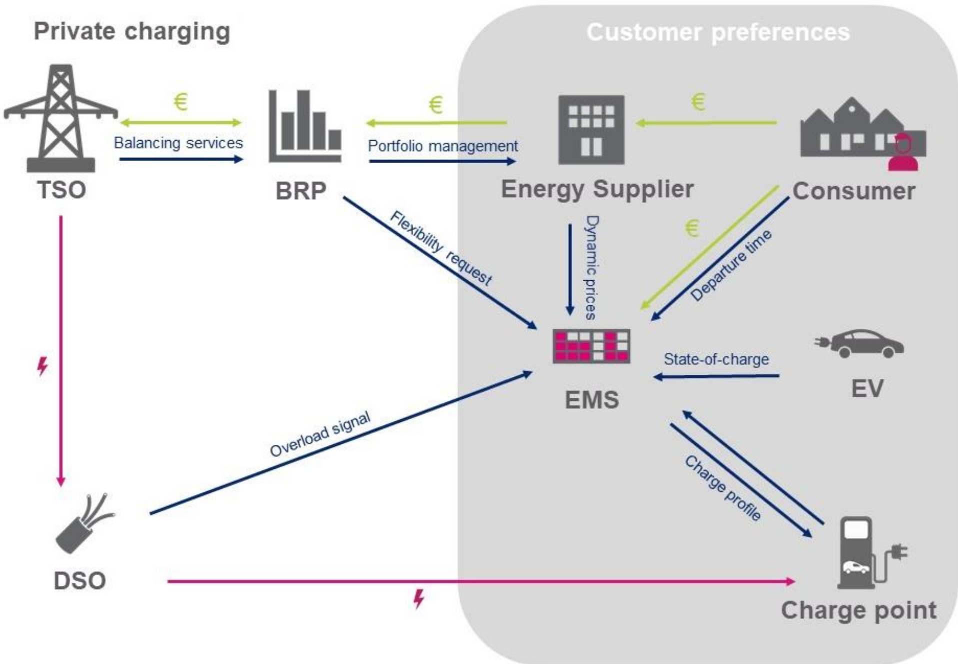

Figure 59, Design of the private smart charging market with the energy management system as the central role.

Table 8, Description of actions for private smart charging

Role	Role	Action	Explanation
TSO	BRP	Balancing services	Adjustment of power depending on the frequency of the electricity system. (Inter)national system which has no locational constraint.
BRP	Energy Supplier	Manage portfolio	Management of portfolio by using demand-response of EVs to adjust position in the market.
Energy supplier	EMS	Send price signal	Depending on the prices on the spot market the energy supplier sends dynamic price signals to EMS for the costs of the electricity.
Consumer	EMS	Send departure time	The consumer sends its expected departure time to the EMS to indicate the moment that the battery needs to be charged.
EV	EMS	Send State-of-charge	The SOC data of the battery is send by the EV for the planning of the charging schedule.
Charging station	EMS	Send connection time	The charging station sends the connection time of the EV for input on the charging schedule.
DSO	EMS	Send overload signal	If an overload of the network is detected the DSO sends an overload signal with the amount of power (kW) which needs to be lowered.
EMS	Charging station	Send charge schedule	Based on the send departure time of the consumer, the moment of connection, the SOC of the EV and the expected prices on the electricity market the EMS calculates the charging schedule. If an overload signal is send by the DSO a new charging schedule is calculated.

6.2.2. Public smart charging market design

The public smart charging market design can be found in Figure 60. In this design there are two new roles added compared to private charging: The aggregator and clearing house. The aggregator has the direct connection with the consumer and can incorporate the preferences of the consumer in the charging schedule. The other role is the clearing house, this role is responsible for the interoperability of charging services. There are two options for public smart charging, with or without a free choice of energy supplier by the consumer. When the consumer chooses its own energy supplier the market design gets more difficult while the current market model is based on the fact that the connection (EAN) is always directly linked to an energy supplier. This decoupling means that the CSO will only have a contract with the DSO for its connection and that the charging card of the consumer is linked to an energy supplier and BRP. The reason both energy supplier and BRP need to be linked to the consumer is because the BRP has the end-responsibility to the TSO for its real-time balance of its portfolio. If these two parties are not connected it means that a party can change the position of a BRP in the electricity market without consequences.

The colors have an equal meaning compared to the last figure, which means that the actions (blue), physical (pink lines) and financial (green lines) interactions are displayed. The customer sends its preferences to the aggregator and the energy supplier the dynamic prices. Based on this information the aggregator makes the first initial flexibility profile of its portfolio. Which gives the aggregator the opportunity to offer flexibility to the BRP day-ahead. The BRP can adjust its portfolio with the use of flexibility, when the flexibility is more interesting than trading on the market. These two parties will have a negotiation about the possibilities and this leads to an iteration in the initial charge schedules of the aggregator. When the charging schedules are established the DSO will check if any problems arise from the charging in the network. If this is the case a voluntary message is send to the aggregators and BRPs who are causing the congestion problem.

Real-time the charging will start when the EV driver shares its departure time. This is the leading factor for the charge schedule. The aggregator will schedule this, based on the preferences of the customer, prices on the market and flexibility need of the BRP. The charging schedule is send to the CSO who sends it to its charging station. If real-time overload is detected by the DSO if will send an overload signal to the CSO who will adjust the charging profiles. The CSO will inform the aggregator about the adjustments.

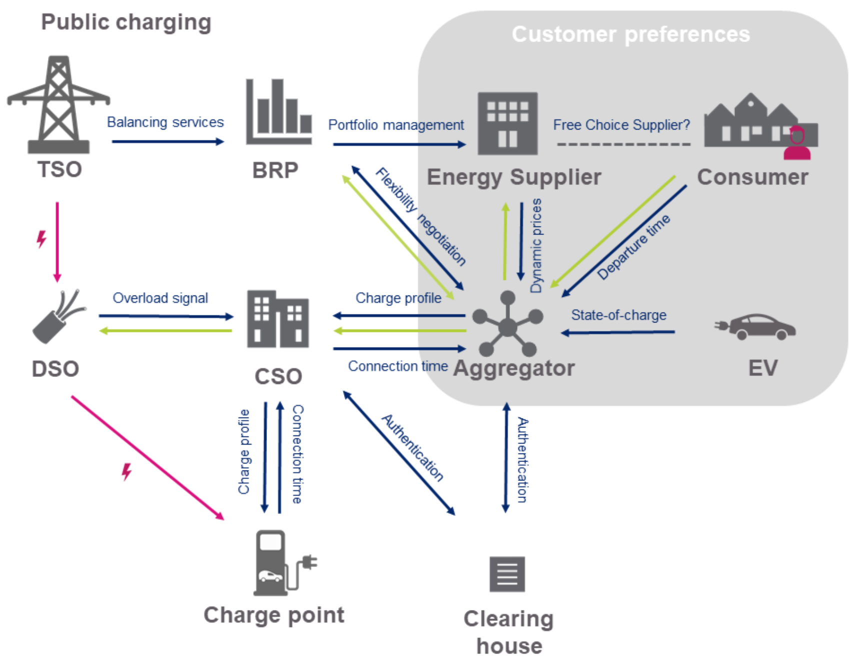

Figure 60, Description of actions for public smart charging

Table 9, Description of actions for private smart charging

Role	Role	Function	Explanation
TSO	BRP	Maintain balance	Adjustment of power depending on the frequency of the electricity system. (Inter)national system which has no locational constraint.
BRP	Energy Supplier	Manage portfolio	Management of portfolio by using demand-response of EVs to adjust position in the market.
Consumer	Aggregator	Send departure time	The consumer sends its expected departure time to the aggregator to indicate the latest moment that the battery needs to be charged. Based on the departure time of the consumer, the moment of connection, the SOC of the EV and the expected prices on the electricity market the aggregator calculates the charging schedule. If an overload signal is send by the DSO a check is done if a new charging schedule is needed
EV	Aggregator	Send State-of-charge	The SOC data of the battery is send by the EV for the planning of the charging schedule.
Energy supplier	Aggregator	Send price signal	Depending on the prices on the spot market the energy supplier sends dynamic price signals to the aggregator for the costs of the electricity.
BRP	Aggregator	Flexibility negotiation	The BRP and aggregator negotiate the flexibility need and potential and adjust the charging schedules according to the arrangements.
CSO	Aggregator	Send connection time	The CSO sends the connection time of the EV to the charging station to the aggregator.
Aggregator	CSO	Send customer preferences	The aggregator receives the preferences of the customer and the SOC of the EV and sends these to the CSO to make the charge schedule.
Charging station	CSO	Send connection time	The charging station sends the connection time of the EV for input on the charging schedule.
DSO	CSO	Send overload signal	If an overload of the network is detected the DSO sends an overload signal with the amount of power (kW) which needs to be lowered.
CSO	Charging station	Send charge schedule	The CSO sends the received charging schedule to the charging station and sends the overload signal to the charging station. Next to that it informs the aggregator about the changes in the charge schedule
Clearinghouse	Aggregator /CSO	Arrange Authentication	The clearinghouse arranges the authentication of the EV-driver at the charging station

6.3. Interactions

Interactions are needed between parties to transfer data to be able to schedule the charging sessions. For these interactions (open) protocols are needed. In Figure 61, a schematic view can be seen.

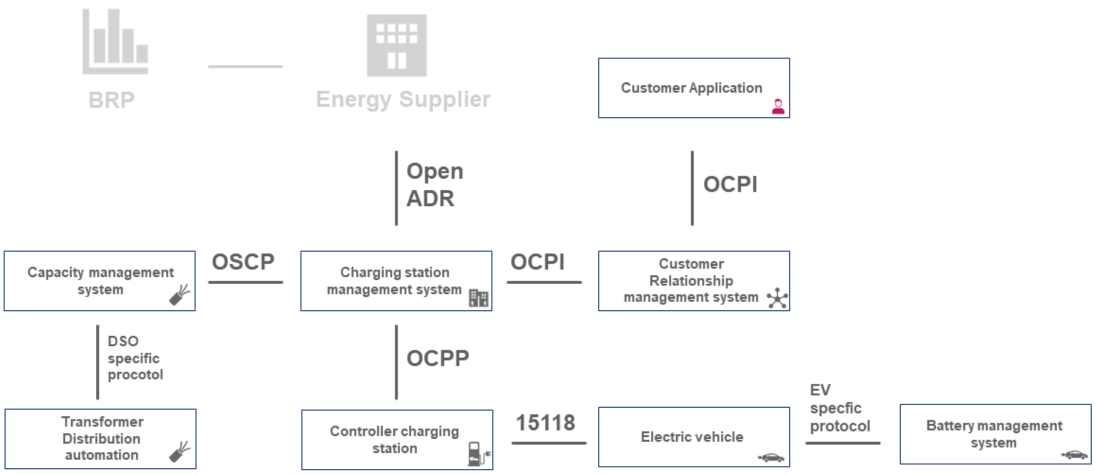

Figure 61, Interactions between roles in the EV system design for flexibility

Transformer distribution automation (light): Measures the load on the transformer and outgoing cables. This data is collected and send to the capacity management system. In combination with the grid topology which contains for example the maximum load of the cables the available capacity can be calculated.

Capacity management system: The goal of this system is to reach an efficient utilization of the network capacity by giving control signals to market players to change the load profile of flexible loads. To be able to actively participate as a DSO in the flexibility system there is a need to have (real-time) measurements of the loads on the electricity network. The first steps to reach these measurements are currently being implemented (distribution automation (light)). The measurements can be used to develop forecasts of the load on the network. These forecasts are needed for the scheduling of the charge profiles of flexible loads while without a forecast it is not possible to decide to postpone a charging session or not. While it is not clear what the cheapest moment or moment with the lowest chance on congestion is. Next to the measurements, the forecast can be enriched with additional data for example: weather forecast, historical use, grid topology, capacity of the network and type of connections.

Charging station management system: The back office of charging stations controls and manages the charge sessions. The management system receives messages of the controller of the charging station about the operations in the field.

Controller charging station: Controls all actions that are performed by the charging station. It communicates with the charging management system of the CSO and can perform local load balancing. The controller can get messages from the EV, for example the SOC of the battery.

Customer relationship management system: This system receives the preference data from the EV driver. Next to this it also manages the other needed customer services for example billing and authentication.

EV: The state-of-charge need to be communicated to the CSO. The EV gets this data from the battery management system of the battery. When the car is connected to the charging station the EV sends the SOC to the charging station. The charging station will pass the data of the EV to the charging station management system.

Battery management system: The battery has a management system which manages for example: the rechargeable battery to stay within the limits of the safe operation area and monitoring the state. The system reports the SOC of the battery and communicates this to the central system of the EV.

Customer Application: The customer needs to be able to put in their preferences. Therefore, an application is needed in which the consumer can indicate their leaving time. This is essential data for the planning of the charge schedule while it indicates the amount of flexibility available. This application can be either a mobile phone app or a service in the EV. Important is that this service is easy to operate [13].

6.4. Implementation

The current adoption of EVs is still low. Hence, it is hard to predict how people will react on new services as smart charging with dynamic prices. When this is compared to research which focusses on smart devices in the household environment, research suggests that a user-friendly design of smart energy appliances is necessary to change energy related behavior of consumers [52]. Next to this, consumers are not willing to spend extra money for smart energy devices. This suggests that new product propositions and services need to be developed to convince the consumer to install smart devices. The first step to reach a higher penetration is to place an emphasis on privacy and security of data gathering by the devices. Not only the ownership of smart devices is low in the Netherlands also the frequency of use is low. In the pilot Your Energy Moment 2.0 the participants used the HEMS only ones a week [74]. A compelling story is needed to convince participants to use smart energy devices in combination with outstanding customer service, the knowledge of smart devices and transparency and protection of the privacy of the customers [75]. To understand the decisions a smart device takes, it is needed that the consumer understands the correlation between the input parameters and the end-decision of the device. When this is unbalanced the consumer will probably not understand the actions taken and will not be satisfied with the smart device.

The flexibility system design that is presented, assumes that there is a high level of connection in the electricity network. This is the case for (most) public charging stations which have recently been upgraded to be smart charging ready, in the Netherlands. This means that the charging stations are connected to a back office and that the charging station can receive and process charging profiles remotely. Although the level of smart meters at households is increasing rapidly, the DSOs have just started implementing the sensors in the transformers on the MV and LV level. Therefore, to implement this flexibility system design in the network an estimation needs to be made of the capacity in the network by the DSO. This would lead to the possibility to test the flexibility system design without a need for an implementation of sensors in the network. The DSO needs to communicate this data to the CSO and the CSO can adjust the charge schedules DA to the constraints of the DSO. In addition to this, lowering the number of iterations by the BRP to only a DA process for portfolio adjustments would increase the manufacturability of the system.

The simulation has suggested that dynamic prices can lead to a damping effect on the load profile of the transformer. This effect will only work for the DSO when the charge schedules have an equal dissemination on national level. If the location of the flexibility asset is not part of the algorithm it is still possible that all EV on the same cable or transformer receive a similar charge schedule. This will still lead to congestion. This can be overcome with by two options either the aggregator uses a location setting in their algorithms or a peer-to-peer communication is needed between cars to reach a local equilibrium.

7. Conclusions and future work

In the beginning of this thesis the design issue has been introduced in chapter 1. Together with the background context of the power system in chapter 2, this has resulted in a list of aspects on which the flexibility mechanisms can be evaluated, see chapter 3. The evaluation is substantiated with the outcomes of the simulation which is presented in chapter 4. The results of the simulation in combination with the evaluation of the aspects, as described in chapter 5, have resulted in a system design which is presented in chapter 6. This last chapter will summarize the outcomes of this thesis and gives future recommendations for the development of the system design.

The simulation has showed that a static signal by the DSO leads to an accumulation of charge sessions. When a static price or capacity profile is implemented, the automation in control of charging results in a static reaction on the cheapest moment or at the end of the restriction period. This results in a higher overload on the transformer than when the DSO does not implement a market mechanism. In addition to this a static signal can trigger high electricity prices and imbalance in the system while the accumulation of charging asks for a high peak demand in installed generation capacity.

Overall, a dynamic price signal leads to a damping effect on the load profile of the transformer. Therefore, the free competition of the market can help the DSO. However, this can only be accomplished when the price sensitivity of the EV drivers is high. Therefore, flexibility services need to offer not only a cost-effective solution but as well additional benefits for the consumer. In addition to this, dynamic prices can still lead to congestion problems in the network on specific moments, for example: when there is a high level of renewable electricity on a peak moment in the network. Therefore, a congestion signal is implemented in the flexibility system. When overload is detected the DSO will send a message to all aggregators who are connected to the congestion point.

This thesis has showed that EVs can deliver a lot of flexibility within their “normal” time schedule. Therefore, the charge schedules can be adjusted without a need for behavioral changes. This is positive for the parties who want to use flexibility of the EVs while behavioral change is difficult to accomplish. However, the system for flexibility needs to have a high level of user-friendliness to order to accomplish the acceptation of the system design.

7.1. List of future recommendations

- Further validation of the assumption used in the simulation made in this PDeng is recommended. The charging need is based on the mobility behavior, because of the lack on specific charging data. Next to this, more neighborhoods with different characteristics need to be added. Interesting is a neighborhood were both work and residential activities take place. Also, the adoption level of EVs is interesting to adjust. In the simulation the adoption of EVs is high. A comparison on the working of the market mechanisms with a certain adoption of EVs can lead to different conclusions. For example: a static profile might be useful with a low adoption of EVs in the neighborhood but with a high-level can have a counter-effect. When this is implemented a recommendation of an implementation order of the market mechanisms can be described.
- The system design presented in this thesis has not been tested in a pilot situation. This means developments are needed to reach an implementation in a small-scale pilot. A theoretical comparison needs to be made of the functions named in the system design to the protocols already existing in the field. If some functions are not supported new functions need to be added. If this is finished, the system can be tested in a pilot environment to validate the functions as presented in the last chapter.
- If new protocols need to be designed, for example to communicate the capacity constraint to the market by the DSO, these need to be open and developed in cooperation with the market. This will give higher development costs because of the needed alignment between parties, however implementation in the long run will be much easier. Next to this it allows new market parties to enter the market easier.
- Flexibility is obtained from EVs which leads to a heavy reliance on the consumer. However little research is executed on the customer acceptance of smart charging. Low costs benefits are expected from offering flexibility, although not offering flexibility will lead to high investments. This makes it important to perform customer research to additional benefits which can be derived from a flexibility system.
- The system design that is presented consist of three major market parties. These parties need to be incorporated in early stages in the development process of the system for the involvement and embedding in the sector.
- When the system design is tested in a large-scale environment it is important to find alignment with the regulator of the DSO and TSO to embed the new system in the regulations in the Netherlands.

Appendices

Appendix A - Capacity connection costs

Table 10 Capacity connection costs [44]

Category	Transmission value (A)	Capacity tariff per year6	Computed capacity (kW) (based on lumpsum use)	Maximum capacity (kW)
1	1x6 (Switched grid)	€2	0,05	1,4
2	3x25	€170	4	17,3
3	3x35	€850	20	24,2
4	3x50	€1400	30	34,6
5	3x63	€1700	40	43,6
6	3x80	€2100	50	55,4

[6] Capacity tariff per year: The level of the transport-dependent consumer tariff is proportional to the computing capacity as used by the network operators, taking into account the coincidence factor. This means that 3x25A is a fifth of that for 3x35A. The capacity tariff is the largest part of the periodic costs that grid managers charge [43].

Appendix B – Overview of the characteristics of the simulation

Table 11, Overview of characteristics used in the simulated neighborhood

Overview of characteristics in the neighborhood		
Number of inhabitants	398	
Adults	308	
Children	90	
Number of EVs	165	
Appartments	117	
Detached houses	6	
Terraced houses	63	
Corner houses	19	
Private charging	24	
Maximum power private	11 kW	
Public charging	141	
Maximum power public	22 KW	
Change that an adult works	0,6	
Battery sizes	30 - 100 kWh	
Fast charging when	<10 km	
Work charging	30%	
Public charging based on SoC	<100 km	- 95%
	100-200 km	- 60%
	200+ km	- 30%
Installed capacity of year	2030	
Tranformer in neighborhood	630 kVA	
*Threshold 630 kVA with power factor	535 kW	
Simulated transformer	400 kVA	
*Threshold 340 kVA with power factor	340 kW	
2 cables	145 A	
2 cables	220 A	
1 cable	260 A	

WORK:

- All adults that work, work fulltime
- People who work leave for work between 6:30 – 9:00
- Every day this has a random adjustment of +/- 30 minutes
- Distance to drive is a fixed
- It is possible to charge at the office
- When the agent arrives at the office it will leave within 8 – 9 hours
- 30% charges at the office

DAY

- Time window for departure between 9:00 and 14:00

- Duration of visit between 30 min – 4 hours
- Chance of charging on location: 15%

EVENING
- Is based on individual agents
- Is based on time of arrival of day or work trip
- The change that someone decides to go on an evening trip is 10% to 40%
- Duration of the trip is 30 minutes to 3 hours
- Chance of charging on location: 15%

WEEKEND
- Time window of departure is 7:00 until 15:00 with a peak between 11:00 and 13:00
- Duration of visit between 3 to 8 hours
- Chance of charging on location: 15%

Appendix C – Predictions installed capacity ECN

Table 1: Major assumptions and input values of all scenario cases, 2015-2050

		Reference scenario			Alternative scenario		
	Unit	2015	2023	2030	2023	2030	2050
Electrification							
Share of EVs in total passenger cars	[%]	2.0%	4.7%	9.6%	12.0%	32.0%	74.0%
Share of HPs in total households	[%]	2.1%	6.5%	7.9%	8.0%	20.0%	69.0%
Conventional load	[TWh]	111.8	111.6	112.2	111.6	112.2	112.0
Additional load EVs	[TWh]	0.5	1.2	2.5	3.0	8.4	21.5
Additional load HPs	[TWh]	0.2	0.8	0.9	0.9	2.5	9.3
Add. load 'Other electrification'	[TWh]	0.0	0.0	0.0	10.0	30.0	90.0
Total final load	[TWh]	112.5	113.5	115.6	125.5	153.1	232.8
Power from variable renewable energy (VRE) sources							
Installed capacity:							
• Wind on land	[MWe]	2,630	6,020	6,330	6,020	6,330	6,800
• Wind on sea	[MWe]	360	4,120	6,060	4,120	6,060	28,900
• Sun PV	[MWe]	1,530	8,640	15,130	8,640	15,130	56,100
• Total VRE power capacity	[MWe]	4,520	18,780	27,520	18,780	27,520	91,800
Full load hours:							
• Wind on land	[hrs]	2310	2670	2860	2670	2860	2900
• Wind on sea	[hrs]	3580	4080	4120	4080	4120	4160
• Sun PV	[hrs]	840	820	820	820	820	820
VRE power generation (uncurtailed):[a]							
• Wind on land	[TWh]	6.1	16.1	18.1	16.1	18.1	19.7
• Wind on sea	[TWh]	1.3	16.8	25.0	16.8	25.0	120.2
• Sun PV	[TWh]	1.3	7.1	12.4	7.1	12.4	46.0
• Total VRE output	[TWh]	8.6	40.0	55.5	40.0	55.5	185.9
Total VRE output (uncurtailed) as share of total final power load:	[%]	8	35	48	32	36	80

a) *Uncurtailed* power generation refers to VRE output *before* any curtailment of electricity production from sun/wind takes place, based on installed capacity and full load hours, whereas *curtailed* power generation refers to VRE output *after* any curtailment of electricity production from sun/wind.

Appendix D – Results of simulation

Table 12, Results of simulation per week, average of 1 run of 12 weeks

	UC-F	SMC	CPP-F	CPP-SMC
€ per kWh spot market charging neighborhood	€0,030	€0,019	€0,121	€0,026
€ per kWh incl. fast and work charging	€0,033	€0,023	-	-
€ per kWh incl. fast and work charging & network	€0,093	€0,083	€0,157	€0,074
Average local charging power per EV [kW]	20,98	2,5	2,5	1,83
Average charging time	0,74	6,37	6,21	8,34
Amount of charged load [kWh]	8670	8298	8393	8667
Overload 340 kW [minutes]	477	17,2	414,5	25,8
Overload 340 kW [kWh]	542,5	9,3	3862,2	13,3
Overload 535 kW [minutes]	9,08	0,00	410	0
Overload 535 kW [kWh]	33,9	0,00	3861,2	0
Number of charging sessions	623	614	619	626
Unfinished charging sessions	10	41	34	39
Fast charge sessions	13	13	13	12

	VC-F (0KW)	VC-F (4KW)	VC-F (10KW)	VC-SMC (0KW)	VC-SMC (4KW)	VC-SMC (10KW)
€ per kWh spot market charging neighborhood	€0,024	€0,026	€0,028	€0,021	€0,020	€0,020
€ per kWh incl. fast and work charging	€0,027	€0,029	€0,031	€0,025	€0,025	€0,023
€ per kWh incl. fast and work charging & network	€0,087	€0,089	€0,091	€0,085	€0,085	€0,083
Average local charging power per EV [kW]	8,9	11,3	15,2	1,9	1,9	2,1
Average charging time [hour]	1,71	1,35	0,99	8,01	7,78	7,14
Amount of charged load [kWh]	8516	8624	8663	8259	8320	8323
Overload 340 kW [minutes]	446	295	325,5	30,9	17	11,6
Overload 340 kW [kWh]	2003,2	808,8	207,6	32,1	13,7	6,4
Overload 535 kW [minutes]	258,6	108	1,2	2	0,7	0
Overload 535 kW [kWh]	1970,6	548	4,3	18,3	2,7	0
Number of charging sessions	640	632	628	633	637	632
Unfinished charging sessions	73	50	26	146	125	96
Fast charge sessions	14	15	15	17	15	14

	DC-F (340 kW)	DC-F (535kW)	DC-SMC (340 kW)	DC-SMC (535kW)
€ per kWh spot market charging neighborhood	€0,028	€0,030	€0,019	€0,019
€ per kWh incl. fast and work charging	€0,031	€0,033	€0,023	€0,022
€ per kWh incl. fast and work charging & network	€0,091	€0,093	€0,083	€0,082
Average local charging power per EV [kW]	18,6	20,2	2,4	2,4
Average charging time [hour]	0,84	0,76	6,64	6,52
Amount of charged load [kWh]	8471	8555	8543	8314,82
Overload 340 kW [minutes]	0	515,8	0	10,1
Overload 340 kW [kWh]	0	387,4	0	6
Overload 535 kW [minutes]	0	0	0	0
Overload 535 kW [kWh]	0	0	0	0
Number of charging sessions	615	623	632	614
Unfinished charging sessions	17	12	47	40
Fast charge sessions	12	12	17	14

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List of acronyms

EV	Electric vehicle
DSO	Distribution system operator
TSO	Transmission system operator
BRP	Balance responsible party
CSO	Charging system operator
MSP	Mobility service provider
HEMS	Home energy management system
SoC	State-of-charge
DR	Demand response
DA	Day-ahead
ID	Intra-day
VCC	Variabel connection capacity
CPP	Critical peak pricing
SMC	Spot market charging
USEF	Universal smart energy framework
SGAM	Smart grid architecture model

List of publications

2018

- R. Fonteijn, M. v. Amstel, P. Nguyen, J. Morren, G. Bonnema and J. Slootweg, "Evaluating flexibility values for congestion management in distribution networks within Dutch pilots," in *The 7th International Conference on Renewable Power Generation*, Copenhagen, 2018.

- J. Kohlmann, G. Halders, M. van Amstel, R. Bernards and J. Slootweg, “Digitalisering van de elektriciteitsdistributie,” in *Energie+*, 2018