Value of vehicle-to-grid (V2G) to distribution system congestion management for the DSO

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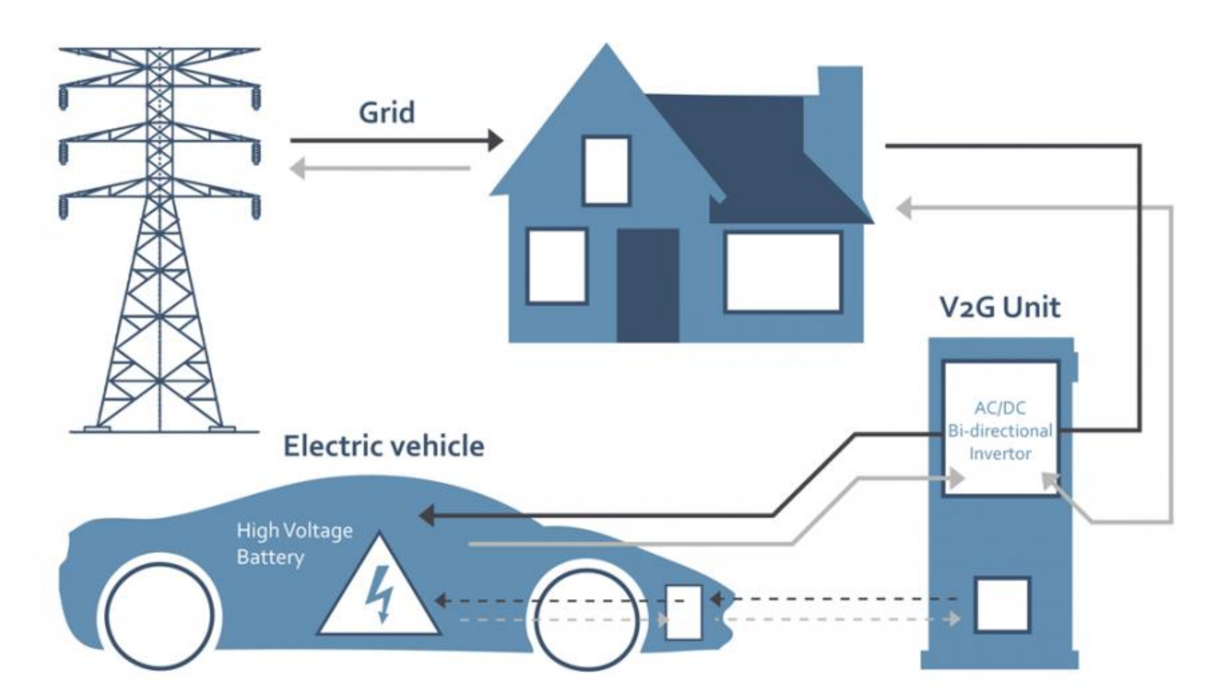

VALUE OF VEHICLE-TO-GRID (V2G) TO DISTRIBUTION SYSTEM CONGESTION MANAGEMENT FOR THE DSO

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Acknowledgements

This thesis is written as part of the thesis project for the master Complex Systems Engineering and Management. The goal of this thesis is to provide insights in the value of vehicle-to-grid charging for the distribution system operator through the simulation of the electrical impact on the low voltage grid. With this thesis I finalize the master program at the faculty of Technology, Policy and Management at the Delft University of Technology.

The readers interested in different applications of vehicle-to-grid charging strategies are referred to chapter 2. Chapter three provides an overview of the implemented charging strategies within this thesis. Readers interested in the electrical impact of electric vehicle charging strategies are referred to chapter 4. For readers interested in the monetary value translation of the impact of vehicle-to-grid for the distribution system operator, chapter five provides the most insights.

Within this acknowledgement section I would like to show my gratitude to the people who have supported me throughout the process of completing this thesis. First of all, I would like to thank my supervisors who supported me throughout the entire graduation process. Jan Anne, thank you for always being available to provide valuable feedback on my thesis and thesis process. Emile, thank you for showing support and guiding me through the process of creating an ABM and interpreting the results following the model. Ivo, thank you for your critical review on my thesis and during the graduation meetings.

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I have certainly learned a lot about electric vehicles, charging strategies, the electricity grid and about myself during the process of writing this thesis. I am proud of the realisation of this master thesis and I hope you will derive value from reading this thesis.

Tim van ‘t Wel
Delft, May 2019

Executive Summary

In the light of the global transition away from fossil fuels, a multitude of solutions are implemented in the Netherlands. A transition towards electrification of appliances is part of these solutions. Usage of heat and mobility is increasingly electrified. This trend is expected to increase over the upcoming years. This electrification will have an impact on the electricity demand and will impact the electricity grid. Furthermore, a transition towards a more decentralized electricity production can be noticed. The introduction of high quantities of these renewables will have major consequences for the low voltage grid. The integration of these transitions in the distribution grid is one of the main challenges for a distribution system operator. However, the transition towards electrical appliances might also possess opportunities to create smart solutions to solve for higher electrical demand and loads within the electricity grid. The batteries of electric vehicles might be utilized to aid the functioning of the grid. The introduction of this charging technique might defer necessary investments for grid reinforcement within the distribution system based on the introduction of higher electricity demand.

The goal of this research is to show the value of utilizing EV batteries using V2G technology. The goal is not only to provide insights into the impact of V2G charging on the low voltage grid, but also to show the economic value of V2G optimization on low voltage assets. Compared to other research regarding this value, this research will apply a more holistic approach by focusing on the electrical impact of EV charging strategies on the low voltage transformers as well as the value that is obtained through these charging strategies.

Based on this societal and scientific relevance, the following main research question is answered in this thesis:

"What is the economic value of vehicle-to-grid congestion management charging to the low voltage electricity grid for the distribution system operator?"

To estimate the value of vehicle-to-grid congestion management for the low voltage grid, an agent-based model is adapted to first estimate the impact of this charging strategy. An agent-based modelling approach allows for the heterogeneity of agents and for interaction of the agents with each other and the environment. This approach also allows for spatiotemporal variables to be included.

One of the important variables of the model, for assessing the impact of charging, is the location. Within this research, a case study approach is chosen. One neighbourhood with future estimated load profiles is simulated in order to understand the value of vehicle-to-grid congestion management.

Because the implemented charging strategy only derives value from the prevention of overload, Nijmegen Lent is chosen as neighbourhood. Within the current infrastructure in the neighbourhood, congestion is present and thus this neighbourhood is an adequate case study. Next to this, the neighbourhood is currently part of a pilot flexibility market to measure the value of flexibility for the distribution system operator. This shows that flexibility is part of a viable alternative for deferral of investments within the area. Additionally, infrastructure for the deployment of flexibility in the area is also in place. The presented results will, however, thus only reflect the situation of Lent and results will not be generalizable based on this one case study. The impact of charging strategies is valued on the basis of the low voltage transformer loads.

The results of the model show that the implemented vehicle-to-grid charging strategy is able to lower maximum load during the simulated period of five working days. Within the smart charging experiment the cumulative maximum load within the neighbourhood is estimated to be between 3040 kVA and 3467 kVA. Within the vehicle-to-grid experiment the cumulative maximum load within the neighbourhood has been lowered to between 2805 kVA and 3096 kVA. Simultaneously, vehicle-to-grid charging is able to improve the utilization rate of the transformers. The average load factor within the smart charging experiment is between 49% and 51%, while the load factor within the vehicle-to-grid strategy is between 53% and 57%. However, the implemented charging strategy is not able to prevent all overload of transformers. 70% of transformers with overload are prevented to have overload through vehicle-to-grid. It can thus be concluded that vehicle-to-grid congestion management could lower the peak load within the distribution grid, but with a 33% electric vehicle share the use cases of low voltage congestion management through vehicle-to-grid remain limited.

In order to assess the economic value created for the distribution system operator through the decrease in electrical peak loads, a net present value analysis of the costs of the alternative without and the alternative with vehicle-to-grid charging is conducted. The electrical load scenarios, resulting from the agent-based model are used as input into the net present value analysis. The required investments in grid reinforcements and the investments for enabling vehicle-to-grid charging are estimated and translated into economic value for the distribution system operator.

From the net present value analysis of the costs of vehicle-to-grid charging and smart charging strategies, it can be concluded that vehicle-to-grid can be more cost effective than grid reinforcement and smart charging in Lent. The costs of grid reinforcement are estimated to be €129.000. The costs of the flexibility alternative including vehicle-to-grid charging is estimated to be €55.000. However, this is under the assumption of minimal distribution of vehicle-to-grid chargers within the neighbourhood. If all present electric vehicle owners are connected through vehicle-to-grid chargers in order to increase the security of supply through this charging strategy, the costs of the vehicle-to-grid alternative is estimated to be €134.000. It can thus be concluded that the distribution system operator will need to research the objectives of security of supply and the costs of a flexibility alternative thoroughly as the number of vehicle-to-grid chargers account for major costs of the flexibility alternative.

Following this research, a number of recommendations are formulated:

- Define and develop a pilot in which vehicle-to-grid is used as congestion management service during peak demand hours.
- Initiate further research in the economic assessment and impact of stacked V2G services in order to lower the costs for congestion management discharging;
- Further research the impact of V2G charging on the low voltage grid through the addition of more case studies with similar demographics and case studies with different demographics in order to enhance the generalizability of the results;
- Further expand the proposed model through the addition of more market based congestion mechanisms and addition of different vehicle-to-grid charging objectives;
- Further research the value of vehicle-to-grid alongside additional sources of flexibility such as smart heat pumps (with the ability to shift loads) in order to assess the full flexibility potential within a residential area;

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Chapter 1: Introduction

In light of the global transition away from fossils fuelling global energy demand, a multitude of alternatives across different industries are being adopted in the Netherlands.
A transition towards the electrification of the energy demand over the past years can be identified (RVO, 2018). The transition towards electricity usage allows for a possibility in reduction of CO_2 emissions. Electricity provided through renewable energy sources is deemed CO_2 neutral and thus allows for a reduction in comparison to fossil fuels. Next to this, electricity can be a more efficient method for meeting demands. For example, electric vehicles are more energy efficient in comparison to fossil fuelled vehicles (Knigge, 2011). The increase in electric vehicles (EVs) and the charging of the batteries of these EVs will have an impact on the electricity system. The impact of the introduction of EVs on the total electricity demand will be relatively small, however, the charging of EVs will increase peak demand and cause potential issues at the distribution level (van Essen & Kampman, 2011). The electrification of energy demand thus might introduce new challenges within the electricity system.
Within the electricity system a transition towards more sustainable generation can be identified (CBS, 2018). Within the last years the share of renewable electricity within the electricity mix has grown in the Netherlands from 1% in 1990 up to 13.8% in 2017 (CBS, 2018; CLO, 2017). The introduction of more renewable energy sources do not only introduce a shift away from CO_2 intensive resources, but also introduce a shift from centralized electricity generation towards a more decentralized approach. Renewable electricity generation from solar and wind energy, two major sources of renewable electricity in the Netherlands, is characterized by its decentralized nature. Introduction of high quantities of these renewables will have major consequences for the low voltage grid (Rooijers, Schepers, van Gerwen, & van der Veen, 2014). The shift towards more renewable electricity sources does not only cause a shift in the location of electricity generation, it may also cause a discrepancy between the timing of supply and demand. This will not only impact the local electricity grid, but this will also impact the energy markets which are not prepared for decentralized capacity on a significant scale (Rooijers et al., 2014). The introduction of renewable energy sources will thus introduce a shift from a centralized electricity system towards a more decentralized system and it will also cause a discrepancy between the timing of supply and demand. Both of these transitions will have an impact on the local electricity grid.

In order to accommodate for a future electricity system as described above, grid operators are researching different alternatives to accommodate these developments. On the local level, distribution system operators (DSO) have the obligation to always be able to deliver electricity to its customers. In order to do so, DSOs install assets with a high capacity in order to supply electricity during peak demand. With the increase in peak demand in the local grid and the increased volatility of decentralized supply DSOs are searching for a smart solution to defer investments in their assets (CE Delft, 2011). However, it is not clear what the effect of smart solutions will be on the technical level. Next to this, it is unsure if smart solutions are preferred from an economic perspective. One of these smart solutions that DSOs are researching is local storage (Netbeheer Nederland, 2011).

Different types of local storage are available to deliver support for local grid development. Research conducted by Klein Entink (2017) shows the possibility of installing new batteries in the low voltage (LV) grid in order to provide services to support the local grid. There is also the possibility of using second hand batteries and congestion management. Congestion management is the balancing of supply and demand of electricity. Finally, the possibility of utilizing EV batteries in order to support local grid operations is explained in Kempton & Tomić (2005).

These studies represent the technical feasibility of different battery storage systems providing services to the LV grid. These studies do not cover the economic feasibility of such systems. In Klein Entink (2017) an attempt is made to quantify the value of battery systems providing LV grid services. However, it is unclear what the benefits are when utilizing EV batteries with vehicle-to-grid (V2G) technology. Utilizing this type of storage will introduce new variables such as travel time and time of arrival of the EV at a V2G charging point. These potential risks regarding the security of supply of this flexibility asset might be of set by the mitigation of costs by utilizing EV batteries instead of the costs for placing new batteries within a neighbourhood. Thus, the problem that can be identified is:

"The economic value of vehicle-to-grid providing congestion management services to the low voltage grid is not clear."

1.2 Research questions

To ensure the above stated problem will be addressed in this thesis, the following research question can be constructed:

"What is the economic value of vehicle-to-grid charging for congestion management to the low voltage electricity grid for the DSO?"

In order to answer this main research question, the following sub questions should be answered:

1. *How are the characteristics of the distribution grid and what vehicle-to-grid strategies impact the distribution grid?*
2. *How could the impact of vehicle-to-grid charging on the low voltage grid be modelled?*
3. *What is the impact of vehicle-to-grid charging on the low voltage grid?*
4. *What is the value proposition of vehicle-to-grid to the low voltage grid and the DSO?*

1.3 Social and scientific relevance

Within this thesis the value of vehicle-to-grid for the low voltage grid is addressed. Providing this service can be seen as part of a solution towards a more sustainable and less polluting energy system. A more imbalanced energy system on multiple levels across the supply chain will need to be coped with by all actors involved. An economically efficient way to cope with challenges, such as growing peak demand, will be in favour for all parties involved (from producer to consumer). This research aims to give an insight in the economic viability of vehicle-to-grid charging to accommodate a future electricity system. As all stakeholders within the electricity system benefit from a broader understanding of the economic viability of V2G for low voltage networks, only a subset of these stakeholders are directly involved. Table 1 shows the different stakeholders directly involved in V2G operations and the interests of these parties in a better understanding into the dynamics of V2G in a low-voltage network.

Table 1: Actors interest in V2G

Stakeholder	Role	Interest V2G
Charge point operator	Deployment and maintenance of charging infrastructure	More attractive customer proposition
Aggregator	Facilitating a platform to aggregate EV battery load	To generate earnings in regards to offering multiple EVs as flexibility load
Utility	Responsible for maintenance and enhancement grid	Avoiding additional expenditures in grid enhancements and power quality issues
Electricity producer	Produce electricity for EV charging	More efficient use of production capacity
EV user	Owner of EV that will be used in a V2G setting	To generate earnings in regards to offering their EV as flexibility load To help the community with EV storage capacity
EV producer	Developer adjusting vehicles to be able to take part in V2G	Allowing the business case of EVs to be stronger and make a more attractive customer proposition
Municipality	Responsible for public charging infrastructure deployment	Accelerating energy transition within the municipality

This research is connected to different streams of literature. First, V2G has been studied based on a system perspective in Kempton & Tomić (2005). These studies show the applications of V2G in different markets and take a broad perspective on different mechanisms that can be used in order to create value through V2G. The first sub question in this research will overlap with this type of research regarding V2G. In this body of research charging behaviour of EV owners is simplified and estimations regarding the impact of V2G are generated. This body of research lacks the ability to gain detailed insights in the behaviour of EVs. All different market models of V2G will have an impact on the low voltage distribution grid. In order to assess the value of V2G for the DSO, the different markets and business models for V2G should be assessed.

Another stream of literature is focussed on the impact of EV charging on the distribution grid. This stream of literature focusses on the effects of EV diffusion on the distribution grid. A part of this research also examines the effect of smart charging on the distribution grid (Verzijlbergh, 2013). Another part of this research focusses on the impact of V2G on different levels of the electricity system (Clement-Nyns, Haesen, & Driesen, 2010).

Within the research of Verzijlbergh (2013) multiple models have been presented to predict the impact of different smart charging strategies and V2G on the distribution network. This body of research focusses on the impact on the electricity system, but does not cover the question regarding the business case of these strategies. The third body of research to which this thesis is connected to focusses on the economic efficiency of (smart) grid investments. In Eyer (2009) and Gil & Joos (2006) for example, the economic efficiency of flexibility is researched and a monetary value is calculated for the

The figure below (Figure 1), summarizes the bodies of literature to which this thesis is connected. It also presents the connection of the sub questions to the literature. Through the combination of these three questions, this thesis will be able to give an elaborated answer on the main research question as presented in section 1.2. This figure shows that no research has attempted to combine the three streams of literature. This research will try to add to current literature in combining insights from these streams of literature into one thesis.

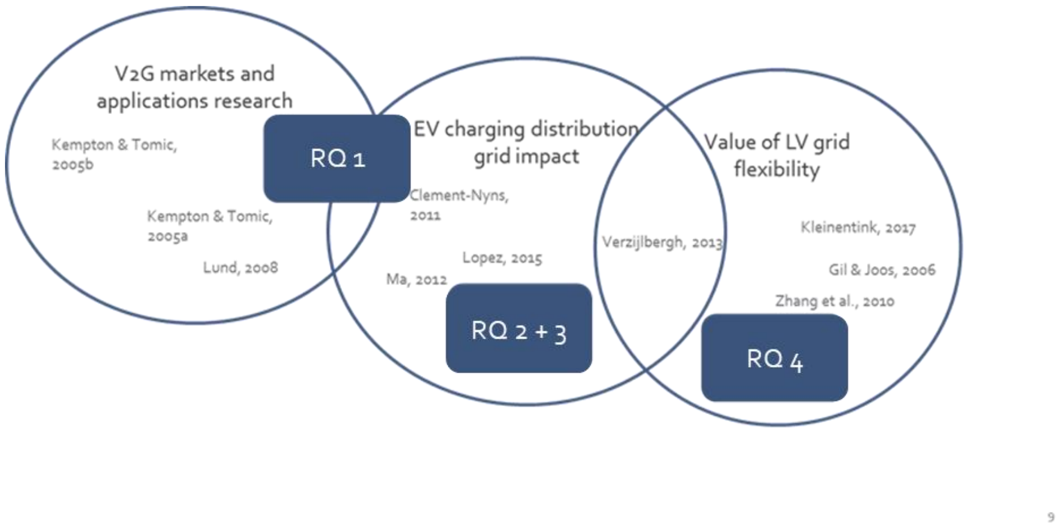

Figure 1: Sub questions related to literature regarding V2G and smart grid cost effectiveness

The goal of this research is to show the value of utilizing EV batteries using V2G technology. Not only to provide insights into the impact of V2G charging on the low voltage grid, but also to show the economic value of V2G optimization on low voltage assets. Compared to other research regarding this value, this research will apply a more holistic approach by focussing on the impact as well as the value that is obtained through different charging strategies.

The results presented in this thesis could be used to aid the decision making process of the DSO in allowing flexible loads in the system in terms of EV batteries. In this research the impact of vehicle-to-grid charging This research also be able to estimate the impact of V2G for real life neighbourhoods and will not be limited to a hypothetical case.

1.4 Methodology

In this section, the methodology used to answer the main research question is described. In order to answer the main research question, four sub questions are answered sequentially. These questions are separated and are assigned suitable methodologies in order to answer these questions.

The first sub question answered is: *What does the electricity system look like and what is the impact of smart charging strategies on the low voltage electricity grid?*

In order to answer this question it is important to note the scope of the question. Smart charging strategies impact all levels of the electricity system, but only the low voltage electricity grid is studied. Next to this, the sub question can be divided into two questions: *"What does the electricity system look like"* and *"what is the impact of smart charging strategies on the low voltage electricity grid"*. The first segment of this sub question is answered through a literature review and an interview with a representative of a Dutch DSO. The literature consists of both scientific literature as well as reports of DSOs. Two main topics are addressed. First, the an overview of the Dutch electricity grid is presented. The key words for this literature research are: "Vehicle-to-grid" OR "V2G" OR "Smart charging" AND "distribution grid" OR "low voltage grid" AND "impact" OR "effect". Second, the role of flexibility is assessed. A literature search with the following key words is performed: "Role" AND "DSO" OR "DNO" OR "TSO" AND "flexibility" OR "smart grid" OR "future grid".

An overview of key words and a small sample of interviews on the role of flexibility for the DSO are presented in order to create a broad but bounded literature research on the most important key words within the field of study. It is assumed that the technical electricity system is described extensively within the literature. However, a future role of flexibility within the operations of the DSO is more uncertain. Hence, the outlook of representatives of Dutch DSOs is added to deal with the limitations posed by the usage of a literature review.

To answer the second segment of the sub question another literature review is performed. However, the scope of this literature review is different. The literature obtained in the first segment is more empirical and qualitative of nature and answers question regarding the current state of the electricity system. The scope of the second performed literature review consists of quantitative modelling research into the effects of different smart charging strategies on the low voltage electricity grid. This research can be described as quantitative modelling research including hypothetical numbers of EVs and charging schemes in order to assess potential impacts of future electricity systems. The objective of this literature review is to assess the potential value of different smart charging and vehicle-to-grid strategies. These results are obtained in order to decide which smart charging and V2G charging strategy will be modelled in order to answer the following sub questions. Simultaneously, the modelling methodology used in the reviewed literature is researched. One of the modelling methodologies is selected in order to answer the second sub question.

Following the literature review performed to answer the previous sub question, an Agent Based Modelling approach is selected to answer the second sub question. One of the advantages of an ABM over a linear programming based model is the ability to model individual agents. This allows the individual households to be heterogeneous in terms of both driving pattern as well as electricity consumption. (Hoekstra, Steinbuch, & Verbong, 2017; Ringler, Keles, & Fichtner, 2016a). An additional benefit of an ABM approach is the ability to capture both spatial and temporal patterns (Sweda & Klabjan, 2011).

An ABM with the ability to capture the impact of EV charging is the Sparkcity model (Hoekstra & Hogeveen, 2017). The Sparkcity model is used to study the impact of EVs in a neighbourhood and the reduction of impact through smart charging (Vijayashankar, 2017). This paper together with Hoekstra and Hogeveen (2017) shows the ability of Sparkcity to model to assess (smart)charging behaviour within a real neighbourhood. The Sparkcity model will be adapted for the purposes of this research. Yilmaz and Krein (2013) present four main challenges in regards to modelling of EV charging impact. The following modelling challenges are identified:, EV models market share, location, driving patterns, electricity demand/supply, and charging strategies (Richardson, 2013).

The effects on the distribution grid heavily depend on the adoption of EV and V2G and this adoption rate is in its turn dependent on geographical location (Schroeder & Traber, 2012; Taylor, Maitra, Alexander, Brooks, & Duvall, 2009). Because of this, a geographical location should be chosen as a case study to assess the impacts on the local distribution grids. The impact of V2G charging strategies cannot easily be generalized because of these location specific attributes. The impact on distribution grids will be largest in urban and population dense areas and the adoption of EV is higher in such areas (Sierzchula, Bakker, Maat, & Van Wee, 2014). The potential of the value for flexibility as congestion management tool is highest in neighbourhoods with a high share of residential connections. These neighbourhoods namely show a clear peak in electricity demand during the day (Klein Entink, 2017). A residential area will thus be selected as case study to research the value of V2G congestion management.

Nijmegen, and especially the neighbourhood Lent, is selected as case study within this thesis. Lent meets the criteria presented before. Lent is a residential neighbourhood, and thus probably has a clear peak in electricity demand during the day. Next to this, a residential area has the potential of having a large fleet of EVs available during the electricity consumption peak. This peak will occur while EV owners will be at home and thus their EVs might be plugged in at home. The number of vehicles per household in Lent is on average 1,1 (CBS, 2016b). This is higher than the average of 0,93 vehicles per household in the Netherlands and the average in urbanized areas is often below this average. A high number of vehicles per square kilometre in Nijmegen (1,137) in comparison to the Dutch average (123) allows for a high number of potential EVs in this area (CBS, 2016a). Next to the relatively large amount of vehicles within the neighbourhood, Lent also suffers from congestion related issues in the electricity grid (Liander, 2017). In order to assess the value of congestion management solutions, congestion must occur within the simulated area. Currently, congestion related issues are solved through the reinforcement of grid assets and no congestion management is considered. However, in the case of Lent, a flexibility market is created as a pilot project to assess the potential of flexibility because of the high increase in electricity consumption in the area (Liander, 2017). However, this flexibility market is a temporary solution before a permanent reinforcement is placed in the area and this time period will not be the focus of this thesis. The neighbourhood will, on the contrary, be prepared for a flexibility market introduction in the future with regards to, for example, measuring equipment in the grid. An additional reason to choose a case study approach is that research regarding the potential of smart charging solutions is often performed within a hypothetical test power system. However, location specific data is an important determinant of the value of these charging schemes and a case study modelling approach will thus create inherent value to the body of literature in this regard. This approach is facilitated by the choice of the Sparkcity model which is able to include GIS location data in the model.

As one of the key challenges of the model, the driving pattern implemented in the model may be one of the key determinants of the results of the model. The driving pattern of EV owners consist of two main variables. First, it is important to determine when the EV owner is driving. Second, it is important to determine the amount of kWh used while driving, this is determined through a number of factors such as distance, speed, other driving characteristics, and environmental aspects. In order to model the driving behaviour, the vehicle batteries can be stored in one aggregate unit and availability can be predicted on the basis of historical data (Lund & Kempton, 2008). However, this could cause the EVs to charge faster than is realistic (Kristoffersen, Capion, & Meibom, 2011). Therefore, individual driving patterns are described to EV owners. This is possible through the selected ABM approach as all EV owners are separate agents and could be equipped with different driving patterns. A probabilistic driving pattern is already present in the Sparkcity model and will thus be used within this thesis. The driving patterns presented in the Sparkcity model are based upon the ALBATROSS model. The ALBATROSS model is an activity based model in order to estimate future travel demand (Arentze & Timmermans, 2000). It was not feasible within this thesis to obtain case specific driving patterns, thus more generic driving patterns are used.

Next to the driving pattern model, the electricity demand and supply are important variables of the model. Within this research, smart charging and vehicle-to-grid are used as a demand response mechanism and only demand is thus taken into account. One of the method used in research into the impact of EV charging impact is aggregated household consumption data, such as in De Haan (2016) and Hague et al. (2015). However, this methodology is not applicable in the case of low voltage distribution charging. Due to the low number of households connected to a transformer, aggregated data would not be representative of the electricity consumption of the certain transformer. This method does not take the heterogeneity of the electricity consumptions of the households into consideration. Therefore, an electricity consumption model will be created and the consumption will be based on the results of the ALBATROSS activity model. This will increase the internal validity of the model as the electricity consumption is able to be connected to the activities of the agents. This is not possible with the previous described methodology.

The last challenge identified by Richardson (2013) is the implementation of the charging strategy. Many different charging strategies exist, and different objectives for these strategies can be identified. An extensive list of all charging strategies is provided in García-villalobos et al. (2014). These strategies all have different impacts on the low voltage electricity grid. Therefore, the control strategy and charging objective are researched in chapter 2 and 3. Following the results of the answers presented a direct control smart charging and V2G charging strategy are implemented in the Sparkcity model. No market forces are modelled in this thesis and (dis)charging is optimized taking into considerations EV battery constraints. Next to this, both charging strategies have a constraint that the EV will need to be fully charged at the end of the charging session. If discharging would cause the EV to not be fully charged at the end of the charging session, the EV will choose to not participate in discharging.

The third sub question can be answered through the implementation of the conceptualization provided as answer to the second sub question. This implementation will be performed in GAMA software using the GAML language. The model will be used to run different experiments of both the smart charging and the V2G charging scenario. In order to map the relevant results, a set of key performance indicators (KPIs) will be developed. These KPIs will cover the total electricity consumption and loadings in the simulated neighbourhood. Next to this, it will need to provide a more detailed set of results on an asset specific basis (e.i. per transformer).

Next to this, it is important to track the state of charge (SOC) of the EVs in the neighbourhood. This metric is assessed to not only review the impact of smart charging and V2G on the electricity grid, but to be able to track the impact of the charging on the level of individual EVs. Through this approach, results on the system level as well as the agent level are presented. The presented results of the model are prone to the assumption made during the conceptualization of the model. In order to verify the impact of the main assumptions of the model, a sensitivity analysis will be performed. In this sensitivity analysis, the input of certain variables will be altered to be able to reflect on the robustness of the results of the KPIs. Next to this, the results presented are validated. This validation is performed to ensure that the model is a reasonable accurate representation of the real world (Xiang, Kennedy, & Madey, 2005). A face validation by an expert is performed in order to ensure that the model is reasonably accurate.

To answer the last sub question, a framework will need to be presented in order to translate the results of the previous sub question into a monetary value. Multiple methods have been introduced to evaluate electricity peak demand and following investments in the electricity grid to a monetary value. One of the frameworks used to assess the value of grid investment is a societal cost-benefit analysis, for examples De Nooij (2011). In a societal cost-benefit analysis all differences in society with and without the project are measured and compared (De Nooij, 2011). A similar approach is the net present value (NPV) analysis as proposed in Klein Entink (2017). This proposed framework only compares the costs of alternatives occurring for the DSO. Because the scope of the presented sub question is on the level of the DSO, this methodology is preferred over the social cost-benefit analysis. However, the proposed framework does not clearly delineate different costs occurring. In order to compare costs of both alternatives a structure of the costs occurring is needed. Such a structure is provided in Overlegtafel Energievoorziening (2018). In this report from Dutch DSO's standardized calculations of different expenses are presented. Overlegtafel Energievoorziening (2018) argues that the majority of costs occurring in a societal-cost benefit analysis are presented in their framework (grid operator cost-benefit analysis), namely expenses for grid reinforcement and flexibility. An additional advantage of this framework is that this framework is designed by Dutch DSO's to estimate the value of flexibility for the DSO, which is in line with the objective of this thesis. Because of the limited added value of a full social cost-benefit analysis and the time frame of this research, the grid operator cost-benefit analysis is used in this thesis. Three peak demand scenarios are used as input for the costs analysis. These scenarios are resulting from answering the previous sub question of this thesis. The values used in order to estimate the costs of the alternatives are partially regulated by the regulator and current known values will be used. Additional valuation is obtained through previously conducted research regarding the value of flexibility in the Netherlands, such as Netbeheer Nederland (2013), Ecofys (2016), and ECN (2017).

1.5 Thesis outline

A combination of the methodology per sub question is shown in Figure 2. Through the combination of three bodies of literature, the value of V2G for the LV grid will be estimated at the end of this research. In chapter 2, different applications of V2G are discussed alongside their impact on the LV grid. In chapter 3, the Sparkcity ABM is elaborated in order to estimate the impact of smart charging and V2G on the local electricity grid within Lent. In chapter 4, the results of different simulations of this model are presented. In chapter 5, the output of the ABM is used as input into a monetary value translation for the DSO. In the last chapter the outcomes of these analyses are discussed and the main research question is answered.

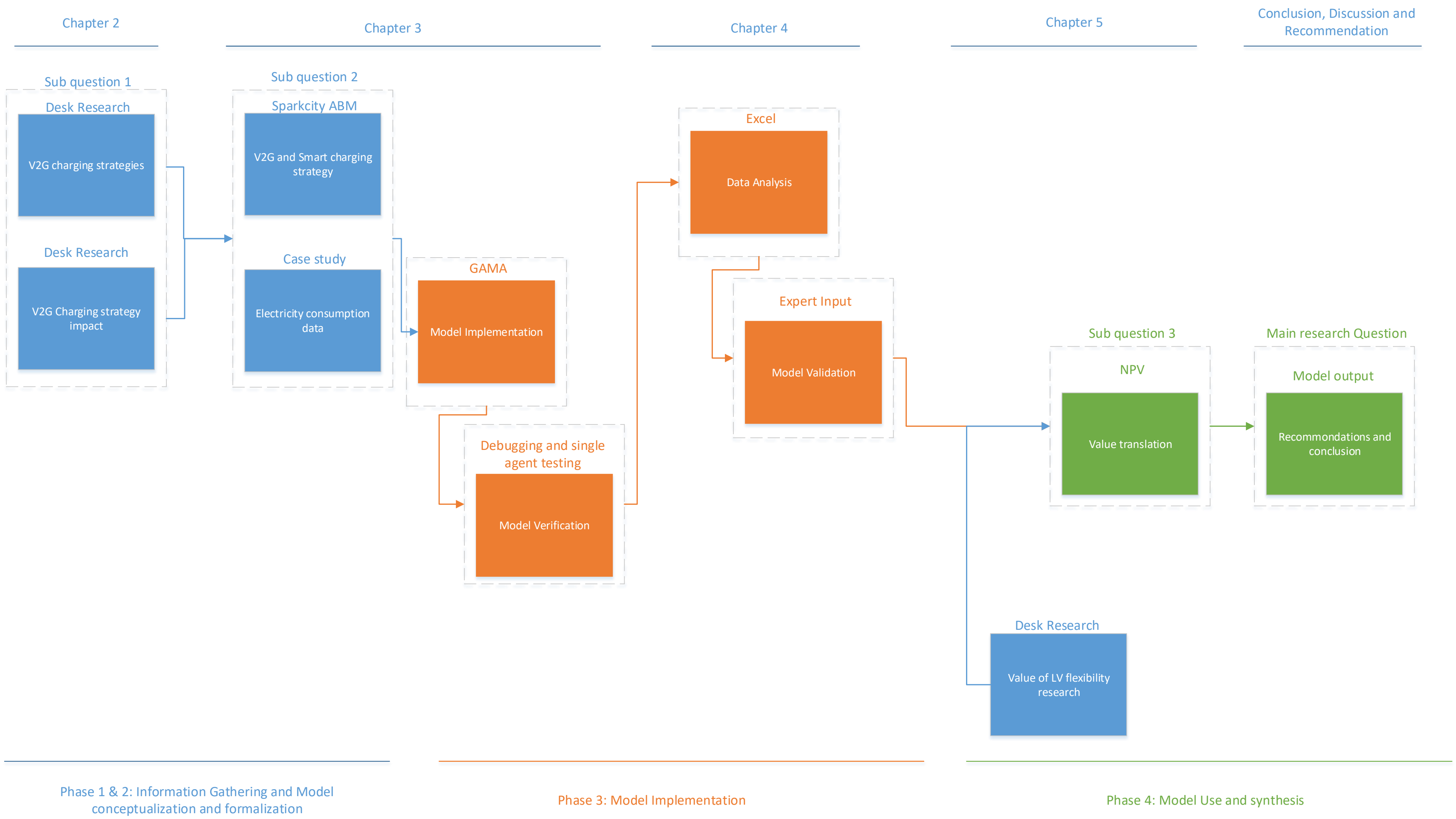

Figure 2: Research Flow Diagram

Chapter 2: Electricity grid and charging strategies

In order to understand the impact of EV charging better and calculate the impact and value of vehicle-to-grid strategies it is important to understand the distribution grid and its foundational blocks. Next to this, it is also important to explore the different types of charging schemes as they have different impacts on the local distribution network. Thus, in section 2.1 a technical analysis of the electricity grid is made and in section 2.2 different V2G charging schemes are presented. In section 2.3, two agent-based models are compared, one of these agent-based models is chosen as basis for the model presented in the next chapter. Next to this, the control strategy for the implemented charging strategy is discussed in this section. The following figure is a representation of the structure of this chapter.

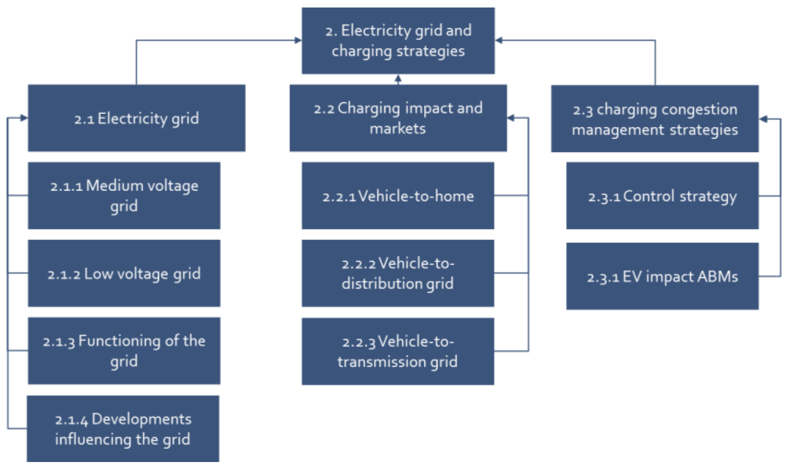

Figure 3: Structure of chapter 2

2.1 Electricity grid

The Dutch electricity network has been built in a hierarchical way (Pagani & Aiello, 2011 M). Starting from large electricity generators towards many different consumers. The electricity network is thus a natural monopoly. Because the unbundling within the Dutch electricity sector, there are two companies that have exclusivity to manage the electricity network in the Netherlands. The TSO and the local DSO. Because of the scope of this research regarding the local distribution network, the high voltage network managed by the TSO is not of interest. The local grid, both the medium voltage (MV) and low voltage (LV) grid and managed by the DSO, is of importance for this research. With the increase in distributed generation, it is important to look into the details of the low and medium voltage networks and how they accommodate the future electricity consumption (Niesten, 2010; Pagani & Aiello, 2012).

2.1.1 Medium voltage grid

The MV-grid consists of four different assets: HV/MV stations, MV-transmission cables, MV-distribution cables, and MV/LV transformers (Grond, 2011). The MV-grid is fed through the HV/MV station and could feed either MV-transmission lines or MV-distribution cables. The MV-grid within The Netherlands has voltage levels ranging from 1 kV up to 35 kV. The MV-grid connects different LV-networks and large energy consumers that exceed the capacity of the LV-grid such as different industries and railways. The MV-grid is typically ring-shaped, this allows the DSO to reroute in case of failures within one part of the MV network (Netbeheer Nederland, 2018).

2.1.2 Low voltage grid

The low voltage network in The Netherlands connects end consumers, such as households and shops, to the supply provided to the HV and MV-grid. Transformers from MV to LV are the heart of this conversion. Most of the LV-grid is 400 V and three-phase. In contrary to the MV-net, problems in the LV-net cannot be locked but should be physically replaced. However, it is possible that only one phase has problems which still allows the other phases to work properly. The LV-network is the largest of the three networks with more than 200.000 kilometres of cable in The Netherlands (Netbeheer Nederland, 2018).

In the figure below, the topology and interconnection of the MV and LV grid is shown. These grids are fully owned by the local DSO. The figure shows both a case with MV-transmission (top) and without MV-transmission (bottom)

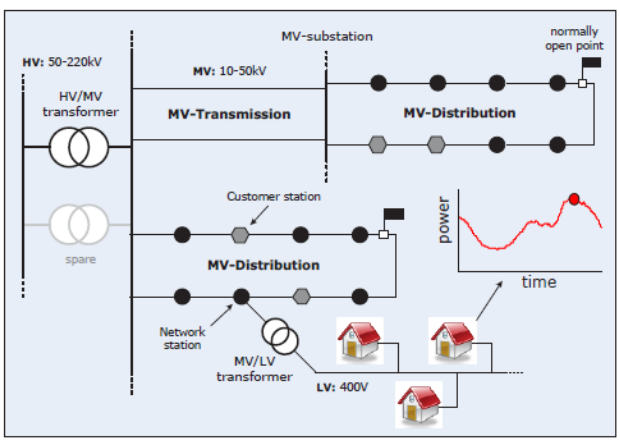

Figure 4: Topology of the MV- and LV-grid (Grond, 2011)

2.1.3 Functioning of the Dutch electricity grid

The Dutch electricity network is tested on reliability every year. This reliability check is in place in order to optimize the functioning of the electricity grid and identify, if deemed necessary, possible locations for improvement. A set of indicators is used to score the functioning of the electricity grid. The indicators are (Netbeheer Nederland, 2018):

1. interruptions
2. Amount of consumers affected per interruption
3. Average time per interruption [min]
4. Yearly outage duration [min/year]
5. Interruption frequency [interruptions/year]

In comparison to similar European countries the Dutch grid is relatively reliable. If outages occur in the Dutch grid, the MV and LV grid are responsible for these and in 2016 these two grids where accountable for the vast majority of the outages that have occurred (Netbeheer Nederland, 2018). These components also have the longest time per interruption and the highest yearly duration of outages (Netbeheer Nederland, 2018). Only the amount of consumers affected per interruption is lower for these two components, but this seems logical as the scale of the HV network is also the biggest.

2.1.4 Developments influencing the network operations

As briefly discussed earlier, the development of decentralized renewable energy sources will change the dynamics within the local distribution grid. The electricity system is built based on a hierarchical structure. This means that the energy is supplied through large generators and fed to the consumers via the high voltage network onto the medium and eventually the low-voltage network. However, with the increasing share of solar PV and wind energy the generation of electricity becomes much more decentralized. The role of electricity consumers may also change from just consumers of electricity to producing a (small) amount of electricity. Consumers that also produce electricity are the so-called prosumers. The network should be provided with flexibility to harness a high share of RES (Denholm & Hand, 2011; Develder, Sadeghianpourhamami, Strobbe, & Refa, n.d.; Verzijlbergh, 2013). The prices of Solar PV systems for residential purposes have been the last couple of declining years and an increase in the number of solar PV installations is expected.

Another development that will have a major impact on the key performance indicators of the distribution grid is the introduction of the heat pump. The government of the Netherlands and multiple local governmental bodies have stated the ambition to reduce the consumption of natural gas in the building environment. To do so, multiple alternatives are available such as: micro-CHP, district heating, or heat pumps. Within this set of alternatives, a numerous amount of different heat pumps exist as well. Two main types of heat pumps can be identified. Ground-source heat pumps and air source heat pumps. The latter has been used most frequently in Europe (Bayer, Saner, Bolay, Rybach, & Blum, 2012). A hybrid heat pump is another alternative two the before mentioned types. The hybrid heat pump combines multiple sources in order to fulfil heat demand, for example renewable electricity in combination with a natural gas burner (RVO, 2013).

The introduction of heat pumps will have an effect on the electricity demand of an household. This will especially occur during the winter due to the higher heating demand. As presented in Love et al. (2017)heat pumps will have a higher peak demand during the morning peak than in the evening peak, thus potentially altering the shape of the a household load profile. The ability of a heat pump to change the electricity consumption is proven in Asare-bediako, Kling, & Ribeiro (2014). These authors state that within a Dutch winter week, a heat pump might increase peak consumption up to 100%. A shift in electricity consumption profiles due to the penetration of, among others, heat pumps is also advocated in Veldman et al. (2010).

Additional load created through the charging of EVs will also have a significant impact on the distribution grid. Especially in combination with the integration of heat pumps and solar PV during winter weeks (Asare-bediako et al., 2014). Different charging strategies for EVs are designed in order to mitigate problems in the electricity grid. In the below chapter, these different strategies are set out.

2.2 Charging impact and markets

Smart charging and V2G could be considered as optimization problems. These optimization problems could however have different optimization goals. Because of this difference between optimization goals, the impact of these strategies will be different for the electricity grid. In the table below, smart charging and V2G applications are summarized. In sections 2.2.1 to 2.2.3 the three different levels of V2G and smart charging applications are elaborated on.

Table 2: V2X services and applications for the electricity grid

	Category	Level	Service
V2X	V2H / V2B	Home / building	Local storage & use
			Peak shaving
			Power backup
	V2G	Local grid (street / city)	Local storage, use & sharing of energy
			Congestion management (+ power quality and voltage control)
		National grid	Balancing markets: frequency balancing, congestion management
			Wholesale energy markets: day-ahead, intraday

2.2.1 Vehicle-to-home

Vehicle-to-home (V2H) or vehicle-to-building (V2B) refers to (dis)charging optimization based on the electricity usage within a small number of homes or buildings. Smart charging in this context is referred to as (V1H or V1B). Three different objectives for EVs and V2H/V2B can be identified. First, as presented in van der Kam & van Sark (2015), smart charging and V2H allow for a better integration of decentralized renewable energy sources. The optimization performed in this study shows an increase in self-consumption of renewable energy up to 38% together with a reduction in demand peaks of 27 to 67%. Using this information, V2G and smart charging could be used to lower electricity extracted from the grid and reduce energy costs. In the case presented in Nguyen & Song (2012), reimbursement costs for V2B provision is taken into account as well as aggregation costs. With these costs included, total energy costs and peak power demand are also reduced. EVs could also provide power backup through V2H applications. Simulations performed by Tuttle et al. (2013) shows that a single EV could provide backup power in case of outages from nineteen up to six hundred hours. This paper also shows the ability for an EV to provide a stacking of the services mentioned in this section. None of these researchers focus explicitly on the impact of V2H optimization on the distribution grid further than peak demand reduction of a household.

2.2.2 Vehicle-to-distribution grid

Smart charging optimizations for the local distribution grid have been performed in a limited number of different studies. One of these studies provides an algorithm for smart charging and V2G based on the load of MV/LV-transformers (Haque, Nguyen, & Kling, 2014). In this paper congestion management is successfully performed on the basis of this transformer load and shows a decrease in peak demand. Chukwu & Mahajan (2014) focus on energy losses in the system and propose a system for which the energy losses in a distribution feeders. The conclusion of this paper is that 95% percent of energy losses could be avoided by deploying V2G. The lack of research regarding congestion management smart charging and the impact on the electricity grid is explicable through the functions and objectives of the DSO. Current activities of a DSO do not include an active management of loads within the distribution grid (Haque et al., 2014; Verzijlbergh, 2013). Thus, a the benefit of V2G modelled for this case is purely conceptual. In order to unlock this value created through smart charging strategies, DSOs should have the ability to actively manage loads in their grid.

2.2.3 Vehicle-to-transmission grid

Multiple studies have been performed in order to estimate the impact of EVs using smart charging control schemes based on the national grid level parameters. The impact of these charging schemes on the local electricity grid have been studied most elaborately out of the three levels of V2X optimizations. In Lund & Kempton (2008) the impact of EVs and V2G charging on a national level is analysed. This paper concludes that the usage of V2G and smart charging technologies will allow for a more efficient energy system. A system that allows to better integrate wind energy as well as lower CO_2 emissions. Verzijlbergh (2013) concludes that a weakening correlation between wholesale prices and electricity demand, caused by the introduction of renewable energy integration and a subsequent smart charging for cost minimizing EVs will be able to cause problems in the local distribution network.

From this section, it can be concluded that a sizable amount of research has been performed in order to explore the value of V2G in multiple markets. The value of V2G lies within these different markets, but the real value for an EV owner with a willingness to use V2G will relate to the stacking together the above mentioned services. It can also be concluded that the translation of impact to value has mainly been explored for the EV owner and for the actors on national level and on the V2B level. It can also be concluded that the maximum amount of value for the DSO is created when optimizations occur at the local grid level instead of V2H or to the national grid. To explore the value of V2G regarding the local distribution network a congestion management based approach on this level will be implemented. In the next section, different V2G strategies for congestion management within the distribution grid are elaborated on.

2.3 Charging congestion management strategies implementation

In this section, the control of strategy implemented within this thesis is decided upon. Next to this, two agent-based models are compared on the basis of their objectives in order to choose a framework for the modelling of the impact of the chosen charging strategy.

2.3.1 Control strategy

Smart charging and V2G can not only be divided in terms of optimization objective. Within the control strategy, two different types can be identified: direct and indirect control strategies (Divshali & Choi, 2016). Indirect control mechanisms work on the basis of incentives. These incentives are mostly monetary and allow for a market to emerge for which EV owners can decide if the reimbursement is worth the flexibility granted to network. On the other hand, direct control mechanisms allow the party that is responsible for optimizing to directly control the charging behaviour of the EV. This has the benefit that no complicated incentive structure will need to be enforced and the possibility of gaming is mitigated. For example, time of use (TOU) tariffs could create an additional peak load as soon as the cheaper tariff is in place (Divshali & Choi, 2016). The same conclusions are derived from the research performed by Verzijlbergh (2013). This study shows that ex ante fixed tariffs do not solve congestion issues in the distribution network.

Because of this, it can be stated that direct control charging schemes are more effective in providing congestion management than indirect control schemes. This in combination with a level of optimization in the local grid will probably be the most effective tool in mitigating problems regarding congestion in the distribution network. Thus, a smart charging and V2G charging scheme will be developed for the distribution network on the basis of a direct control strategy. The control scheme will be presented in the next chapter.

2.3.2 EV impact agent-based models

Different ABMs have been developed to study decentralized smart grids to tackle future challenges in the distribution network regarding congestion. An extensive review of these studies have been published in Ringler, Keles, and Fichtner (2016). In multiple studies Kays et al. (2011, 2013) have implemented a smart grid with simulated profiles and behaviour. Multiple other studies have been conducted in this regard. Existing literature on ABM usage within this type of problem setting has been limited so far and all published papers are recent. For the purpose of the main research question proposed in this research different similar studies have used ABM. The PowerACE model has been developed to study the integration of EVs in the energy system and the Sparkcity (formerly ABCD model) have been developed to answer similar question in this regard. In order to make a more elaborate decision on the methodology used in this research both of these models will be researched in more detail down below.

PowerACE Model

The PowerACE model is developed in the context of the European Energy System Analysis project REFLEX. The PowerACE model is an ABM that focusses on the wholesale electricity market including both short-term dispatching and long-term capacity planning. This model is designed to test the impact of an introduction of policy measures or flexible low-carbon technologies. The market that is simulated is the German market, but updates have also included the French markets. Although the PowerACE model is designed on a national market level it has also been used in contexts of introduction of more decentralized energy technologies such as RES and EVs on a local level. However, the focus of this model on the national level instead of the low voltage grid is a discrepancy between the objective of this thesis and the PowerACE model.. An example of a more decentralized model present in the literature is the ABCD model or Sparkcity model. This model is explained in the next paragraph.

Sparkcity Model

Different studies have been performed within the Sparkcity model as developed for the Dutch Knowledge Platform for Charging Infrastructure. The Sparkcity is a multi-purpose model able to provide insights into (Hoekstra and Hogeveen, 2017):

1. Public space and Policy making;
2. Local electricity grid balance;
3. Technological developments such as vehicle-to-grid
4. Charge network supply and demand

One of the advantages of the Sparkcity model is the ability to implement real neighbourhoods in the model. This aids the ability of the model to influence the decision making processes and allows for more realistic case studies. The model uses the GAMA-platform which is specifically designed for a spatiotemporal agent-based simulation (Grignard et al., 2013). As discussed within the literature review section, both spatial/mobility and temporal parameters are important to discover the impact of EVs on the distribution grid. Hoekstra and Hogeveen (2017) emphasizes the possibility of V2G implementation and optimization based on the electricity grid which is in line with the research questions proposed in this thesis. Another advantage of the Sparkcity model is the implementation of dynamic behaviour of driving patterns. Additionally, the Sparkcity model has been used to study the impact of EVs in a neighbourhood and the reduction of impact through smart charging (Vijayashankar, 2017). The increase in load through EV charging is defined in different parameters within this research. The previous papers show the ability of Sparkcity to model the (smart)charging behaviour within a real neighbourhood. In comparison to the PowerACE ABM this model is the more complete and able to answer the questions raised within this thesis. Next to this, the researcher will not be able to develop a model as elaborate as the Sparkcity model within the time limit of this thesis and will therefore use the existing model as a start and will add the ability of bidirectional charging for EVs.

From this chapter it can be concluded that multiple charging strategies exist on different levels of the electricity grid. It can also be concluded that V2G charging strategies derive maximum value through the stacking of different services. However, in order to understand the value of stacked services, these services need to be analyzed separately first. This thesis will focus on the congestion management of the low voltage grid. In order to derive maximum value for the DSO through this type of V2G charging schedule, a direct control charging mechanism should be implemented. Furthermore, two agent-based models researching the impact of EV charging are compared. It can be concluded that the objectives of the Sparkcity model aligns most to the objectives of this research. Therefore, the Sparkcity model will be used as basis of the analysis of the following chapters. Within the Sparkcity model, a direct control congestion management smart charging strategy and vehicle-to-grid strategy will be implemented. The description of the model and the additions to the model are presented in the next chapter, chapter 3.

Chapter 3: Model Description

In this chapter, the Sparkcity agent-based model is altered. To align with the objectives of this thesis, additional charging strategies and electricity consumptions will be introduced. In order to gain insights in the impact of smart charging strategies the model is adapted to be able to simulate a neighbourhood, including the low voltage electricity grid, and the impact of different charging strategies on the DSO assets within this neighbourhood.

In section 3.1 the key performance indicators of the model will be presented together with the modelling objective and the following requirements. In section 3.2 the model is formalized. The agents and their (inter)actions will be specified and the implemented model will be verified. Figure 5 is a visual representation of the structure of the following chapter.

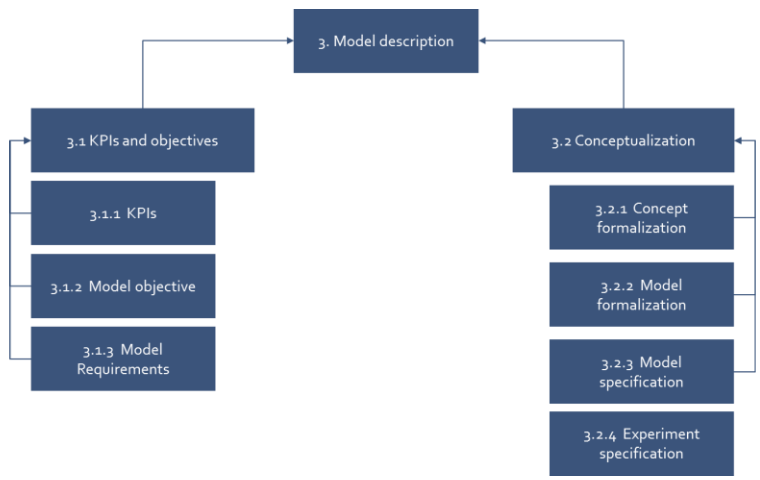

Figure 5: Structure of chapter three adapted from Van Dam, Nikolic, & Lukszo (2013)

3.1 Key performance indicators and modelling objectives

The Sparkcity model used in this research will aid in answering the questions raised in chapter 1. The model will be adapted in order to answer the question on the impact of smart charging and V2G charging on the LV-grid within the neighbourhood of Lent. Multiple key performance indicators (KPIs) should be tracked in order to gain insights into the behaviours within the neighbourhood and the resulting charging impact of EVs on the LV grid.

3.1.1 Key performance indicators

The KPIs of the model are presented in Table 3. These KPIs are regarded as the main output parameters of the created model and will give insights in the impact of EV charging strategies on the LV grid within the neighbourhood as well as the behaviour that results in these outcomes.

Table 3: Key performance indicators overview

Key Performance Indicators
Electrical load per 15 minutes per transformer
Overload per 15 minutes per transformer
State of charge per EV
Cumulative kWh charged
Cumulative kWh discharged

Following the KPIs a model objective specific for this research can be identified. It is important to identify the model objective in order to create a complete model and an exhaustive list of outcome parameters that could aid a more complete answer to the second sub question in this thesis.

3.1.2 Model objective

Following from the KPIs as presented in Table 3 a modelling objective can be identified. The objective is *to attain a better understanding of the effects of smart charging and V2G charging strategies on the overall electricity consumption within the Neighbourhood of Lent, Nijmegen*.

To gain a better understanding of the effect of different charging strategies on the electrical load within the neighbourhood, first the neighbourhood should be modelled. Secondly, the electricity consumption should be modelled and thirdly the charging need and charging strategies should be developed. It is expected that smart charging strategies cause lower peaks in electrical load within the neighbourhood and it is also expected that V2G charging schemes will introduce a lowering of the peaks occurring during times where demand is higher than the capacity of the current local network. In order to check these hypotheses it is important to vary the input parameters and set multiple conditions in order to conclude on the robustness of the results as will be presented in the next chapter. Following this objective and hypotheses, some requirements can be derived.

3.1.3 Model requirements

Requirements are defined as necessary conditions in order to meet the set objective. Thus, the requirements for the model follow the set model objective. This will lead to a minimal viable model and violation of these requirements will render the results of the eventual model to be incomplete and unusable. Following the modelling objective the following requirements can be derived:

- The model should provide information on the KPIs set in 3.1.1;
- The model should represent the neighbourhood Lent;
- The model clarify the effects of different charging strategies on the electrical load within the relevant components of the distribution grid;
- The model should be able to accompany different scenarios in order to explore the robustness of the results;

Understanding the KPIs, objective, and the requirements for the model allows to expand the model and the details the model contains.

3.2 Model Conceptualization

After the introduction of the Sparkcity model in chapter 2 and the outline of the purpose of the model for this thesis in the previous section, the content of the model should be created. In this chapter, first, the concepts within the model will be formalized and extended upon. Next to this, these concepts will be formalized in a model narrative in section 3.2.2. After the implementation of the model in the GAMA environment, the parameters for the experiment will be set and elaborated upon.

3.2.1 Concept formalization

The concept formalization phase starts with the introduction of the different agents and their environments. The agents represented in the model will be the base of the model. This base will be expanded through the addition of different actions and interactions between these same agents. The table below (Table 4) shows the agents present in the model that are of relevance for the modelling objective within this thesis. As the Sparkcity model is multi-objective not all agents present in the model are deemed important for the modelling objective in this thesis. Therefore, these agents and their actions will be out of scope for this thesis. For further information on the model Hoekstra and Hogeveen (2017), Vijayashankar (2017) could be consulted.

Table 4: Overview of important agents

Agents
House
People
EV
CP
LV transformer
Smart charging aggregator
V2G aggregator

The first agents to include are: houses, people, EVs, CPs, and LV transformers. These agents are physically present within the neighbourhood and are thus a key characteristic of the Lent area.

Houses are agents at which people spend their day whenever they are not occupied with activities outside of their homes. Next to this, not only are people and houses connected, houses are also connected to certain assets of the distribution grid through electricity cables, LV transformers. Because of the case study approach, it is important to simulate electricity consumption per house that is as close to the real world as possible. It thus becomes important to attach the electricity consumption to the household rather than the people in the neighbourhood as this causes the electricity consumption of a house to stay constant.

The people within the neighbourhood will have one mayor characteristic, their activities during the simulation. Both their electricity consumption pattern and their EV usage will depend on this variable.

EVs are the next agents present in the model, EVs will be assigned to people in order for them to travel to their desired destinations. Conventionally fuelled vehicles are out of scope for this research as they do not affect the electrical load within the distribution grid. They will also have minimum interference with EVs during the simulation period.

The logically following agent to be implemented is the charging point. In order to track the effect of EV charging on the distribution grid is important to investigate the charging points within the neighbourhood.

Within the Sparkcity model an elaborated strategy for CP deployment is developed (Vijayashankar, 2017). It can be argued that the deployment of chargers through the neighbourhood will alter the charging behaviour of the EVs. However, within this study the potential impact of charging strategies will be explored. This renders this section of the model out of scope and the CPs will be always available for EVs to be charging.

The impact of charging strategies on the distribution grid is the main question to be answered by the model and thus this distribution grid should be modelled. As presented in the research questions, this thesis will try to give insights into the low voltage distribution grid. This grid consists of two main components, cables and LV transformers. Of these two components, the capacity of the LV transformer is the limiting factor (Verzijlbergh, 2013). Therefore it can be assumed that it is important to look into the capacity of the LV transformers in order to solve potential problems in overloading of assets within this part of the grid. Next to this, the transformers are logical places to make 'smart' and track electricity consumption. Most likely this will not be performed at the cable level, but at a transformer level. Because the transformer information will be used as input for information on electrical load it is important to track the changes in electrical loads with different charging strategies on these locations and not in the cables themselves.

To perform different charging strategies, different aggregators are introduced. These aggregators will have information on current loads of transformers and have predictions regarding future loads. This will be used as input in order to optimize for the lowest electricity consumption per time unit for the connected transformer of the CP. Two separate aggregators are created to separate the decision making logic between different charging strategies. This could also be performed within the same aggregator, but is chosen to be separated for the convenience of modelling.

3.2.2 Model formalization

The first step in the model formalization is the creation of a small model narrative. Afterwards a more detailed unified modelling language (UML) diagram is created.

The model narrative of the model is:

An agent wakes up in the morning and starts preparing to go to work. When the agent is ready to go to work, the agent will take either an EV or a vehicle with an internal combustion engine. The agent drives to work and starts working, meanwhile the installed solar PV installation at home will generate electricity. At the end of the working day, the agent will take its vehicle and drive back home. Once home, an EV owner will plug in his EV and decide at what time he will take the car tomorrow. When the car is plugged in to the charging point, the aggregator will schedule the actual charging of the EV based on the content of the EV battery and the expected electrical load on the transformer to which the CP is connected. The EV owner will start to prepare for dinner and use a higher amount electricity in its home. After this, the agent will lower its electricity demand and possibly leave the house for an evening trip. Later during the evening, the agent will go to sleep and wake up for work in the next morning.

Additionally to the model narrative an UML class diagram of the agents is presented in … . The UML class diagram shows the attributes of all agents and the relationship between the agents. It also shows the operations of all agents.

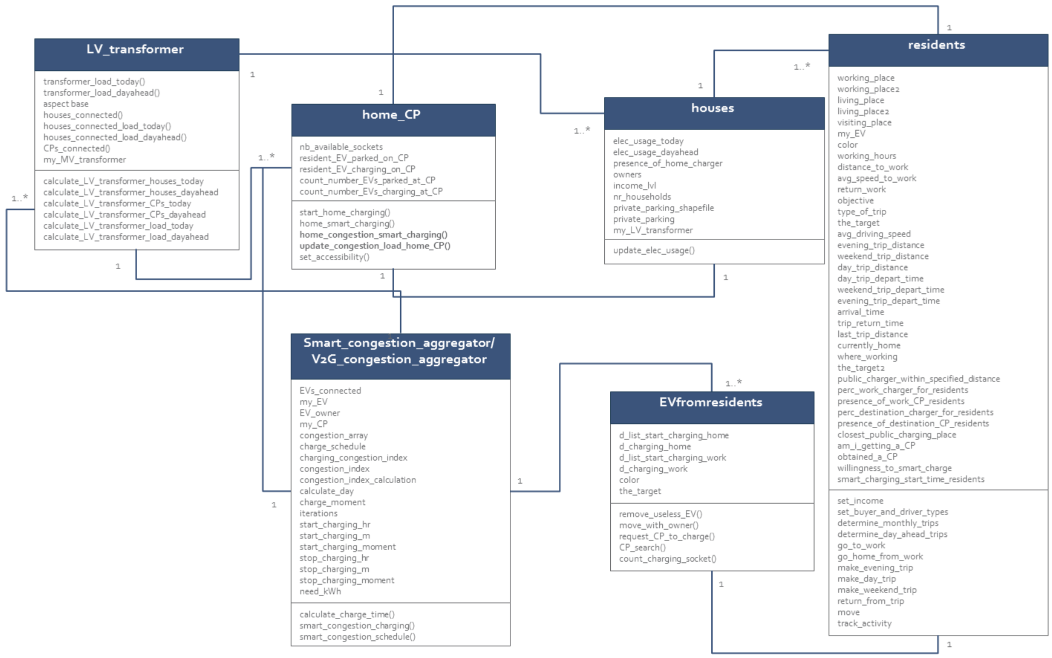

Figure 6: UML class diagram

3.2.3 Model specification

In this section, the model specification of the main behaviours within the model are presented. A charging strategy is chosen and designed for implementation within the Sparkcity model. This formalization is necessary in order for implementation and thus the ability to answer the second sub question. This specification is structured around the main components present in a multitude of regarding the impact of EVs on the grid (e.g. Clement-Nyns, Haesen, & Driesen, 2010) (Table 5).

Table 5: Elements of an EV charging impact model

Model component
EV share
Driving pattern
Charging scheme
Grid topology and load

The Sparkcity model is used to derive the number of EVs in the region. Next to this, the ALBATROSS activity model is implemented in the Sparkcity model and can thus be used as input for the eventual calculation on the impact of charging behaviour. In order to address the latter two topics of Table 4, first, charging behaviour algorithms are designed. Based on the conclusions in section 2.1 a direct control scheme for smart charging and V2G will be designed to calculate the impact of EVs within different scenarios. Afterwards, the assumptions for the expected electrical load on the grid will be elaborated on.

Charging scheme

As presented in the previous chapter. Smart charging based on the V1G principle has two processes that allow for the optimization of EV charging based on the load within the local grid: moment of charge and charging speed. These two principles are the basis of the algorithm implemented within the Sparkcity model. First, the moment of charge optimization is elaborated on. Secondly, the ability to change charging speed is added to the algorithm. Additionally, the ability for bi-directional charging is added as a feature in the algorithm.

Moment of charge optimization

First smart charging, is able to shift the electrical load in time. This shifting makes it possible to delay the charging of the EV battery to a more beneficial moment. The moment for shifting the charging load depends on the goals and objectives of the smart charging algorithm. As the goal of this model is to avoid potential peaks in electrical loads within a neighbourhood, the most opportune time for charging is a time with the lowest electrical load in the assets that are expected to reach their maximum capacity fastest. Following the analysis in chapter XX potential load issues will arise in the LV grid and especially the transformers and the feeders. These assets will thus be used in performing the first sequence of the algorithm.

This level of optimization is also supported by Figure 7 to Figure 9. Figure 7 is a representation of the electrical load of one household. Considering one EV with the ability to charge with a charging capacity of 10 kW and a request for charging of 30 kW but without smart charging, Figure 8 is created. This figure shows the time of arrival, 18:00, and is charged immediately. This creates a peak load on household level. With the EV able to smart charge Figure 9 is created. The peaks have shifted to a different hour based on the lowest electrical load during the available charging hours. It can, however, be concluded that no reduction in peak power is to be witnessed because of the high electrical load of the charger compared to the standard household load. From the comparison of these figures, it can be concluded that a single household level optimization is likely to not be effective in reducing a peak load within the neighbourhood. Most likely is that a new peak load will be created through the charging of EVs, but the peak load is just transferred to a different time. It can also be concluded that a smart charging algorithm with the sole purpose of shifting loads will not be sufficient to decrease peak loads in a low system level optimization.

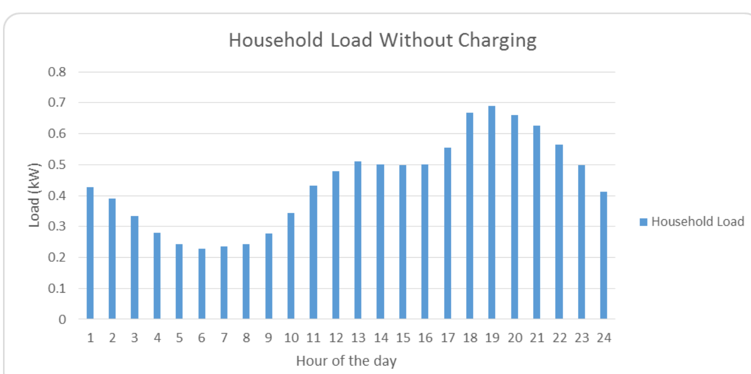

Figure 7: Average household load data (standard profile)

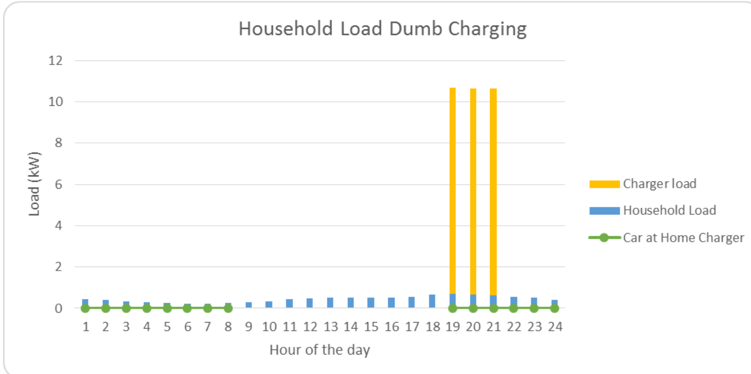

Figure 8: Basic household load including 10 kW EV charging

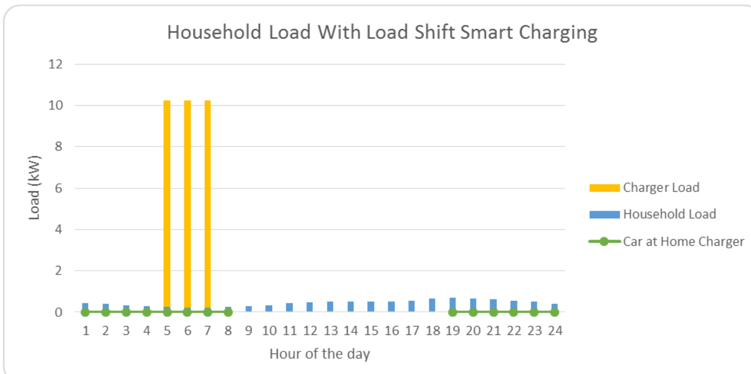

Figure 9: Basic household load including 10 kW load shift smart charging

The conclusion from this two folded. Firstly, the level of analysis should not be household level, but on different assets within the neighbourhood. Secondly, if the goal is to reduce a peak in electrical load, an algorithm for smart charging should also be able to curtail the amount of power supplied during a given time. Following Verzijlbergh (2013), MV/LV transformers are more easily overloaded than MV distribution cables and thus the transformers will be the asset in the system that will be the objective for optimization.

Charging speed optimization

After shifting the load to a more beneficial hour, the algorithm also needs to become more dynamic to allow for a better integration of EVs within the electricity network. This flexibility is created through the ability of chargers to not only be in a state of charging or not charging, but to allow the chargers to differ in charging speed over time. Figure 9 show the smart charging algorithm without charging speed optimization and the following Figure 10 shows the effect of different power outputs of the charger on the electrical load.

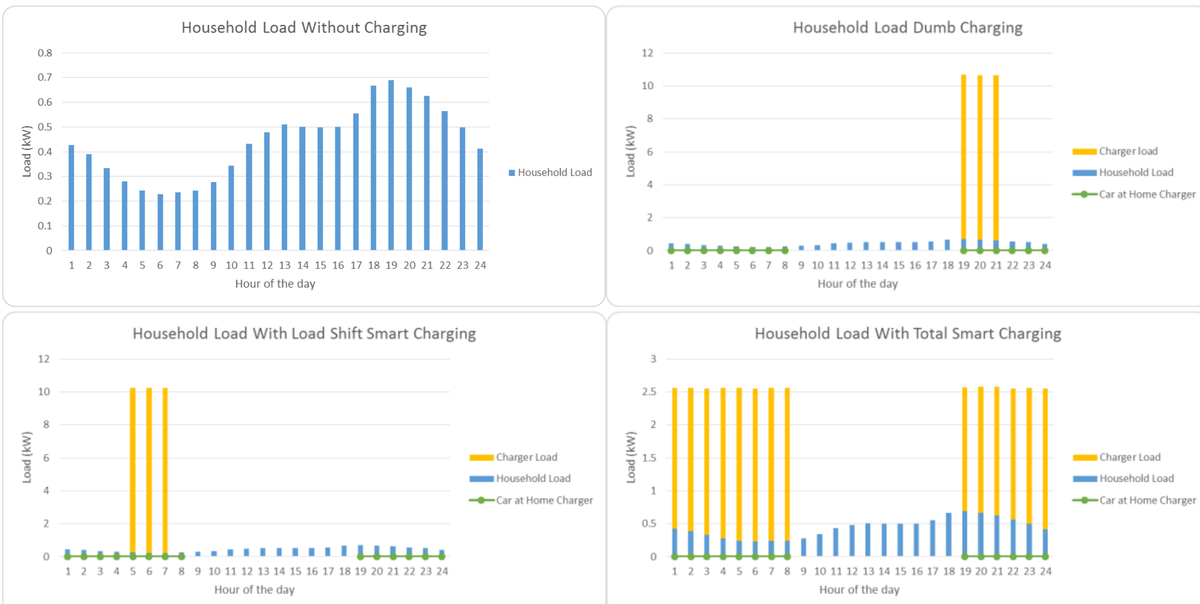

Figure 10: EV smart charging

The power output in the above figure is based on a percentage of the maximum power output of the charger. It can be concluded that a significant lower load is reached by dividing the charging optimization to 1% of the power output of a 10 kW charger. A division into smaller steps does not show a significant improvement and will thus not be pursued for this algorithm. Because of this insight into the importance of energy curtailment for reduction of peak loads within small systems, this is feature is added within the algorithm for smart charging. A flow chart of the created algorithm for smart charging is shown in appendix C.

Bi-directional charging

The bi-directional component of the algorithm is based on the previous two components of smart charging, but the ability to discharge energy from the car into the grid is added. The main assumption for this algorithm is that bi-directional charging should not have any impact on the ability for the owner to use the EV and will thus have the same assumption as smart charging and normal charging. At the end of the charging session the EV needs to be fully charged. If this constraint does not allow energy to be discharged from the battery of the EV, the EV will not participate in V2G charging and will only perform the smart charging algorithm.

V2G could be implemented in many different manners and is applicable to different markets. These markets all have their own objective and ways to earn money. Next to this, the discharge of the EVs can be used for different purposes and the trigger for discharging can be altered between two types of peak shaving. The first objective could be to reduce the all peaks that occur in the system and shift the load of this peak to a more beneficial moment. The second objective could be to only trigger discharge within EVs when the system predicts a potential overload within the system. The first case would be preferential in the overall electricity market at which profits could be made during high electricity prices through discharging and this energy could later be charged at a time for which the electricity price is lower. On the other hand, the FCR market and a DSO market are focused on specific moments in which the demand and supply of energy are not well balanced. Therefore, the algorithm for bi-directional charging in a DSO market will only trigger when an overload is expected at a certain asset within the system. The advantage of this type of V2G charging is that the concerns regarding battery degradation are mitigated because the amount of times that V2G will be needed over a year are less (Bishop et al., 2013). Appendix C shows the flow chart for V2G charging as will be implemented in the model.

Grid topology and load

In this section the grid topology of the modelled region is presented. Next to this, the input on household electricity usage is elaborated on. A representable Dutch household load profile is expanded upon through the inclusion of additional load objects such as heat pumps and solar PV.

Grid topology

The grid topology of the neighbourhood within Lent is provided by the local DSO in this region (Alliander) and includes LV-lines, LV-transformers, MS-cables, and MS-transformers. A representation of the grid in Lent is included in Figure 11. Because an agent-based model is used as the modelling method, it is possible to connected different agents (houses) to assets within the electricity grid and by this means calculate the load in different assets. Next to this, the loads of the charging points is added to the relevant assets. This allows the different charging behaviours of different cars to be mapped on specific assets within the system. The load of the charging points is calculated through the schedules of the EVs prepared by the algorithm provided in 3.1.

Figure 11: Electricity grid of Lent

Electricity load

Typical household loads are on the verge of change through the electrification of different devices within the household. Following Veldman et al. (2010) there are three major developments that will change the electricity usage on the household level next to the adoption of EVs:

1. Demand growth of normal electricity use;
2. Usage of new technologies for heating (e.g. heat pump, and EV);
3. Generation of electricity by photovoltaic panels;

These three major developments will need to be accounted for in the scenario of 2030. In the upcoming sections these three major developments and the daily electricity use and generation for a winter week are explored in order to develop a new daily load profile for households for 2030. Figure 12 shows the structure of the future electricity consumption and generation is constructed.

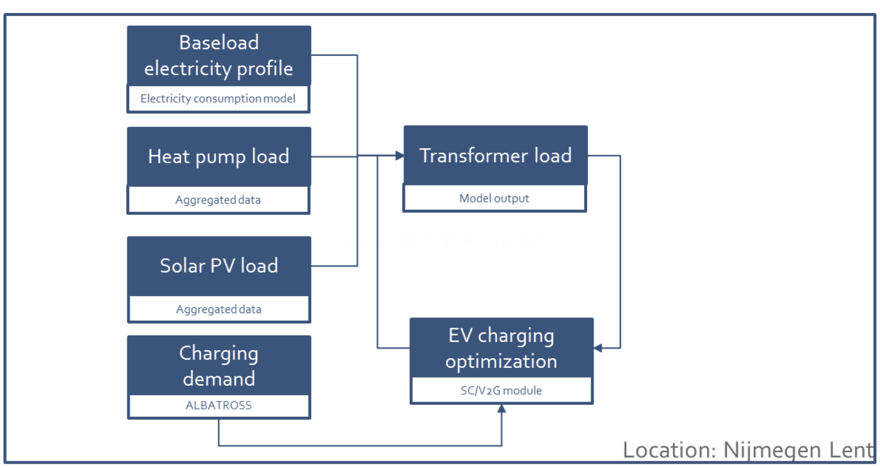

Figure 12: Electricity demand flow diagram

Household load

The electricity load within the area consist of a base load electricity usage excluded the needs from additional electrical appliances. In other research, he household load is represented by a standardized Dutch winter household load profile as presented by NEDU. . Within multiple studies regarding expected electricity use within a neighbourhood a factor is used to account for an increase in electricity usage over the years. This growth factor is often 1% (Klein Entink, 2017) and (Kleiwegt, 2011). However, within the chosen ABM approach, the heterogeneity of the electricity usage in the neighbourhood is able to be modelled. Therefore, all agents will have their own electricity consumptions over the day. The model implemented is from now on called the electricity consumption model Figure 13. In order to enhance the internal validity of the model, the moment when electricity consumption lowers is connected to the ALBATROSS model and when an EV owner leaves the house. Next to this, the evening electricity consumption is connected to the arrival time at home of the EV owner. The amount of kilowatt consumed during the different periods are : sleep, 0.2; morning, 1.25; day, 0.4; evening, 2.2; night, 0.3. These values are chosen in order to reflect typical residential consumption pattern. In order to increase the external validity of the model, the electricity consumption of the households present are modified with a modifier based on an estimated yearly electricity consumption as estimated by the municipality of Nijmegen and the local DSO (Figure 14).

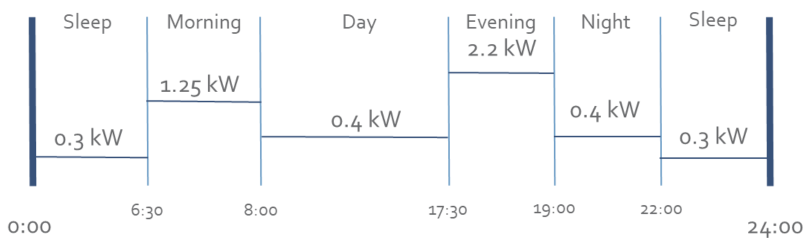

Figure 13: Representation of the electricity consumption pattern per household

Figure 14: Yearly electricity usage per building in Lent

Heat pump load

The municipality of Nijmegen has stated the vision to transition away from fossil resources to provide fuel for heating purposes in the whole municipality in 2050 (Municipality of Nijmegen, 2018). In order to do so, Buildings have to use other sources to meet the heating demands in the area. One of the solutions is to use heat pumps. Heat pumps can be hybrid or full electric, but in this model only the full electric version is used. Heat pumps will have an additional electricity demand on top of the current household load model. Typical loads for heat pumps for winter periods are presented in Figure 15. These figures are a representation of heat pump load in a winter week in Great Britain, but will be used as input for the Dutch neighbourhood as well. Heat pumps are also a source of flexibility and could provide demand response within the same market as V2G. However, in this model, the electrical load of heat pumps are used in input rather than a variable. Studies on the effect of flexibility provided by heat pumps are, for example, Hong et al. (2012). Figure 15 shows the input for the electrical demand for a heat pump in a winter week. This data is retrieved from Love et al. (2017). The study conducted by Love et al. (2017) is the most extensive study into the aggregated load data of heat pumps so far. An additional advantage is that this paper investigated empirical heat pump electrical load data rather than calculating the demand based on heating demand. Because of this, data provided in Love et al. (2017) is used instead of constructed data as presented in Asare-bediako, Kling, & Ribeiro (2014), Meerkerk (2015) and Veldman et al. (2010).

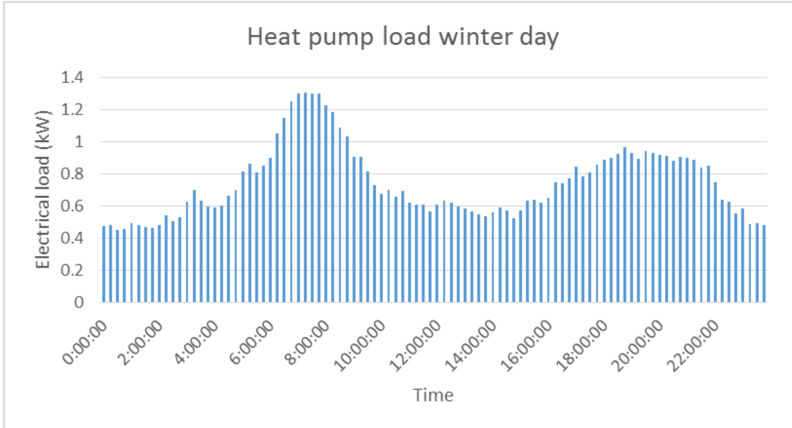

Figure 15: Heat pump daily load profile winter week (Love et al., 2017)

Photovoltaic load

The last technological development that will have a significant impact on the distribution network are photovoltaic solar panels. The impact of solar PV will most definitely be during summer time for which the electricity generated is greater. The diffusion of solar PV technology will be the most impactful on the electricity network (Elshof Beng, 2016).Because of the timing of electricity generation, mainly during summer days, the self-consumption of solar PV is rather low. The electricity demand standard deviation will threefold with a high penetration of solar PV in the neighbourhood (Elshof Beng, 2016). This electricity thus will need to be transported by the DSO imposing new challenges to the DSO. Because of the impact of decentralized generation on the distribution grid it is of interest for this research to include solar PV generation behaviour. Figure 16 is a representation of a winter day generation profile for a household solar PV system. The load of the solar PV installation is represented with a negative load as this load is supplied within the network.

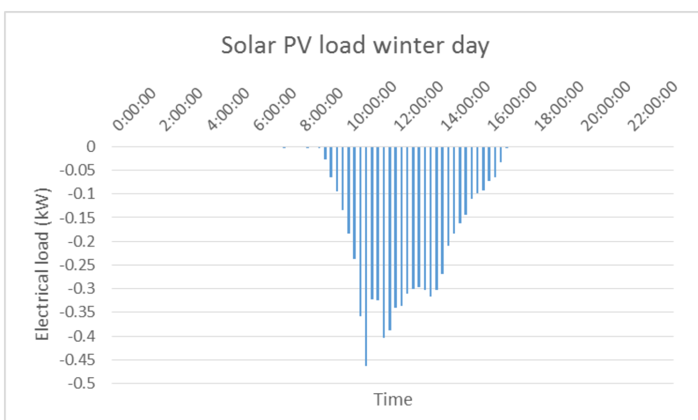

Figure 16: Solar PV electrical load (Haque et al., 2014)

3.2.4 Experiments

Two different experiments are created in order to answer the second sub question in this research. In the following chapter, set up of experiments and variables are discussed as well as the approach to the sensitivity analysis. Following this approach, the results of the experiments and the conducted sensitivity analysis will be presented in chapter 4.

Experimental setup

In order to analyse the impact of V2G charging on the electricity grid, two experiments are defined: experiment 1 (smart charging, SC) and experiment 2 (vehicle-to-grid charging, V2G). One of the experiments consists of a base case, excluding vehicle-to-grid charging, and the other experiment includes the ability of EVs to charge bidirectional. In both smart charging strategies and experiments it is decided upon a 100% implementation of the chosen strategy. This results in the setup as presented in Table 6.

Table 6: Shares of charging strategies over EV population

	SC	V2G
EV share (%)	30%	30%
Smart Charging share (%)	100%	100%
Of which V2G capable (%)	*0%*	*100%*

To compare both experiments to each other it becomes important to use the same metrics in both cases. These metrics are the KPIs and have been defined in section 3.1.1. These five KPIs will provide a comprehensive review of the impact of V2G charging on the electricity grid. In order to understand certain behavioural patterns, more information might be gathered trough other metrics, if deemed necessary. In order to cope with the variance in values over different runs median values over the runs will be presented. Next to this, the 25% confidence interval will be shown and will be called "Low". The 75% confidence interval is presented as well and is called "High".

Variable setup

Many different variables are included within the Sparkcity model, both direct and intermediate variables are included. However, not all variables are of importance in answering the second sub question in this research. The main variables that will influence the results of the experiments are defined in the table below (Table 7).

Table 7: Input variables and values

Variable	Value
Households (#)	1342
Car ownership (car/household)	1
EV share (%)	33
Heat pump share (%)	33
Solar PV share (%)	33
Starting state of charge (%)	Gauss(75, 0.25)
Battery capacity (kWh)	One off(30, 40, 50, 60, 70)
Working hours (h)	8

Sensitivity Analysis

The presented model might be sensitive to changes in input variables, as described in the previous section. In order to check the robustness of the outcomes and thus the value of the presented model, a sensitivity analysis is performed. In this sensitivity analysis different input parameters are modified to check for the robustness of the results under different sets of parameters. A list of variables that will be considered in the sensitivity analysis are presented in Table 8. The results of these modifications will be exhibited in section 4.3.

Table 8: Variables for sensitivity analysis

Sensitivity Analysis
EV share
Charging point capacity
Electricity consumption model

The presented model within this chapter is implemented in GAMA and the Sparkcity model. The results of the experiments defined in this section are presented in the next chapter of this research including a sensitivity analysis of the variables described in table 8.

Chapter 4: Results

In this chapter, the results of the implemented conceptual model presented in the previous chapter is discussed. The input parameters are discussed in section 3.2.4. Two scenarios will be presented. First, the smart charging experiment is discussed. This experiment is also known as the alternative zero and is the benchmark for the second scenario. The second experiment consists of vehicle-to-grid charging. Afterwards, the load of MV/LV transformers in both scenarios is discussed. Next to this, a sensitivity analysis is performed in order to evaluate the robustness of the results presented. A graphical representation of the structure of this chapter is presented in Figure 17.

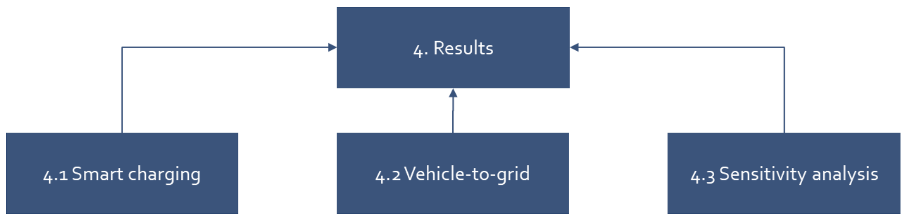

Figure 17: Structure of chapter 4

Figure 18 shows the average connected technologies. These technologies include EVS, HPs, and Solar PVs. Also the number of houses connected to the transformer is shown in the blue bars. The graph shows the even distribution of technologies over the transformers. The standard deviation of the number of connected technologies is rather low. Because of this it is expected that the variation of the electricity consumption of households between the different replications of the simulation is rather low. The standard deviation for the number of houses connected is zero in all cases because the location of the houses and transformers are fixed and thus the same connection appears in all replications.

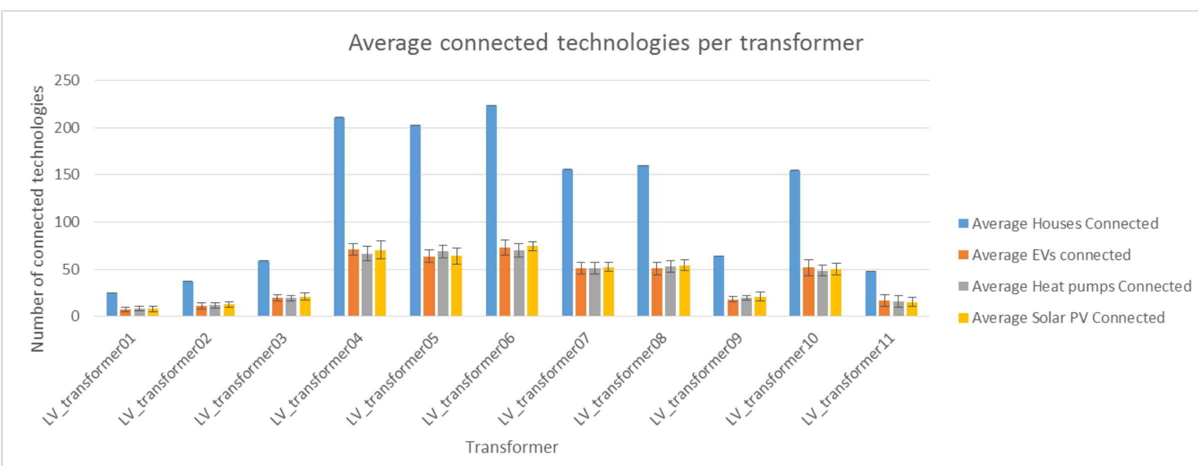

Figure 18: Average technologies connected per transformer

4.1 Smart charging

First, the results of the smart charging experiment are presented. The presented results follow the structure of the KPI's provided in section 3.1. Because the implemented model consists of multiple variables with a randomly distributed value, a number of replications of the experiment is performed. A number of replications is performed in order to deal with randomization effects. The number of replications of the smart charging scenario is set to 12. The variability within the KPI's are relatively low with this number of replications. The median values of the KPI's will be presented alongside the 25% and 75% interval. The final values at these intervals and the median value of the KPI's will be used as input into three electricity consumption scenarios called: Low, Median, High. These scenarios will be summarized at the end of this section.

An overview of the overloaded transformers in the neighbourhood is displayed in Table 9.This table shows the transformers of interest within Lent. The table also presents the capacity of the transformers calculated on the basis of the number of houses connected to the transformer. It shows three transformers of 100 kVA, one of 250 kVA, and five transformers with a capacity of 400 kVA. The maximum load occurred during the different simulations of the first experiment. If the maximum electricity demand of a transformer is higher than the capacity of the transformer, the transformer will be overloaded. The last parameter shown in the table is the load factor. The load factor is calculated by dividing the maximum load divided by the average load on the transformer during the simulation. A load factor near 100% shows that there is a very small peak in electricity demand and the peak is close to the average. A load factor near 0% shows that the peak is high in comparison the average consumption. A lower load factor allows for more value created by flexibility solutions. Flexibility solutions are mostly considered in the case of a low load factor because of the expected short times of overload on the electrical appliance. Average residential neighbourhood transformer have typically a load factor of around 50% (Humayun, Degefa, Safdarian, & Lehtonen, 2015). The load factor of the overloaded transformers show the potential of these transformers to be supported through flexible resources.

Table 9: Transformer load in smart charging experiment

Transformer	Capacity (kVA)	Low			Median			High		
		Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)
Transformer 1	100	65	No	46	69	No	49	74	No	50
Transformer 2	100	128	Yes	46	137	Yes	47	151	Yes	47
Transformer 3	250	269	Yes	43	276	Yes	46	317	Yes	44
Transformer 4	400	526	Yes	51	550	Yes	52	585	Yes	52
Transformer 5	400	444	Yes	51	457	Yes	53	487	Yes	53
Transformer 6	400	413	Yes	53	430	Yes	54	456	Yes	54
Transformer 7	400	324	No	51	341	No	54	395	No	51
Transformer 8	400	296	No	54	322	No	53	341	No	54
Transformer 9	250	144	No	52	154	No	52	167	No	52
Transformer 10	400	332	No	53	357	No	53	383	No	53
Transformer 11	100	98	No	48	104	Yes	50	110	Yes	52

Table 9 shows all transformers of interest in the neighbourhood. This table shows six overloaded transformers. However, within the 25% interval, one of these transformers (transformer 11) is not overloaded. No additional transformers are overloaded in the 75% interval. Because of the small difference between the scenarios and the change in overloaded state, transformer 11 is of special interest in future examination of the results. The table also represents the load factor of the transformers. This load factor is constant over the different intervals. Only a small variance can be noted between the final values of the intervals. Following the table it could also be noted that a higher maximum load does not necessarily lowers the load factor (for example, transformer 1). Because of the increase in peak load, a lower load factor could be expected. However, the high scenario consists of higher demand over the total duration of the simulation and thus the average electricity consumption level is higher, resulting in a higher load factor. Load factors are similar to the load factors presented in Humayun et al. (2015). Input for Table 9 is provided through load profiles of all transformers included in the smart charging experiment. An example of a transformer load profile is presented in Figure 19.

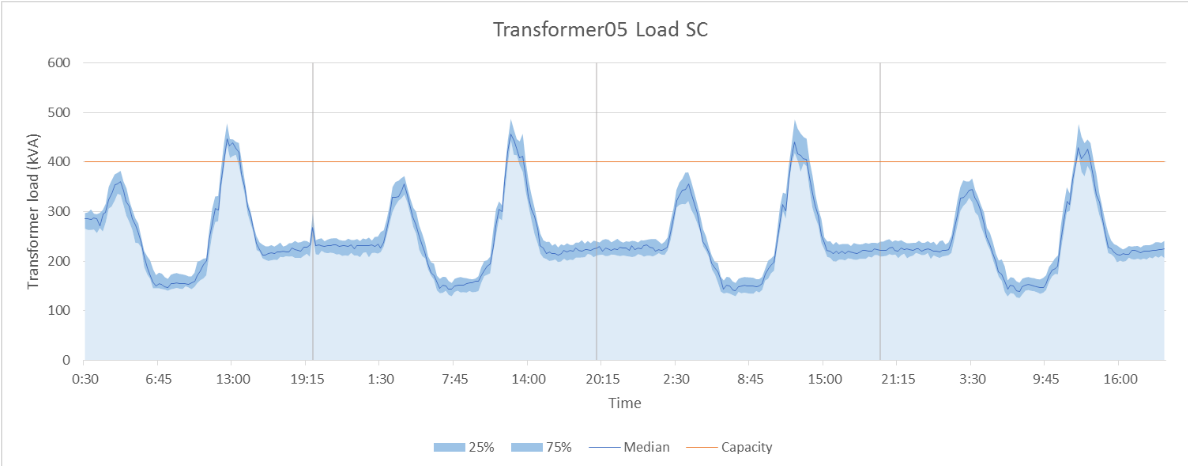

Figure 19: Load profile of transformer 5 in smart charging experiment over four days

Figure 19 is a representation of the load profile of transformer 5 in the smart charging experiment. The y-axis represent the Transformer load in kVA and the x-axis represent the time during the simulated working week. The vertical grey bars represents the separations of the days within the simulation. The orange line at 400 kVA represents the capacity of the transformer. Furthermore, the blue line represents the median values of the twelve replications of the smart charging experiment. The dark blue surface area represents the 25% and 75% interval range. No distinction is made between the sources of the transformer load. Ten peaks in electricity demand can be identified, evenly distributed over the four working days. First, a morning peak can be identified around 07:00. This peak is caused through the increased consumption per household during the morning following the electricity consumption model together with a peak in electricity demand from heat pumps (section 3.2.3). An evening peak is created through the arrival of residents from work. It can be noted that the evening peak is higher than the morning peak and the evening peak causes overload during all simulated working days. Following the figure, electricity demand during the night is substantially higher than during the day (peaks excluded). This additional demand during the night is caused by the smart charging of EVs during the night. EV charging demand is delayed and optimized for low electricity demand on the transformer. The transformer loads of all other transformers are presented in appendix D.

Additionally, a dip in electricity consumption is presented at midnight of the first day (not presented in Figure 19). This dip in electricity demand is not expected during this time and is not present in all other days of the week, but is present at all transformers (appendix D). The dip in electricity demand is entirely caused by the lack of EV charging during this period. This is due to a bug in the implemented model in which the transition on first simulated day is not functioning properly. However, this is not the cause of the additional electricity demand during the same night when compared to the other nights. To research the cause of the higher demand during the first night, the demand for EV charging should be examined. This demand is dependent on the SOC of the EVs. The average SOC of the EVs within the neighbourhood is presented in Figure 20.

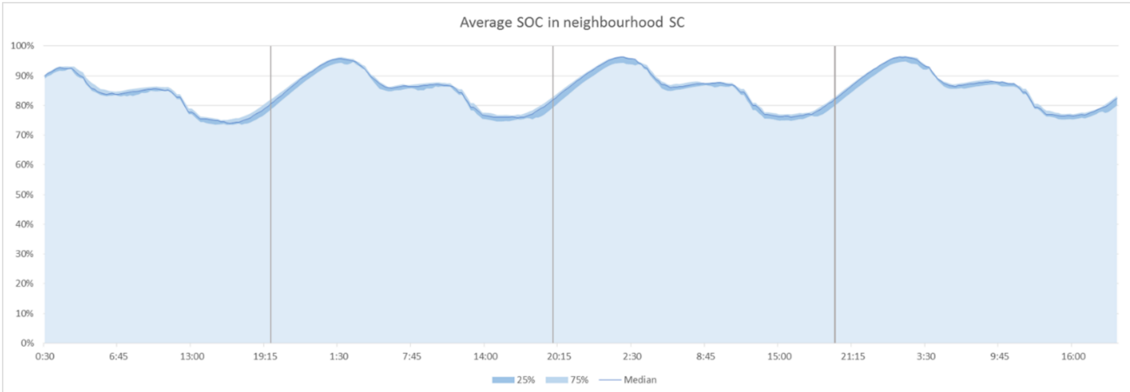

Figure 20: Average state of charge in neighbourhood in smart charging experiment over four days

Figure 20 is a representation of the average state of charge of all EVs within the neighbourhood. The y-axis represents the state of charge, based on the number of kilowatt-hours present in the battery and the battery capacity of the EV. The x-axis presents the time during the simulation. The blue line represents the median value of all replications and represents the average SOC. The dark blue surface area represents the 25% and 75% interval. The four work days can be identified separately and a similar pattern can be identified over these days. However, the observed behaviour on the first day is different in comparison to the upcoming days but is not presented in the figure. A lack of charging during the morning on the first day and the initial SOC of the EVs at the start of the simulation are the cause of the higher EV charging demand and thus electricity demand during the night from the first to the second day. It can also be noted that the SOC peaks occur shortly after the peaks in Figure 19. This can be explained through the cumulative nature of the kWh present in the EV battery during the charging period. To research if the high transformer loads during the night are caused through EV charging demand and to further investigate the impact of smart charging on the transformer load, EV charging demand is plotted in Figure 21.

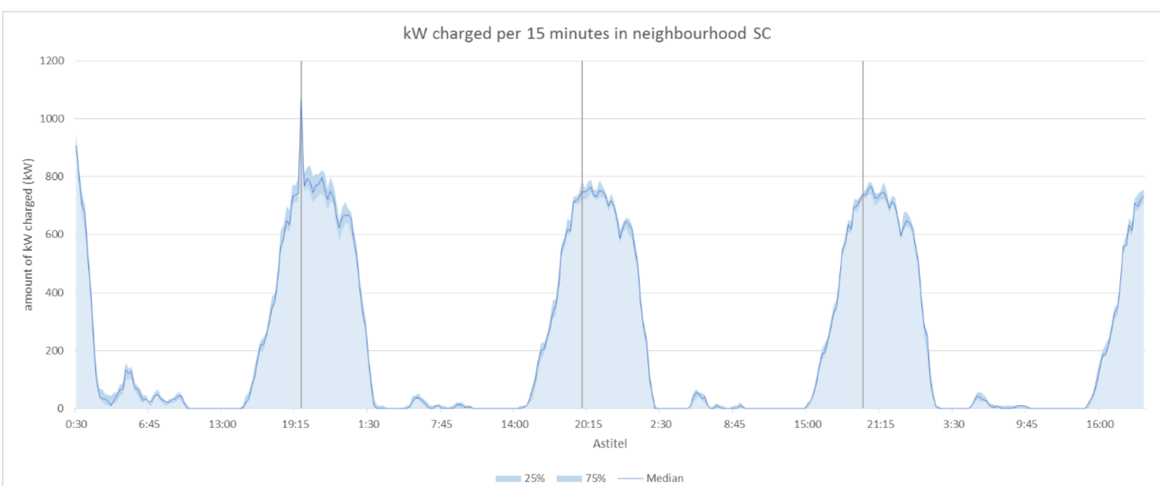

Figure 21: kW charged per 15 minutes in smart charging experiment over four days

Figure 21 is a representation of the actual amount of kilowatts charged every fifteen minutes. The y-axis represents the cumulative amount of kilowatts charged in the neighbourhood every 15 minutes. The x-axis represent the time during the simulation. Following Figure 21, four peaks in the amount of charging capacity used can be identified. Three of these peaks are similar, during the night of day two, three, and four. The peak on the fifth day is only half of the peaks in the neighbourhood. Midnight of day five is the end of the simulation period and thus the peak is only plotted up until this moment. Next to this, the peak during the night of the first day is higher than all other peaks which is not presented in the figure. The cause of this peak is explained through the low average SOC at the start of the night in Figure 20. Figure 21 is the evidence that the increased electricity demand during the night, as presented in Figure 19, is due to charging of EVs. Additionally, it can be noticed that the peak of EV charging during the first night is causing the additional transformer loads during the first night in comparison to other nights. Discharging is not possible within the smart charging scenario and thus equals to zero.

This research aims to quantify the impact of V2G charging on the low voltage electricity grid and specifically the impact of charging on the load of MV/LV transformers. The impact of the implemented V2G charging strategy will focus on the overloads occurring at transformer level within the neighbourhood. Therefore, the next section is focussed on the overload of transformers.

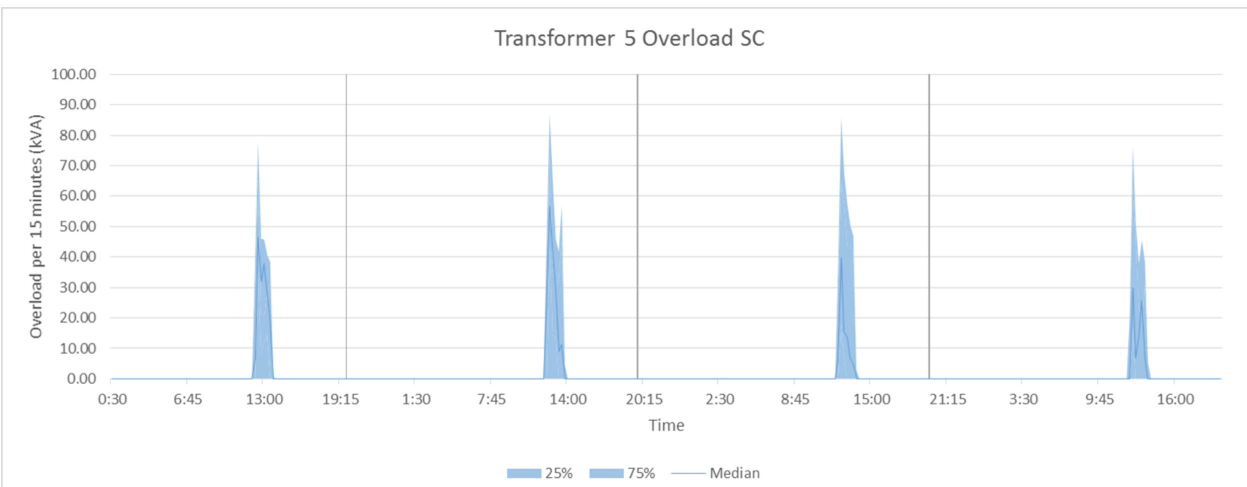

Figure 22: Overload of transformer 5 in smart charging scenario over four days

Figure 22 presents the overload of one of the transformers (transformer 5) over four working days. The y-axis represents the overload in kVA per 15 minutes. The x-axis presents the time during the simulated period. Five peaks can be identified in this figure. These five peaks all start during the late afternoon and last for around an hour. The figure does not show overload during the morning as this is not occurring within this transformer. However, overload during the morning peak is present in two other transformers. The time of overload in total in the neighbourhood is examined in further detail in Figure 23.

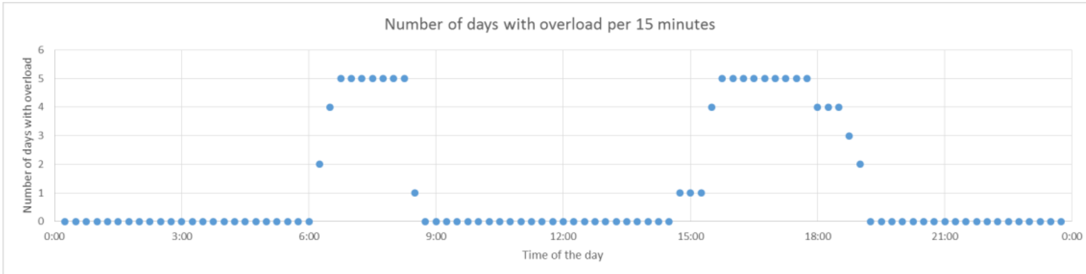

Figure 23: Number of overloaded days for at least 1 transformer in the neighbourhood

In Figure 23 the number of days with overload within a particular time period is shown. From this figure the two peak periods with overload can clearly be derived. Every day at least one transformer is overloaded during the timeslots of 06:45 until 08:15 and from 15:45 until 17:45. In this time period at least one transformer is overloaded during the days of the simulations. From this figure it can be deduced that the evening peak lasts longer than the morning peak. During one of the simulated days, the so-called evening peak already starts at 14:45. The evening peak, at latest, ends as early as 19:00. Earlier, it was already concluded that the evening peak was higher than the morning peak. Figure 23 only shows the moments when overload is occurring, the amount of overload is not specified in this figure. The following figure represents the cumulative overload over the entire neighbourhood.

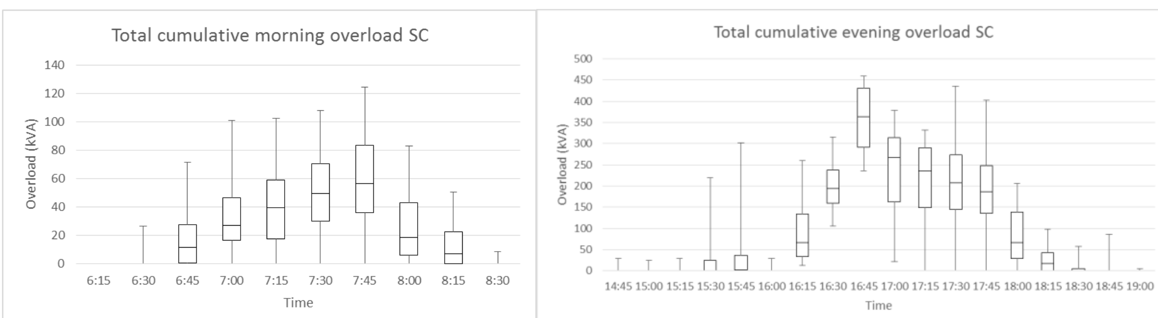

Figure 24: Total cumulative overload neighbourhood in smart charging experiment

Figure 24 represent both cumulative morning and evening overload in the simulated neighbourhood. The y-axis represents the overload in kVA. The x-axis represents the time of the simulation for which the overload is occurring. This figure demonstrates in further detail that the evening peak last longer and is higher than the electricity demand peak in the morning. It also shows the variability of the magnitude of overload. Following figure 6, a maximum 400 kVA overload is possible at 17:45 while the minimum of overload could also be equal to zero. However, the 25% to 75% interval is relatively close the median value. Because these values are more representative than the maximum and minimum value, the final values within this interval will be used as input as scenarios for the economic assessment in the following chapter. First, the results of the V2G charging experiment are presented.

4.2 Vehicle-to-grid charging

In this section, the impact of V2G charging on the LV grid is assessed. First, the results of the V2G experiment are presented. Next to this, a comparison between the smart charging scenario and the V2G scenario is made. First, a summary of the transformer loads is presented in Table 10.

Table 10: Transformer load in vehicle-to-grid experiment

Transformer	Capacity (kVA)	Low			Median			High		
		Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)
Transformer 1	100	65	No	48	70	No	50	77	No	51
Transformer 2	100	100	No	56	103	Yes	61	120	Yes	58
Transformer 3	250	250	No	50	250	No	54	262	Yes	57
Transformer 4	400	402	Yes	64	415	Yes	67	439	Yes	68
Transformer 5	400	400	No	56	400	No	60	400	No	65
Transformer 6	400	400	No	54	400	No	58	400	No	62
Transformer 7	400	331	No	51	356	No	51	390	No	51
Transformer 8	400	300	No	53	322	No	54	357	No	52
Transformer 9	250	144	No	51	153	No	52	177	No	48
Transformer 10	400	319	No	51	343	No	54	376	No	52
Transformer 11	100	95	No	50	100	No	55	100	No	61

Table 10 represents the load of all transformers in the simulated neighbourhood. This table shows that not all overload within the transformers is solvable using V2G. The reasons why V2G is not able to solve this overload is examined later within this section. Within the low scenario, only overload in transformer 4 is not able to be solved. Four other transformers are relieved from overload through V2G charging of EVs. Within the median scenario, two transformers are not relieved from overload. However, overload in four other transformers is prevented. For the high scenario, overload is prevented in the case of three transformers. The transformers with overload in the smart charging scenario, but without overload in the V2G scenario have maximum loads equal to the transformer capacity. Due to the V2G strategy implemented only the minimum amount of discharge is provided in order to prevent overloading. It can thus be concluded that all amount of overload is created equally. However, transformers do not have such a hard constraint at 100% capacity. Transformers are able to function normally up to 120% for a period of time. This will, however, decrease the lifetime of the transformer. Furthermore, it can be concluded from Table 10 that the load factor of the transformer, for which overload is prevented, is higher. For example, transformer 2 is overloaded during the smart charging scenario in all three scenarios and has a load factor of 46%,47%, and 47%. Within the V2G scenario the load factor equals 56%,61%, and 58%. It can thus be concluded that V2G does not only prevent the overload of the transformer, but V2G also allows for a better utilization of the current transformer. This is also shown in Figure 25, which presents the load profile of transformer 5.

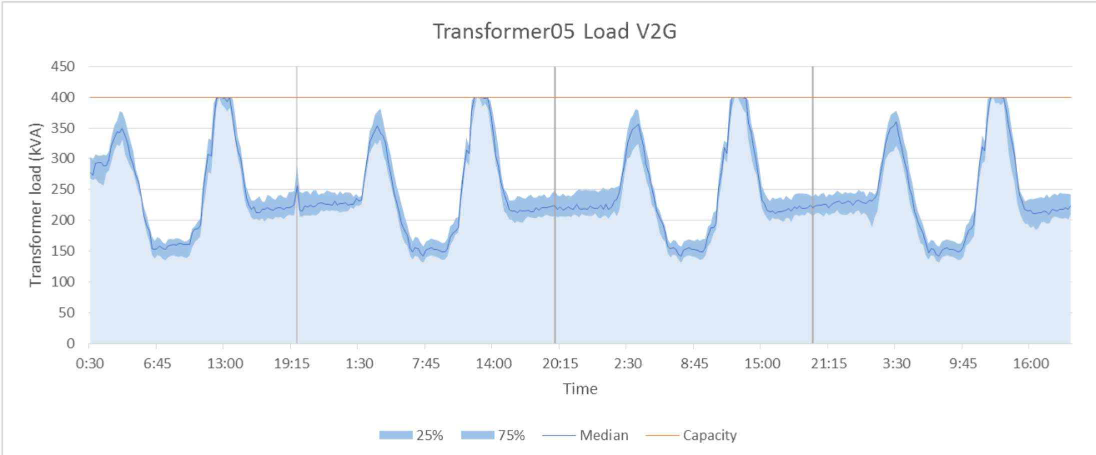

Figure 25: Transformer 5 load profile in vehicle-to-grid experiment over four days

Figure 25 represents the load profile of transformer 5 within the V2G experiment. The load profile of Figure 25 is similar to the load profile of the same transformer within the smart charging scenario (Figure 19). The load on transformer 5 within the V2G experiment during the morning peak and during the midday are equal to the loads of transformer 5 during the smart charging experiment. However, the evening peak load is different between the two experiments. Within the smart charging scenario a maximum load of more than 470 kVA is reached. Within the V2G scenario, the maximum load is equal to the capacity of the transformer. Additionally, the load during the night has not changed dramatically. Because the amount of discharge needed is spread evenly over the night, the load during the night only slightly rises while the peak of the transformer is drastically reduced. As the EVs have to discharge upon arrival at home shortly after, the SOC of EVs within the neighbourhood is expected to be different in comparison to the smart charging experiment.

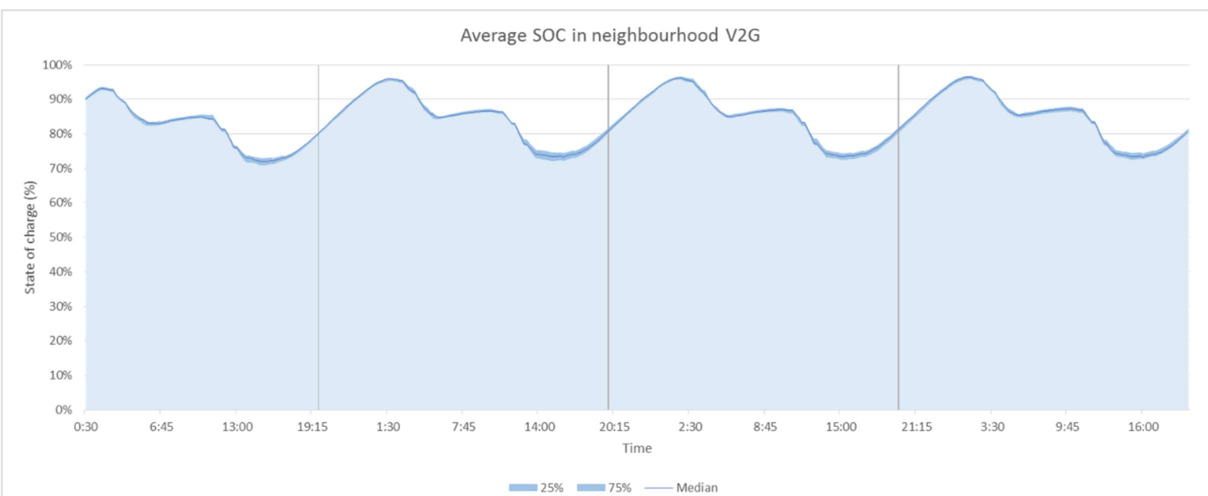

Figure 26: Average SOC of all EVs in neighbourhood in vehicle-to-grid experiment

When examining the average SOC within the neighbourhood it can be concluded that discharging, in order to prevent overloading of MV/LV transformers, does not significantly impact the average SOC within the neighbourhood. The presented case only has limited moments of discharging and the discharging of a small amount of EVs does not influence the average SOC within the neighbourhood. Next to this, the EVs are constraint to not discharge over 30% of their capacity and are also constraint to be fully charged at the end of the charging session. Therefore, a similar SOC pattern arises as to the smart charging experiment. It can thus also be concluded that V2G does not necessarily has to decrease the battery level of the EV at the end of the charging session. Within the total CP capacity used within the neighbourhood, a significant change in comparison to the smart charging scenario is expected.

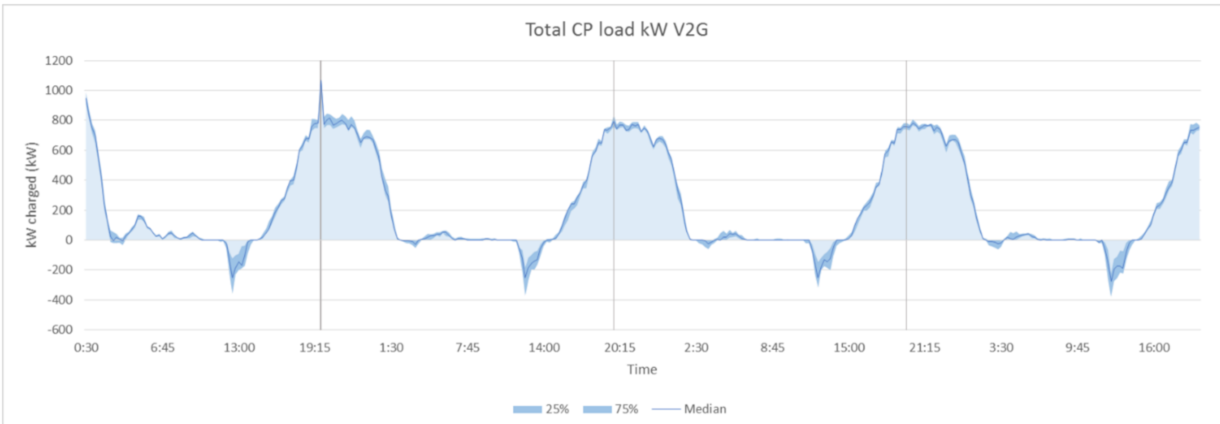

Figure 27: Total kW (dis)charged in neighbourhood in vehicle-to-grid experiment

Figure 27 represents the total cumulative kW (dis)charged during the vehicle-to-grid experiment. When comparing Figure 27 to Figure 21 it becomes apparent that within the V2G experiment EVs are able to discharge and do so regularly. Every day during the evening peak load on certain transformers EV start discharging to provide congestion management services. It can also be noted that EVs do barely discharge during peak hours in the morning peak. The reason for this is twofold. First, the morning peak in electricity demand is lower than the evening peak and thus less overload exist during the morning peak in the neighbourhood. However, from Figure 24 it becomes clear that overload still exists in the morning. However, the chosen V2G strategy is not able to handle overload during morning. This is because of the constraint that an EV should be fully charged at the end of a charging session. An EV will not provide V2G services if it is not able to fully recover the discharge later within the charging session. If this constraint would not be in place more discharge would occur during the morning. It can also be noted that the amount of discharge is relatively low to the amount of kW charged during a night. This is caused by a relatively low amount of overload in the presented system. The overload within the area is not as high as the charging demand of the EVs within the neighbourhood. This would suggest that smart charging of EVs is necessary to accommodate for a high penetration of EVs within the network. If these EVs would not be able to smart charge, additional overload will be created. The times of overload during the smart charging experiment are now more closely compared to the times of overload occurring during the vehicle-to-grid experiment.

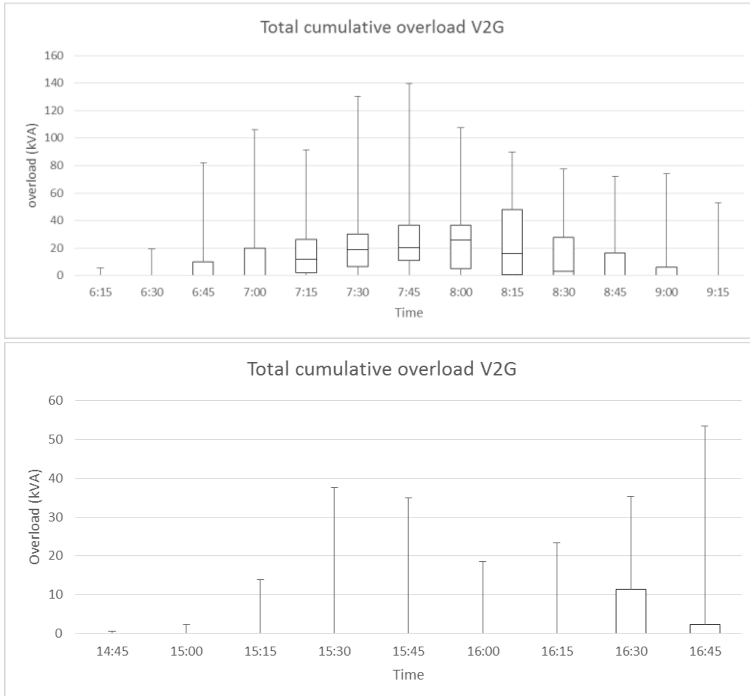

Figure 28: Cumulative overload neighbourhood in vehicle-to-grid experiment

Figure 28 presents the cumulative overload of the simulated neighbourhood. First, the morning peak is presented, afterwards the evening peak is shown. From this figure it can be concluded that V2G is able to completely prevent overloading of the simulated transformers during the evening peak. However, the implemented V2G strategy is not able to cope with the overload of transformers during the morning peak in electricity consumption. Within the model, all amounts of overload are treated equally. However, lower amounts of overload are preferred within real life transformers as transformers are able to deal with a small amount of theoretical overloading.

Key insights

- The implemented smart charging strategy is able to shift charging demand from the evening into the night;
- The implemented smart charging strategy will not create a new peak during the night but will distribute the charging load evenly based on the load of the transformer;
- Within a smart charging scenario of Lent, overload of transformers will still occur;
- Peak electricity consumption will be higher in the evening than during the morning;
- The implemented V2G strategy is able to prevent almost all overload present in the neighbourhood;
- The implemented V2G strategy is better in dealing with overload at the start of the charging session than at the end of the charging session;

The robustness of the results presented within this chapter so far are researched trough a sensitivity analysis. This sensitivity analysis include all major input parameters as presented in chapter 3.

4.3 Sensitivity Analysis

A sensitivity analysis is performed in order to explore the impact of vehicle-to-grid under different circumstances. In section 3.2.4 the variables part of the sensitivity analysis are presented. The variables used within the sensitivity analysis are part of three of the most important determinants of grid impacts as stated by Richardson (2013). These variables are: EV share, charging point charging power, and the electricity consumption model.

First, the results of the alternations of the values for EV share are presented. The EV share is altered within the smart charging and V2G experiment and is changed to 20% and 50%.

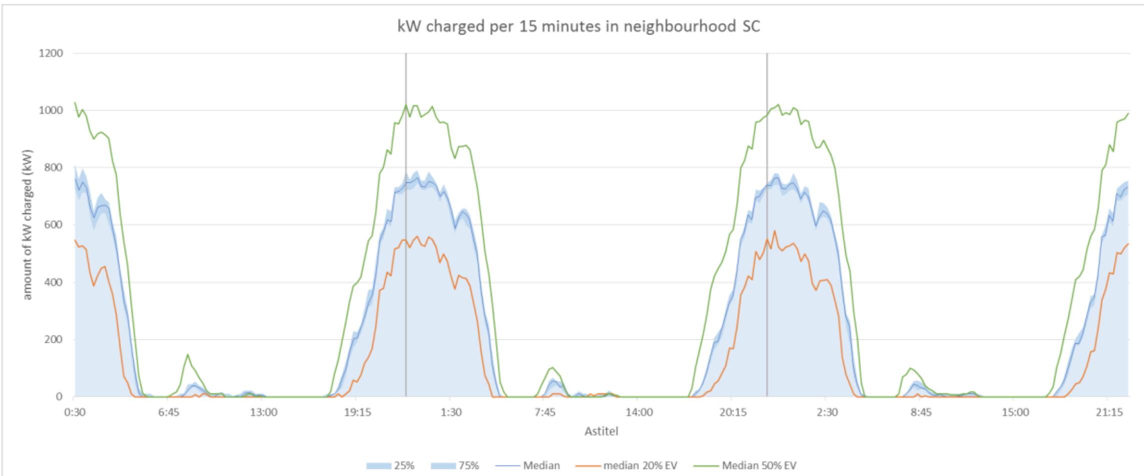

Figure 29: Total CP charging in neighbourhood in smart charging experiment including sensitivity analysis

The above figure shows the total CP load within the neighbourhood throughout the simulation period. The blue surface and line represents the total CP load as presented in 4.1. The green line represents the median CP load of five replications with 50% EV market share and the orange line represents an EV market share of 20%. It can be noted that the charging patterns during the day are the same in all simulations. This is because of the charging strategies implemented within the model. EVs charge at moments for which the load in the transformer is lowest which is based on the electricity consumption of households. The amount of charging load is also well distributed, 20% EV share has lower CP loads and 50% EV load show higher loads.

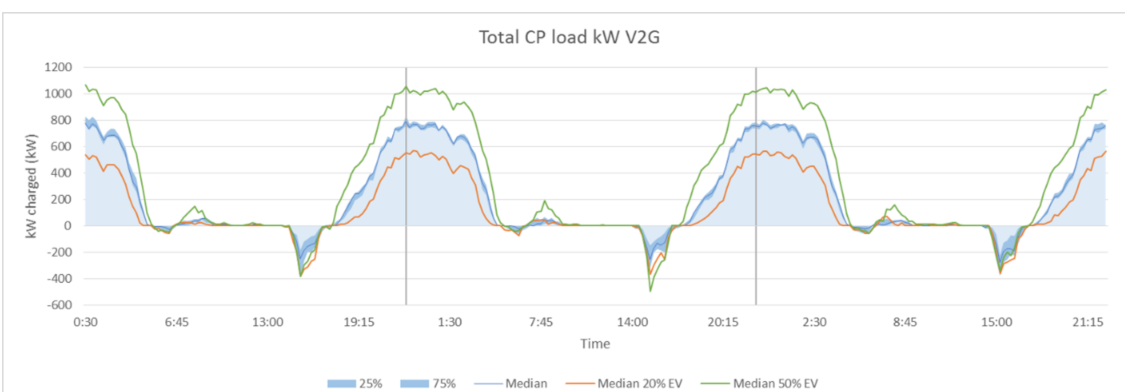

Figure 30: Total CP charging in neighbourhood in V2G experiment including sensitivity analysis

Figure 30: Total CP charging in neighbourhood in V2G experiment including sensitivity analysis. Figure 30 is a representation of the amount of kilowatts charged in the neighbourhood for the V2G experiment. The altered values for EV market share follow a similar pattern and the distribution is similar to the distribution as presented within the smart charging experiment. However, the difference of amount of kW discharged during peak loads is lower than for the charging of EVs. This is caused by the limited amount of overload present in the system and thus EVs will not discharge linearly more when more EVs are present. It could also be noted that the amount of kW discharged in the 20% market share case is similar to the amount of kW charged in base case.

Table 11: Transformer load summary V2G experiment with sensitivity analysis

Transformer	Capacity (kVA)	ECM 90%			ECM 100%			ECM 110%		
		Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)
Transformer 1	100	68	No	52	70	No	50	86	No	50
Transformer 2	100	102	Yes	64	103	Yes	61	124	Yes	63
Transformer 3	250	250	No	57	250	No	54	250	No	66
Transformer 4	400	412	Yes	70	415	Yes	67	550	Yes	68
Transformer 5	400	400	No	62	400	No	60	420	Yes	75
Transformer 6	400	400	No	60	400	No	58	402	Yes	75
Transformer 7	400	348	No	51	356	No	51	400	No	58
Transformer 8	400	308	No	57	322	No	54	394	No	58
Transformer 9	250	151	No	55	153	No	52	200	No	52
Transformer 10	400	372	No	51	342	No	52	400	No	57
Transformer 11	100	96	No	55	100	No	55	104	Yes	68

Table 11 presents the results of the sensitivity analysis performed on the values within the electricity consumption model. This model shows that a decrease in the values of the electricity consumption model does not alter the state of the transformers much. It can, however, be noted that the load factor is higher when the values in the electricity consumption model are lower. When the electricity consumption model is altered and the values are increased with 10%, it becomes apparent that two transformers reach an overloaded state during the vehicle-to-grid experiment. This means that the EVs present at the transformers are not able to deal with the additional load generated by the households. This result shows that the robustness of the number of transformers for which overload is solved within Lent is low. A 10% alteration of the peak load of the base consumption of households shows that a 33% EV share is not able to provide discharge in case of overload in an additional two transformers in comparison to the base case.

The last variable that is presented in this sensitivity analysis is the charging power of the CPs within the neighbourhood. Within the previous sections, the charging power of the CP is set to 11.04. However, the charging power of chargers has increased over the last years. In order to show the robustness of the results presented in this chapter, the charging power of the CP is doubled and transformer loads for these two cases are compared for the V2G scenario.

Table 12: Transformer load summary in V2G experiment with sensitivity analysis

Transformer	Capacity (kVA)	CP 11,04			CP 22,08		
		Max Load (kW)	Overloaded	Load Factor (%)	Max Load (kW)	Overloaded	Load Factor (%)
Transformer 1	100	70	No	50	79	No	57
Transformer 2	100	103	Yes	61	113	Yes	64
Transformer 3	250	250	No	54	250	No	56
Transformer 4	400	415	Yes	67	475	Yes	72
Transformer 5	400	400	No	60	400	No	69
Transformer 6	400	400	No	58	400	No	69
Transformer 7	400	356	No	51	384	No	53
Transformer 8	400	322	No	54	344	No	58
Transformer 9	250	153	No	52	177	No	53
Transformer 10	400	342	No	52	388	No	53
Transformer 11	100	100	No	55	100	No	60

Table 12 shows the transformer loads within experiments with different CP loads. With the charging power defined in chapter 3 compared to a charging power twice as high, no significant difference in results can be found. With the introduction of charging power around 22 kilowatts, no additional congestion is resolved. The table shows that with the introduction of higher charging powers for V2G chargers for charging as well as discharging, the maximum load within the transformers is increased. Furthermore, the load factor within these transformers is also higher with the additional charging capacity. However, no transformer overloading state has been altered through the change in charging capacity. It is thus concluded that the results of the model are robust for changes in charging power.

In order to translate the presented impact of V2G charging in comparison to smart charging in the next chapter, three load scenarios are created. These three scenarios will include the 25%, median, and 75% interval values as a basis. The amount of kilowatts discharged per scenario will also be used as input. The implemented V2G strategy is, however, not capable in preventing overloading of all transformers. Because the implemented V2G charging strategy is not able to solve issues regarding overload within certain transformers, V2G will not be considered as a solution for the overloading issues regarding these transformers.

Chapter 5: Cost effectiveness

As described earlier, the flexibility provided through V2G charging has a value for the DSO. This value is created through the avoidance, delaying or the deferral of costs for the DSO in regards to distribution assets (Eyer, 2009). In order to assess this value, the net present value (NPV) method is used. In order to assess all costs occurring in both scenarios, the framework provided by Overlegtafel Energievoorziening (2018) is used. This framework is specifically developed in order to assess the value of flexibility sources in comparison to grid reinforcements. First, the costs of the grid reinforcements are estimated. Afterwards, the costs of flexibility are calculated based on the results of the previous chapter. Figure 31 is a graphical representation of the structure of this chapter.

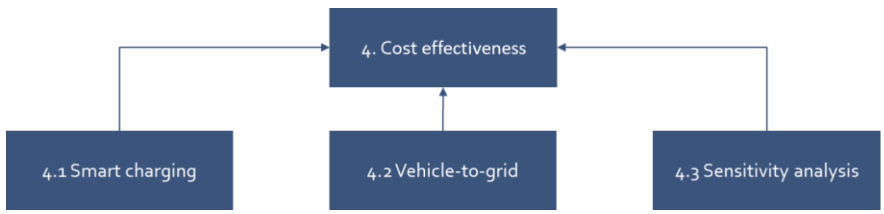

Figure 31: Overview of chapter 5 structure

To determine the value of the deferral of grid investments the NPV of the experiments with and without V2G charging should be compared. The NPV is calculated using Equation 1. The NPV is calculated using cash flows (C) during different time periods (t) which are affected by a discount rate (r). In the following two sections, the value of the cash flows are determined for both smart charging strategies. These values are determined on the basis of three electricity consumption scenarios. The base scenario consists of the median electricity consumption pattern presented the previous chapter. Following Overlegtafel Energievoorziening (2018) a low and high scenario are included. The 25% and 75% quartile represent these scenarios. Afterwards, a sensitivity analysis of the determined values is performed before the chapter is concluded.

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t}$$

Equation 1: NPV calculation

The discount rate used in the NPV analysis is fixed and regulated through a regulated working average cost of capital (WACC). This WACC is altered every four years and set to 3.1% until 2021 (Authority for Consumers and Markets, 2017). The value of WACC after 2021 is unknown, but is assumed to remain the equal to latest known WACC, 3.1%. The flexibility provided through V2G charging is expected to last 10 years. After this period, the uncertainty regarding future electricity consumption scenarios becomes too high to be relevant. Therefore, only the cash flows during this ten year period are calculated in this NPV analysis. This implies that potential future investments in transformers in the V2G scenario are not taken into account. It also implies that the residual value of the reinforced transformers should be taken into account at the end of the analysed time period.

5.1 Valuation of grid reinforcement

In this section, the total costs of grid reinforcements are described. Values used as input are presented in the table on the next page. As presented in chapter 2, the assets of the DSO can be split into two main categories: cables and transformers. Within this research, only transformers have been researched and more specifically LV/MV transformers. Therefore, this NPV analysis will also exclude all assets except for those transformers. The total costs for grid reinforcements are calculated through a combination of capital expenditures and operational expenditures. However, operational expenditures are not unique to a grid reinforcement alternative. Operational expenditures are assumed to be equal in case of a reinforced transformer when compared to the flexibility alternative. Therefore, only capital expenditures are taken into account in the cash flow calculation of the grid reinforcement alternative.

The NPV of reinforcements are calculated through the capital expenditure. However, if the length of time of flexibility does not equal the lifetime of a transformer, the transformer still has a value. In order to take this into account, the costs of the reinforcements during the calculated time period should be deducted by the normalized residual value. The residual value is calculated on the basis of the lifetime and the method of depreciation. Following rules set by the Authority for Consumers and Markets (2017), the depreciation of assets is linear over the lifetime of the asset. The lifetime of the asset is assumed to be 40 years (Authority for Consumers and Markets, 2017). The costs for the reinforcement of one transformer are estimated to be €50.000 (Klein Entink, 2017). The residual value of a transformer after ten years is thus €37.500.

5.2 Valuation of flexibility

The valuation of the flexibility alternative is characterized as an alternative with less upfront costs, but with higher yearly costs. The upfront costs within this alternative consist of the number of V2G chargers placed times the price difference between a smart charger and a V2G charger because alternative 0 consists of smart chargers. The additional costs of V2G chargers is estimated to be €500 (Van Beek, Moorman, & Andriosopoulos, 2018). Operational expenditures of V2G aggregation are assumed to be similar to the aggregation costs of smart charging. Other costs occurring during the time period are costs per kWh supplied trough V2G charging with remuneration for potential battery degradation per kWh. This cost is assumed to be 4 eurocents per kWh (Moorman, 2017). Next to this, a flat electricity tariff is assumed. Therefore the electricity remains constant over the day and the additional charge of kWh after V2G is not recognized as additional costs. The costs of this additional charge are diminished trough the returns on the delivery of electricity while discharging.

The amount of kWh needed to be discharged during a year is estimated on the basis of the results presented in the previous chapter. The results over this week will be used as benchmark winter week. Following the analysis in the previous chapter, no overload is expected during the summer. During the fall and spring, half of the amount of overload occurring during the winter is expected. During the winter a similar amount of flexibility needed is expected each week, the winter is assumed to have a length of 12 weeks. Thus, the amount of kWh expected to be provided through V2G charging is assumed to be 1935, 8743, and 14022 for the low, median, and high scenario. It should be noted that these values only account for transformers for which V2G was able to fully prevent overload. The transformers for which V2G is not able to resolve overloading issues, reinforcement is preferred.

The before mentioned values are summarized in the following table (Table 13):

Table 13: Overview of variables for NPV analysis

Variable	Amount
WACC	3,1 %
Duration	10 years
Transformer	€50.000
Lifetime	40 years
Depreciation	linear
▲ V2G charger capital expenditure	€500
battery degradation compensation	€ 0,04 per kWh

The total amount of kWh discharged over the year is calculated on the amount of discharge needed during the simulated weeks. These values are ordered per transformer as different scenarios have different transformers for which V2G charging is deployed. The following table shows the values per transformer.

Table 14: kWh discharge per year per transformer

Transformer	kW discharged during simulation		
	Low	Median	High
Transformer 1			
Transformer 2	72,17		
Transformer 3	48,78	334,24	
Transformer 4			
Transformer 5	158,48	951,70	1767,58
Transformer 6	43,06	169,20	529,70
Transformer 7			
Transformer 8			
Transformer 9			
Transformer 10			
Transformer11		2,01	39,67

5.3 Valuation comparison

The values presented in 5.1 and 5.2 are used as input of the NPV calculation and presented in Figure 32.

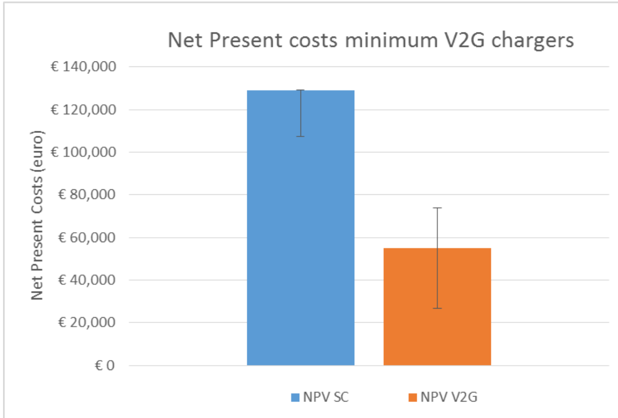

Figure 32: NPV analysis of both experiments

Following the values presented, Figure 32 presents the NPV of the costs of both the smart charging and the vehicle-to-grid experiment. Both median scenarios are presented as the NPV costs and the low and high scenario are included through the addition of error bars. From the figure, it can be concluded that the net present value of the costs of the smart charging/grid reinforcement alternative is equal to €129.000. The value of the low scenario is €108.000. The value of the high scenario is equal to the median scenario because the number of reinforced transformers are equal and thus the costs of these scenarios are equal. Within this presented research of Lent, the V2G experiment is shown to be more cost effective than traditional reinforcement measures. The costs for flexibility through V2G are estimated to be €55.000 euros, which is a reduction of 57%. However, the spread in costs of the V2G experiment among the different load scenarios is higher than for the grid reinforcement alternative. The low scenario with V2G is estimated to have costs with a NPV of €27.000 and the high scenario of €74.000. As these results show a positive value for V2G congestion management for the DSO, other objectives of the DSO apart from monetary value are not taken into account. Security of supply, sustainability of the system, presence of market forces, the limitation on electricity usage, and environmental and spatial effects are factors that should be considered when comparing both alternatives (Overlegtafel Energievoorziening, 2018). The security of supply and the limitations of electricity usage within the neighbourhood might become an issue within the proposed V2G scenario. The availability of EVs during periods of overload is uncertain and might become a burden for electricity users in the area in periods with low EV discharging potential and high demand. The presence of market forces could also be debated in the presented V2G scenario. The total amount of kWh needed to be provided is assumed to be solved with the least number of EVs possible. Within this scenario, the supply side of the market is thus artificially bounded.

A sensitivity analysis is performed in order to compare the costs of the alternatives under different values of the variables presented in Table 13. This sensitivity analysis is performed with values ten percent greater and smaller than the initial values stated in this table. This sensitivity analysis shows that differentiation in the values of single variables does not cause significant change in the relative cost effectiveness of the alternatives presented. However, differences in values higher than ten percent may cause difference in the revealed cost effectiveness of V2G charging. Other decision variables for the DSO might cause the values of the variables to alter. One of the considerations for DSOs is security of supply. The availability of EVs able to provide V2G services is an important decision variable in this consideration. The presented NPV of the costs of the flexibility alternative is based on a minimum number of V2G chargers needed to provide for the maximum amount of discharge needed to defer transformer overload. However, more V2G chargers are needed to sustain security of supply for the amount of discharge needed. As the availability of V2G chargers can increase available V2G capacity within the neighbourhood this variable is altered in Figure 33. The number of V2G chargers per EV is changed in this figure. This variable is altered from the minimum amount of chargers needed up to the level for which every EV has an installed V2G charger available.

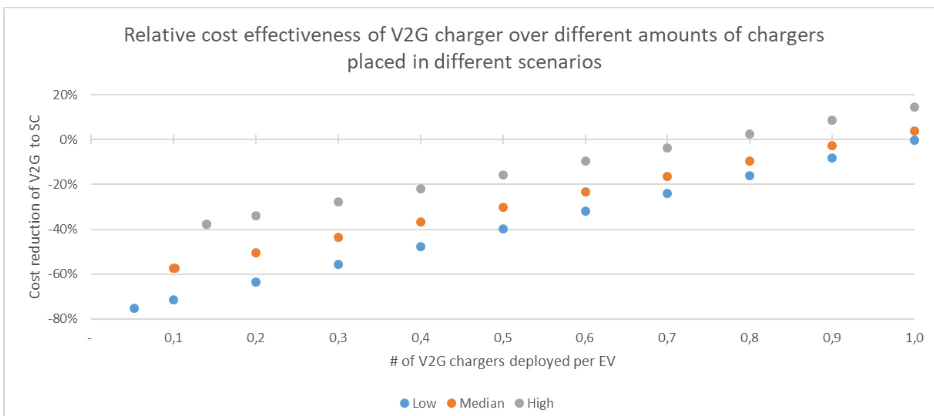

Figure 33: NPV of costs of both alternatives including various deployment of V2G chargers

Figure 33 shows that the additional value of V2G charging is dependent on the number of chargers placed within the neighbourhood. With a minimum amount of chargers, V2G flexibility is more cost effective than reinforcement measures within a smart charging setting. With all EV smart chargers replaced with a V2G charger, V2G charging becomes less cost effective than the smart charging alternative. Therefore, it is important for the DSO to balance the objective of security of supply and affordability.

It can thus be concluded that V2G congestion management is able to lower the costs of grid support by the DSO with a considerable amount. However, the security of supply through the number of EVs able to provide V2G congestion management services is an important determinant in the costs of this alternative. With a high number of EVs able to provide congestion management support, V2G congestion management services is not a viable economic solution for the DSO. However, if V2G charging aggregation and services could be combined within stacked services, the DSO might share costs of V2G charging with other stakeholders and through these stacked services, the economic value of V2G for DSO congestion management services could be improved.

Conclusion

The following research question is answered in this thesis:

"What is the economic value of vehicle-to-grid congestion management charging for the low voltage electricity grid?"

To answer this question, an agent-based modelling approach is used. Two charging strategies and their impacts on the low voltage electricity grid are compared in this thesis. A smart charging congestion management strategy is simulated and compared to a vehicle-to-grid charging congestion management strategy. Afterwards, the impact of these strategies is compared and translated into economic value for the distribution system operator.

The findings within this thesis support the conclusion that vehicle-to-grid congestion management allows the maximum load in MV/LV transformer to be lowered within Lent. It also supports the conclusion that vehicle-to-grid charging is able to prevent overloading of transformers caused by high electricity demand. However, the implemented vehicle-to-grid strategy is not able to deal with overload occurring at the end of the charging session. Additionally, not all overload is able to be prevented through vehicle-to-grid charging.

The results of thesis support the conclusion that vehicle-to-grid congestion management is a cost effective method for future congestion management grid support in Lent. The deployment of vehicle-to-grid chargers at transformers with the potentiality of preventing overload through vehicle-to-grid charging is estimated to be more cost effective than the deployment of a smart charging strategy and chargers in combination with grid reinforcement alternatives. Nevertheless, a deployment of vehicle-to-grid chargers to all EV owners instead of a smart distribution of chargers might cause the vehicle-to-grid alternative to be less cost-effective than the smart charging alternative. It should also be noted that other objectives should be considered during the comparison of a flexibility, vehicle-to-grid, alternative to a reinforcement alternative.

The answer to the main research question is reached by answering multiple sub questions. These questions are the structure of this thesis. The answers to these sub questions are presented below.

How does the Dutch distribution grid look like and what vehicle-to-grid strategies influence the distribution grid?

The Dutch distribution grid can be separated into two main voltage levels: medium voltage, and low voltage. The medium voltage levels are typically around 26 to 3 kilovolt. The low voltage grid levels are typically around 1500 to 230 volt. The medium voltage distribution grid consists of transformers and underground cables and connects the high voltage grid to the low voltage grid as well as medium energy consumers. The low voltage grid connects the electricity grid to small electricity users such as households and small businesses. The low voltage grid mainly consists of underground cables and is connected through transformers to the medium voltage grid.

Vehicle-to-grid charging strategies have been designed to meet a multitude of objectives. To support the low voltage grid, the medium voltage grid, the high voltage grid as well as different energy markets. The different applications are summarized in the following table (Table 15). Most vehicle-to-grid chargers are connected to the low voltage grid and will thus impact the low voltage grid in different manners. Although all vehicle-to-grid services impact the low voltage grid, vehicle-to-grid with an objective within the low voltage grid is the most effective in providing congestion management at this level. The most effective congestion management services are presented through a direct control of chargers schedules in order to optimize transformer loads.

Table 15: Vehicle-to-X applications and services

	Category	Level	Service
V2X	V2H / V2B	Home / building	Local storage & use
			Peak shaving
			Power backup
	V2G	Local grid (street / city)	Local storage, use & sharing of energy
			Congestion management (+ power quality and voltage control)
		National grid	Balancing markets: frequency balancing, congestion management
			Wholesale energy markets: day-ahead, intraday

How could the impact of vehicle-to-grid charging on the low voltage grid be modelled?

Answering this question aids to identify the impact of vehicle-to-grid charging through the identification of the means to answer following questions. Both agent-based modelling and linear programming are approaches to simulate EV charging behaviour. A form of agent-based modelling such as a multi agent system or agent-based model is preferred over linear programming due to the autonomy of the agents in the model and the heterogeneity of the agents within the system. This approach also allows for a agents to interact with each other and react to changes in the environment. Special care should be taken when designing the EV market penetration, location, driving patterns, electricity demand and supply, and the charging strategy. The following figure represents the conceptualization of these modules (Figure 34).

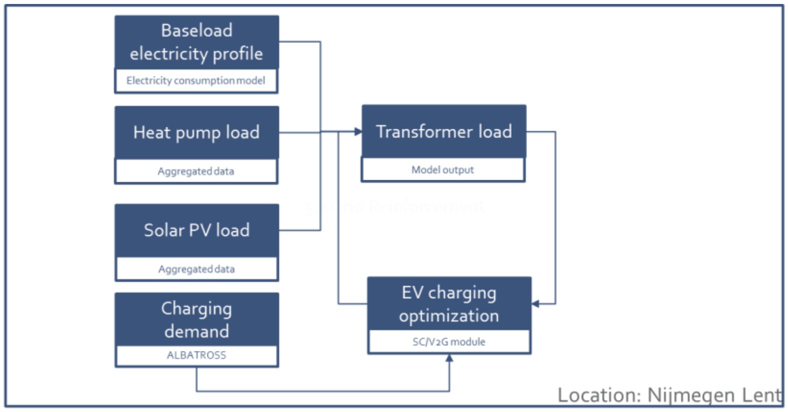

Figure 34: Conceptual model of implemented agent-based model

What is the impact of vehicle-to-grid charging on the low voltage grid?

The implementation of the above mentioned conceptual model can be seen as a tool in evaluating the impact of vehicle-to-grid charging and smart charging on the low voltage electricity grid. The impact is evaluated through the comparison of the two charging strategies and their impacts on the low voltage electricity grid. This thesis proposes charging strategies for which the impact of vehicle-to-grid charging can be calculated through the amount of overload present in the transformers at the low voltage level. The amount of kVA overload in the total neighbourhood within the smart charging experiment is … kVA. Within the vehicle-to-grid charging experiment the total overload is reduced to … kVA. At least half of the transformers with overload during the smart charging experiment is not overloaded in the vehicle-to-grid experiment. Additional consideration in the valuation of these variables should be considered. Through the addition other sources of flexibility as well as a more market based congestion mechanism the model could be added on. Next to this, the addition of other loads than household loads could increase the validity of the model.

What is the value proposition of vehicle-to-grid for providing low voltage congestion management for the DSO?

The value of vehicle-to-grid charging and the prevention of overload is present in the deferral of investments in grid reinforcements. In order to assess the value of vehicle-to-grid it is compared to the alternative of grid reinforcement together with the smart charging of electric vehicles. Through a net present value analysis, the costs of these two alternatives are compared within this thesis. With a minimum amount of vehicle-to-grid chargers placed in order to prevent overload in the transformers, vehicle-to-grid might be more cost effective than a combination of smart charging and grid reinforcements. However, if all electric vehicle owners are equipped with a vehicle-to-grid charger by the DSO, a vehicle-to-grid congestion management service would not be more cost effective than grid reinforcements and smart charging for the neighbourhood of Lent.

Discussion

In the first section of this chapter, the results presented in a previous chapter are discussed. Furthermore, the impact of the main assumptions of the model created in this thesis are discussed in this section and future research recommendations are presented. Next to this, the methodology of this research is reflected upon.

In the second section of this discussion the barriers for implementation of the presented EV charging aggregation strategy are discussed. Within this section, the social, technical and institutional barriers of implementation of V2G charging for congestion management are discussed.

Literature Comparison

First the impact of smart charging concept is compared to similar studies such as Verzijlbergh (2013). In Verzijlbergh (2013) the concept of valley filling smart charging is shown with a similar method. Verzijlbergh (2013) concludes that smart charging is able to avoid the creation of an additional peak in electricity demand.

Second, the ability of peak electricity reduction is modelled in Mahmud et al. (2016) and Wang et al. (2013). Both present a peak shaving V2G algorithm in order to reduce peak demand in electricity. The reduction in peak electricity consumption were concluded to be between 10% and 37% respectively in Mahmud et al. (2016). When comparing these results to the presented in chapter 4, it becomes apparent that the ability of V2G to reduce the peak in electricity demand within this research is lower. This difference between peak reduction is most likely caused by the introduction of a stationary battery in Mahmud et al. (2016). This is not the case for presented research in chapter 4.

Third, the insight into the cost effectiveness of EV batteries are V2G is also backed up in the current scientific literature. In Lassila et al. (2012) the feasibility of peak shaving in a distribution system is presented together with the potential savings of this measure. Next to this, Chakraborty et al. (2017) concluded that V2G charging capacity could decrease costs for the grid operator. This finding is also presented in Ecofys (2016). Within this report the costs of flexibility provided by EVs is compared to the costs of grid reinforcements.

Furthermore, if overload in grid assets is expected every day a source of flexibility as provided by EVs might not be desirable due to lower predictability and thus security of supply in comparison to other more consistent measures such as a stationary battery. This is primarily the case because one of the main objectives of the DSO is to provide reliable distribution of electricity. The ability of EVs to not be present at the charging station because the owner is not at home might cause an issue in light of this objective. Further research should aim to quantify the impact of EV availability with vehicle-to-grid charging on the security of supply.

This research provides insights in the impact of V2G charging on current electricity grid of Lent. Results obtained from this research might thus not be taken as representative for the value of V2G for congestion management within the whole of the Netherlands. The most important specifications of the presented case are: residential area, current overload present, high average car ownership. For neighbourhoods with similar characteristics as Lent, results might be more in line with the presented results. The proposed model in this research is created in a flexible manner and allows other neighbourhoods to be imported next to the Lent case. To create more generalizable results, similar neighbourhoods to Lent should be imported into the model and analysed. Through this addition, the value of vehicle-to-grid congestion management for this group of similar neighbourhoods becomes more clear. Next to this, neighbourhoods with different characteristics should be evaluated. These neighbourhoods should be evaluated to get more generalizable results of the value of low voltage congestion management in the Netherlands. Areas with different types of dwelling would allow for different charging and electricity demand and have different results than the results presented in this thesis. Furthermore, the impact of V2G charging during the summer should be evaluated to create a better understanding of the value of V2G year-round. The impact of V2G over the total year could also be estimated better through a change in length of the simulation. An extension of the simulated period up to one year or even the length of the duration for the flexibility solution would increase the accuracy of the impact of V2G charging. The presented model could also be added on through the addition of different smart and V2G charging strategies. As presented in chapter 2, multiple objectives for V2G exist. The impact could be calculated on the basis of the presented model. A multi objective V2G charging could also be implemented in order to assess the value of stacked services of V2G charging.

Assumptions

The models used within this research are based on a number of assumptions influencing the results provided in this research. A list of these main assumptions is presented below:

- DSO is always incentivizing EVs to discharge in time of overload;
- Willingness to V2G is 100% and fixed;
- No other types of V2G are deployed;
- No congestion will occur during summer;
- The EV owner would like to have a 100% SOC at the end of charge;
- EV owners only charge at home and not outside of the neighbourhood;
- EV charging only occurs at home and home charging is always available;
- Only household loads are present in the transformer;
- Electricity demand is forecasted perfectly;

The first presented assumption might have a big impact on the results of the research. It is assumed that the DSO is always able and willing to incentivize EV owners to discharge during periods of overloading. This might not be the case. Within this research, a hard limit on the capacity of the transformer is set on 100%. From this point onwards the DSO values all overloading the same. This is a simplification. Small amounts of overloading are not a problem due to the nature of the transformers. However, high amounts of overloading during a time period will be of concern for the DSO. Therefore it is likely that the DSO will not value all overload equally. Next to this, an EV owner might not want to participate in V2G congestion management at a certain period in time with low value because the owner might earn more revenue by providing other services within the stacked services that V2G could provide. An extension of the current model is recommended to include a pricing scheme for the flexibility provided. An example of this pricing scheme is presented in Takagi et al. (2011). However, an auction based charging scheme is not practical because auction cannot deal with the instantaneous decision made by EV agents .

Within the presented research, it is assumed that no transformer overloading will occur during the summer period. However, V2G charging has also be linked to the integration of renewable energy sources and specifically high volumes of solar PV (Drude, Carlos, Junior, & Rüther, 2014). The peak production of electricity through solar PV would be expected to be during the day and the ability of EVs to integrate these renewables would be different than when providing V2G services in times of overloading issues due to excessive demand. Therefore a recommendation for further research is to include summer electricity demand and generation into the model in order to assess the value of V2G charging in this period of the year.

The last assumption that will be mentioned is the assumption that EV owners only charge at home and home chargers are available at any moment. In the real world, both privately owned and public chargers are expected in Lent. Public chargers have a different dynamic compared to home chargers. At home chargers, the EV owner is expected to plug in the EV when arriving home. With public charging, however, the time connected to a charging point during the week will be lower. This is because the charging point will be shared with other EV owners. The charging dynamics will thus be different as well as the availability of EVs and discharging capacity. A recommendation for further research would be to include both home and public charging points and charging behaviours in order to gain a more realistic insight into the value of V2G for congestion management purposes.

Additionally, further research should be conducted on the number of V2G charging points desirable for the DSO. The DSO should consider the economic objective and security of supply issues regarding the availability of V2G charging availability in order to assess the economic value of V2G congestion management further.

Research methodology

Research regarding the impact of EV charging and the impact of EVs on the electricity grid have mainly been performed in a LP environment or within a MAS framework. This research, however, uses an ABM approach. The advantages are: heterogeneity, indirect interdependence. This heterogeneity is important to model in order to assess the availability of EVs in order to aid grid operations and in order to assess the fluctuating individual electricity demand. Next to this, the issues that are solved through V2G charging are not solvable by the actions of one agent. The behaviour of other agents also influence the behaviour of the agent through the change in electricity demand on the transformer level.

However, it should also be noted that the introduction of agent based modelling does not only have advantages. Through the nature of the V2G charging strategy hard constraints on the charging of EVs are set. Because of these hard constraints and an optimization goal, a lower peak electricity consumption, this problem could also be viewed as an optimization problem. Optimization problems are often best solved using linear programming. A multi agent system could also be used as a possible framework in order to address the aggregation of EVs to lower electricity peak demand.

Another contribution to the research field, in regards to the methodology used, is the creation of the so-called electricity consumption model**.** Clement-Nyns et al. (2010)**,** Mets et al. (2010)**,** and López et al. (2015) all use a standard household electricity consumption profile in order to describe the electricity demand of households. This does not allow for a variety in electricity consumption between different households. Next to this, the availability of the EVs for V2G charging are varied over the day and the electricity consumption is not coupled to these activities. Within the presented electricity consumption model, the activities of the EV owner are coupled to the electricity consumption of the dwelling. This allows for a better representation of the electricity demand over the length of the day. A disadvantage of the proposed method is that the data used from this model cannot be used in order to conclude on aggregated size. The electricity consumption model is similar in shape in regards to a standardized electricity consumption profile, but is not a representation of real world household consumption. Because a Dutch standard household electricity profile does not have to be representative of the future household electricity usage in Lent this is not a problem for this small case study but will become a problem when the size is scaled. However, it should be noted that the inclusion of real life electricity consumption data is preferred over an estimation through modelling of electricity consumption. However, individual household electricity consumption is not shared because of privacy issues. It is recommended to further develop insights in household electricity data in a not intrusive manner in regards to privacy in order to more accurately predict the electricity consumption of households.

Barriers for implementation

Multiple barriers are present for the realization of V2G charging infrastructure and strategies. Some of these barriers are technical. An example is battery degradation. EV batteries will deteriorate due to the amount of charging and discharging cycles depending on the services provided. The flexible usage of bidirectional charging options will cause the battery to start ageing faster. Another challenge are the high investment costs for V2G charging hardware. Currently, V2G charging equipment is still in the development phase and upfront costs are thus still high. Next to this, the chargers are still relatively bulky compared to smaller regular chargers. This delays the possible penetration of V2G charging to the market.

Furthermore, social challenges exists in regards to the willingness to participate in V2G charging schemes. Range anxiety and minimum range are examples of two important determinants in order for an EV owner to participate in V2G (Geske & Schumann, 2018). This is a concern among car owners with regards to EVs in general, but the introduction of V2G and sharing energy from the battery of the EV will create new concerns regarding this anxiety (Sovacool & Hirsh, 2009). Next to this, in order for V2G to become effective, high penetrations of EVs will be necessary. The share of EVs has increased over the last years, but current low shares do not allow V2G to be utilized to its full potential (Geske & Schumann, 2018).

Next to technical and social barriers, institutional barriers exist for the implementation of V2G congestion management in The Netherlands.

First, the role of the DSO within a smart grid context will be changed. Through the introduction of smart grids, new business opportunities will arise and possibly new actors will be introduced into the energy system (ECN, 2014). Most likely, the DSO will have a more active role within this new market structure. In order to accommodate the DSO to take a more active role in grid operations alternative remuneration schemes and distribution tariffs should be developed in order to incentivize the DSO

(Ruester, Schwenen, Batlle, & Pérez-Arriaga, 2014). Under the current legislation, it is unclear of the DSO might purchase flexibility from a third party for congestion management purposes (PWC, 2017b).

Second, the energy provided by discharging is taxed twice (PWC, 2017b). The energy that will be provided through V2G charging will be taxed and the additional kWh charged after the discharge will also be charged. This causes a disincentive of the EV owner to participate in any V2G charging scheme. To address technical, social and institutional barriers, a V2G pilot should be initiated in order to gain experience with a V2G charging scheme specially designed for low voltage congestion management.

Recommendations

Following these results a number of recommendations are made:

- Define and develop a pilot in which vehicle-to-grid is used as congestion management service during peak demand hours.
- Initiate further research in the economic assessment and impact of stacked V2G services in order to lower the costs for congestion management discharging;
- Further research the impact of V2G charging on the low voltage grid through the addition of more case studies with similar demographics and case studies with different demographics in order to enhance the generalizability of the results;
- Further expand the proposed model through the addition of more market based congestion mechanisms and addition of different vehicle-to-grid charging objectives;
- Further research the value of vehicle-to-grid alongside additional sources of flexibility such as smart heat pumps in order to assess the full flexibility potential within a residential area;

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Appendix A: Literature Review

As EVs gain attention as a solution to combat GHG emissions, the adoption of EVs has been studied several times in scientific literature. This research has been fragmented over the years and for this reason multiple review studies have been conducted already. After these reviews have been conducted new research has been published and these will be used as input for a literature review regarding adoption of EVs and V2G technology.

Vehicle-to-grid adoption

Infrastructure development is critical for the adoption of electric vehicles and vehicle-to-grid technology could be a smart solution to integrate EVs in to the distribution grid. For this reason it is important to look into the drivers and barriers of V2G technology. Limited research has been conducted to identify barriers and drivers. Different barriers and limitations of V2G have been identified by Dehaghani and Williamson (2012). However, these barriers are bounded towards technological barriers and limitations and do not take into account socio-technical obstacles. Following Ortt, Langley, and Pals (2015) these technological limitations are indirect factors that form barriers, but cannot describe all present barriers and drivers for a technology. Next to technical barriers, socio-technical barriers for V2G technology have been identified (PWC, 2017a; Sovacool & Hirsh, 2009). The aim of Sovacool and Hirsh is to guide research and alter the research agenda on vehicle-to-grid technology. Because of this, practical applicability on how to overcome the identified barriers is rather low. Research in this area has not matured yet and there is a lack of quantity in this regard.

Distribution grid

The risks of integration of large scale adoption of EVs onto the distribution network is due to a number of factors. EVs are mainly charged during peak demand hours (Spoelstra, 2014) which will incentivize new investments in extension of the grid. A possible solution to this is to charge EVs using renewable energy sources (RES). However, the penetration of RES is insufficient to meet demands for EVs (Brouwer, Kuramochi, van den Broek, & Faaij, 2013). Next to this, the diffusion of EVs is outpacing smart grid technology implementation in the Netherlands (Eising, van Onna, & Alkemade, 2014). A possible solution to combat this problem is the implementation of smart charging strategies and vehicle-to-grid technology. Vehicle-to-grid technology has the ability to enhance technical performance of the grid in terms of efficiency, stability and reliability (Habib, Kamran, & Rashid, 2015; Yilmaz & Krein, 2013). This efficiency has been researched in different literature. However, this effect has been researched with a static amount of EVs and V2G chargers.

Vehicle-to-grid optimization

One of the streams of literature that is considered is research regarding optimization of vehicle-to-grid charging taking into account grids of different sizes. For this optimization it is important to take into account what the primary objective is for which the charging is optimized for. Next to this, this body of research is largely quantitative in nature and heavily depends on input data for driving behaviour and electricity usage. Five different studies are reviewed on these factors and the most important limits and conclusions will be shared as well. These factors are seen among the most important variables in the reviews study conducted by Green, Wang, and Alam (2011) and Richardson (2013). All reviewed papers are recent submissions (within the last 10 years). Research regarding V2G dates back longer than this period, but with the recent increase in EV penetration the subject of grid impact of EVs has only become an issue in the past years. The results are summarized in **Error! Reference source not found.** below.

Firstly, Lund and Kempton (2008) is reviewed. The approach used in this paper is a modelling approach in which two different energy systems are defined. First, the national energy system of Denmark is modelled and secondly a system is recreated with a similar size to the Denmark case, but not including CHP which is more representative for industrialized countries. Denmark is chosen due to the high implementation of wind energy which has an intermittent character. The basis of the analysis is the EnergyPLAN model which integrates the energy needs for the electricity, transport, and heat sector. The objective of this analysis is to match excess energy supply due to wind energy together with demand. Internal transmission problems that might arise are not taken into account and it is assumed that all cars are able to provide services when present. This research has a main objective to show the potential of V2G for obtaining a more efficient energy system, but this research does not fully harness the potential of V2G. The first parameter for which the efficiency is calculated through a minimization in the amount of excess energy provided. However, the bidirectional component of V2G is not taken into account in this matter because the way this minimization is performed is through a shift in charging pattern and not in discharging pattern.

Secondly, Clement-Nyns, Haesen, and Driesen (2011) is reviewed. In this paper, a different grid and thus different scope is used. Within this paper, energy losses are optimized within a local distribution grid, taking into account both voltage regulation and congestion management. Within such an analysis, the driving behaviour becomes more important than in Lund and Kempton (2008) because of the lower amount of EVs present in the system. To take this into account a 1000 different profiles are created and used for the analysis. The research of Clement-Nyns et al. (2011) uses multiple data sources from different countries, Belgium and the Netherlands, and different years, load data from 2011 and EV penetration projections from 2030. The model presented in this research also is not mentioned to be validated which lowers the impact of the results and conclusions that could be derived from this research.

Thirdly, Ma, Houghton, Cruden, and Infield (2012) is reviewed. In this research, the utilization of the energy within the batteries of EVs is maximized. This is done within the same network as the previously discussed paper (Clement-Nyns et al., 2011). However, Ma et al. (2012) focus on the impact of V2G on one specific bus in the system and do not downscale this network. Because of the focus of this research, the integration of RES are not taken into account but a purely price-based optimization is conducted. This optimization has not been verified, nor have the authors included a sensitivity analysis as part of this paper. The papers main contribution to the literature is thus that there is a possibility of a multi agent V2G model including grid constraints and mobility data. Next to this, the extensive modelling of battery behaviour could be useful in future research.

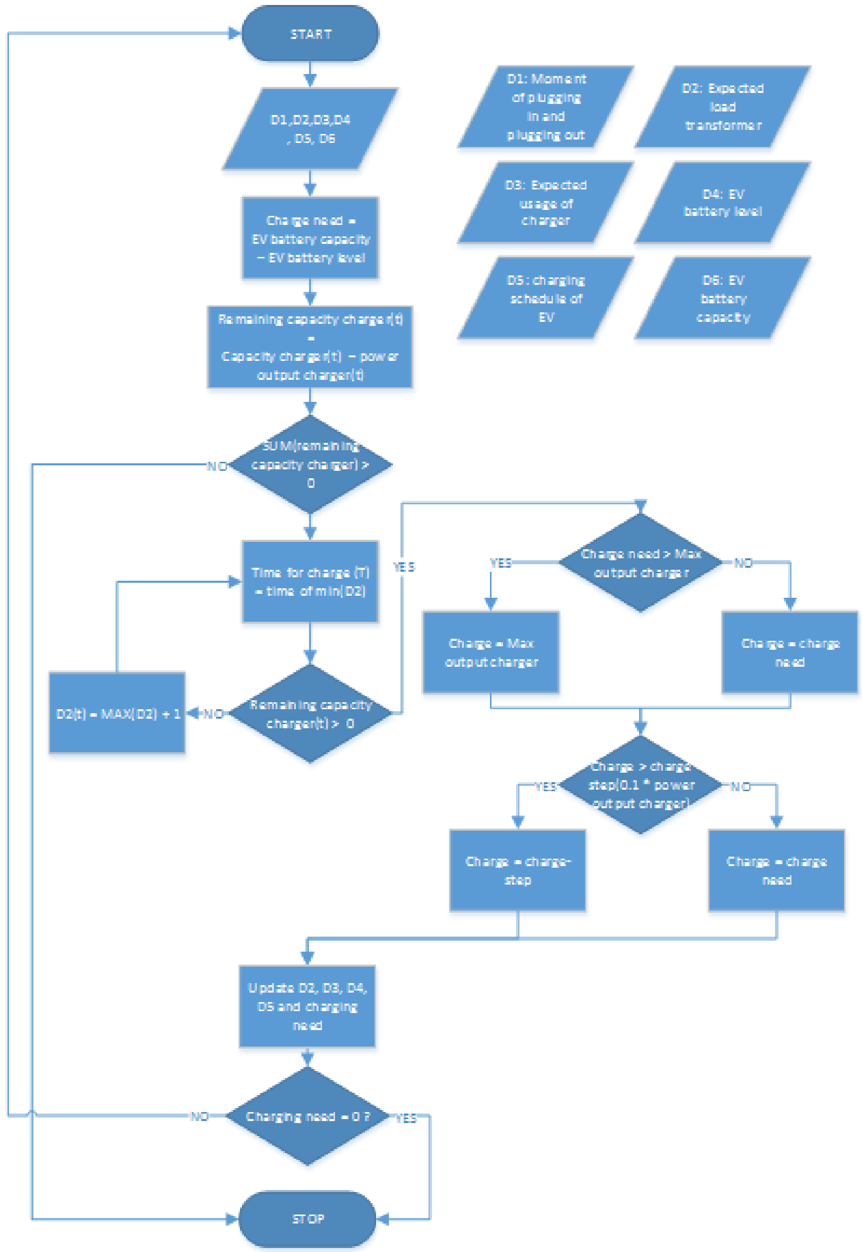
The fourth reviewed paper is Verzijlbergh, De Vries, and Lukszo (2014) . This research is part of a PhD paper by Verzijlbergh. This paper mainly focusses on the impact of EV charging on the distribution network in the Netherlands. V2G application is mostly left out of scope during this research, but this paper is still included due to the detailed congestion market mechanisms that are presented in combination with EV impact calculations. Next to this, within the full thesis research has been performed regarding V2G and therefore this research can be noted as influential research regarding modeling of congestion management in low voltage distribution networks in the Netherlands. Within this reviewed literature, EV charging models are presented to mitigate problems caused through EV charging in an extensive manner. The research, however, does not elaborate on this statement by providing bidirectional charging solutions for] congestion caused through different appliances than EV charging such as high electrification of household products and heat pumps. This research has included V2G within the scope in Verzijlbergh (2013), but in this case V2G is part of the unit commitment market for wholesale prices within the Netherlands and not within a potential DSO congestion management market.

The last research that is reviewed is Lopez, De la Torre, Martin, and Aguado (2015). Within the research performed by Lopez et al. (2015) a single day is simulated on an hourly basis integrating both distributed generation and EVs with V2G capabilities. Within this setting, different agents perform an optimization based on the costs of their load. This research has a different scope in comparison to the previous discussed researched because V2G is not the only way for agents to perform load shifting and cost minimization but other forms of flexibility, such as air conditioning, are also used within this optimization. Although this optimization is performed behind the meter and thus out of scope of the DSO, the combined optimizations are bound to the technical feasibility of the grid. Within this research the mobility behaviour has not been modelled extensively and the departure and arrival times of EVs at the nodes are not well defined. This is probably because of the scope of the research focusing on EV as well as other flexibility solutions instead of merely EV as flexibility solution.

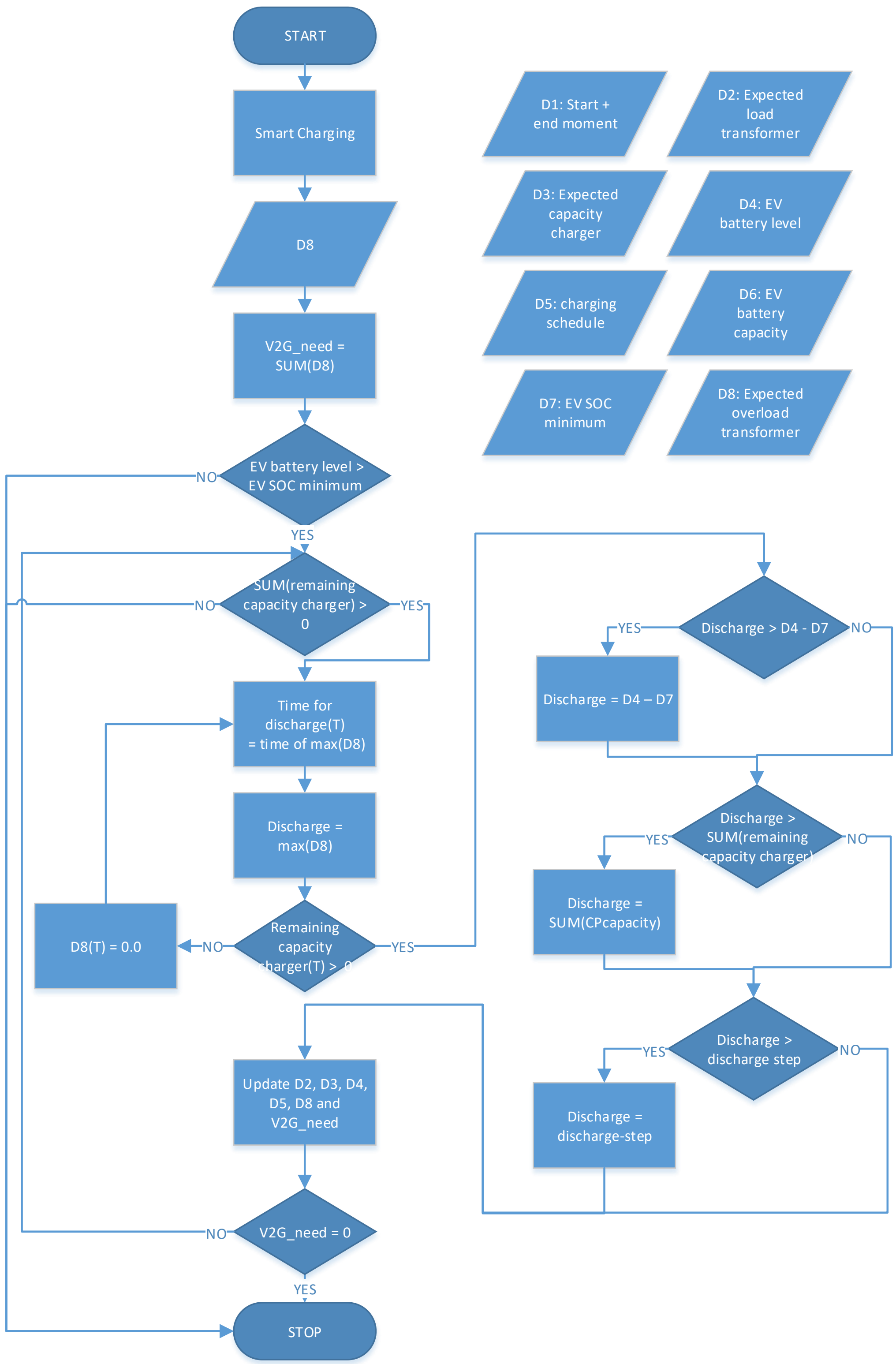
Appendix B: Charging strategy flow chart

In this appendix, the flow charts of both implemented charging strategies is presented. First, the smart charging flow chart is presented. Afterwards, the V2G flow chart is shown.

B.1 Smart charging



B.2 V2G charging

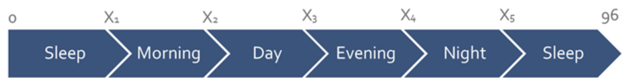


Appendix C: Electricity consumption model

In this appendix, the input variables of the model are presented. Multiple input parameters of the model are based on a distribution or random number generator. The distribution of these input parameters over the simulations are shown in this appendix.

As described in chapter 3.1, the electricity consumption model is based on a normal distribution for three out of five variables. Furthermore, the other two variables are based on the Albatross model which have their own distribution. Table 16 is a representation of the input parameters used for the electricity consumption model for the base demand for electricity per household.

Table 16: Electricity consumption model



	X1	X2	X3	X4	X5
Variable	Dependent	Independent	Independent	Dependent	Independent
Mean	X2 - 6	(based on Albatross model)	(based on Albatross model)	X3 + 6	88
Standard deviation	3	-	-	3	6

The following graphs (Figure 35 to Figure 39) show the resulting outcomes for the input parameters of the electricity consumption.

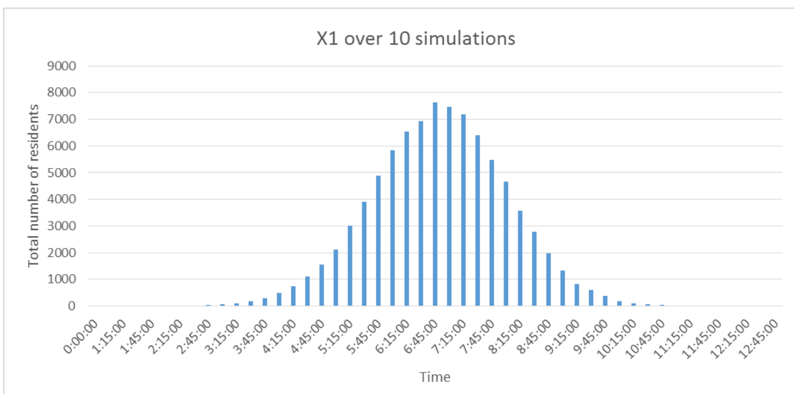


Figure 35: Distribution of variable X1 over 10 simulations

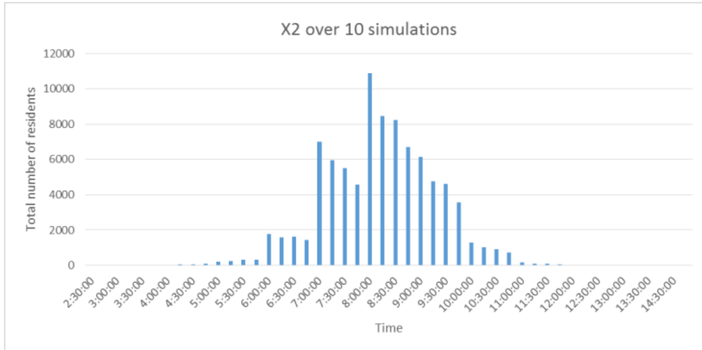


Figure 36: Distribution of variable X2 over 10 simulations

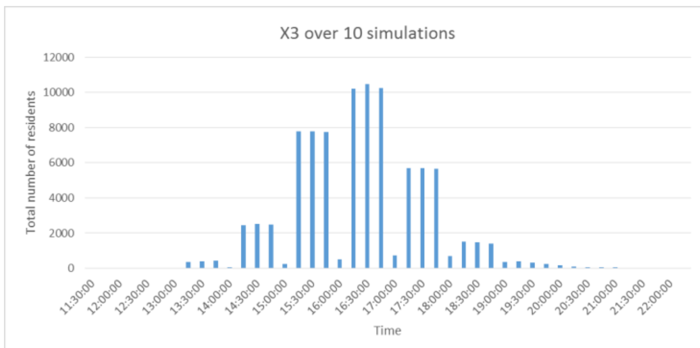


Figure 37: Distribution of variable X3 over 10 simulations

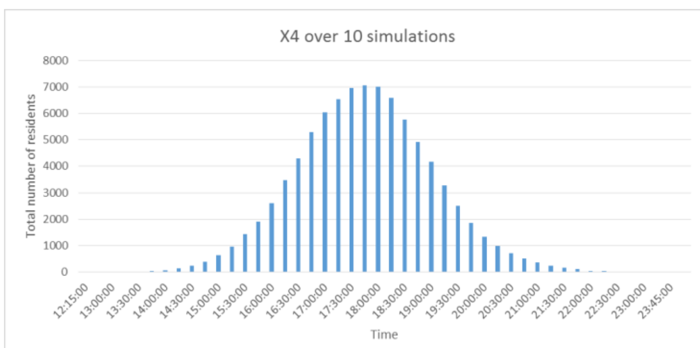


Figure 38: Distribution of variable X4 over 10 simulations

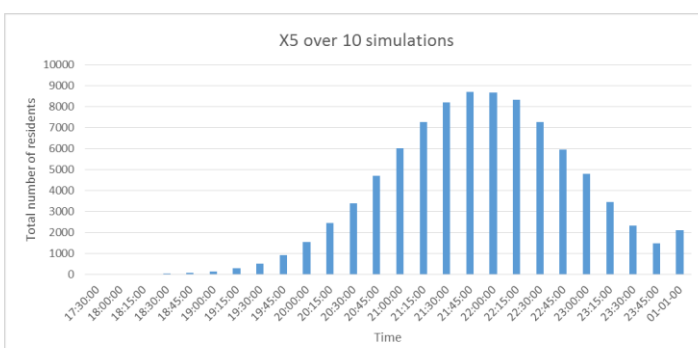


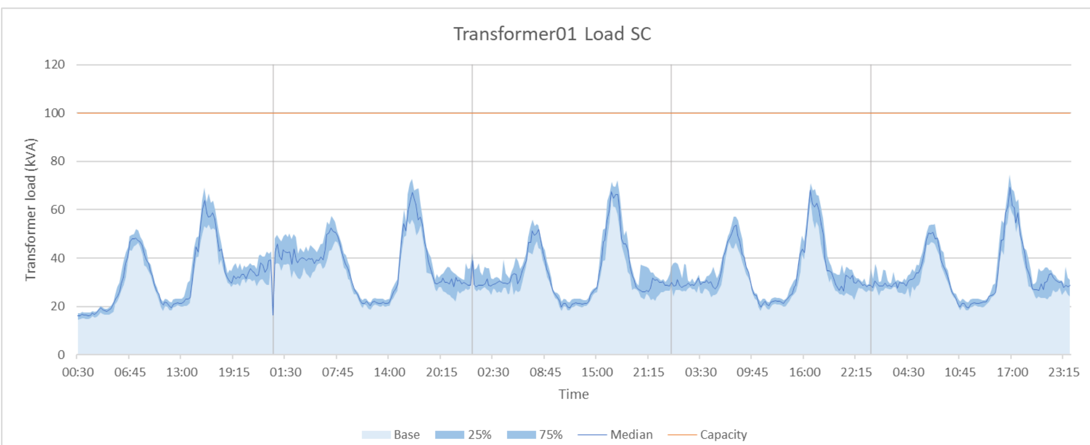
Figure 39: Distribution of variable X5 over 10 simulations

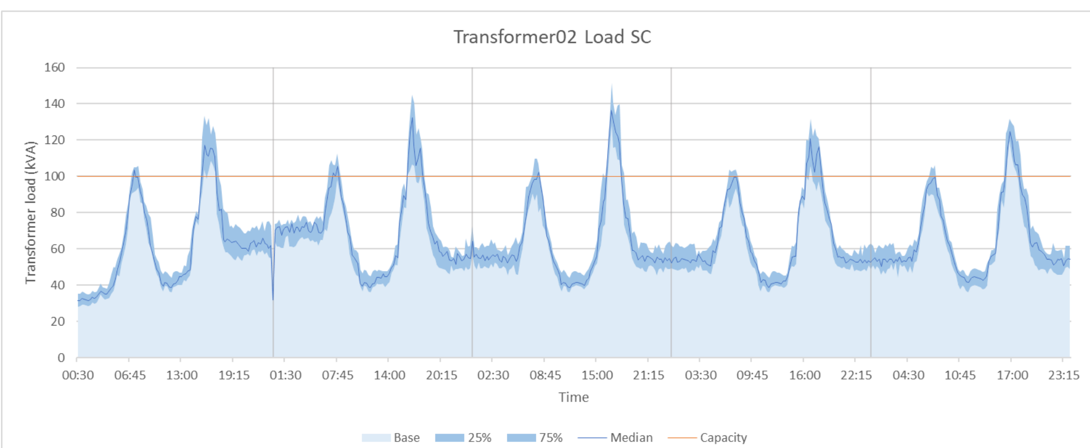
The previous graphs show the amount of residents on the y-axis and the time on the x-axis. The variables X1 and X5 show a typical normal distribution pattern. This is as expected as this is modelled. The mean value per resident is, however, dependent on the input from the albatross model. Figure 35 and Figure 38 show that this albatross based value does not affect the overall normal distribution of the values for X1 and X5. The values of X2 and X3 represent the values generated through the albatross model. The distribution of these variables cannot be described as a normal distribution but have a general shape similar to a normal distribution. Figure 39 shows the distribution of X5. This distribution is similar to a normal distribution, however, the right hand of the distribution is cut off at 0:00. It is expected that within the residential area of Lent the electricity consumption per household is low from midnight until the value of X1 during the next day.

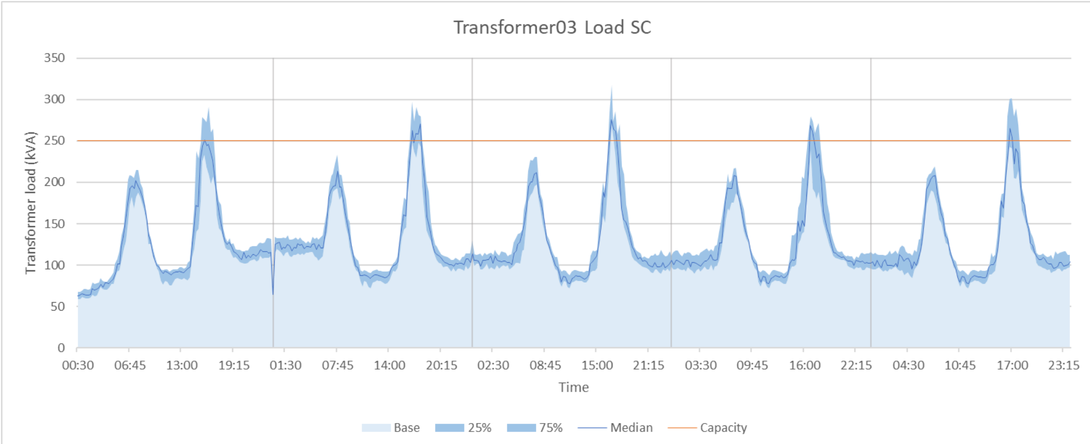
Appendix D: Transformer loads

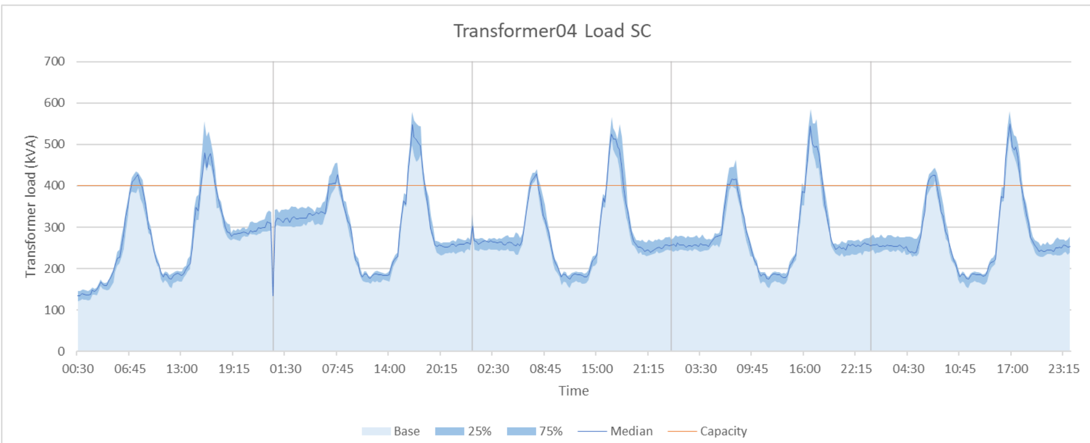
In this appendix, the transformer loads of the individual transformers is presented. These transformer loads are the input for the summarizing table on transformer loads within the neighbourhood presented in chapter 4. This appendix first covers the transformer loads of the smart charging scenario and afterwards the V2G scenario is presented. All transformer loads are presented equally. However, the values on the y-axis are dependent on the maximum capacity of the transformers and thus is different for the transformers. The graphs represent the total load of the transformer per 15 minutes. The dark blue line represents the median value over the number of replications of the experiment. The light blue area represents the variations recorded in these replications and ranges from the 25% to the 75% interval. Different sources of demand are not specified. The orange line in the graph represents the capacity of the transformer. The vertical grey lines represent the separation of the days within the simulation. The number of replications for the smart charging scenario is twelve and the number of replications of the V2G scenario is ten.

D.1 Smart charging transformer loads






Transformer03 Load SC
Transformer load (kVA)
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
09:45
16:00
22:15
04:30
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer04 Load SC
Transformer load (kVA)
700
600
500
400
300
200
100
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
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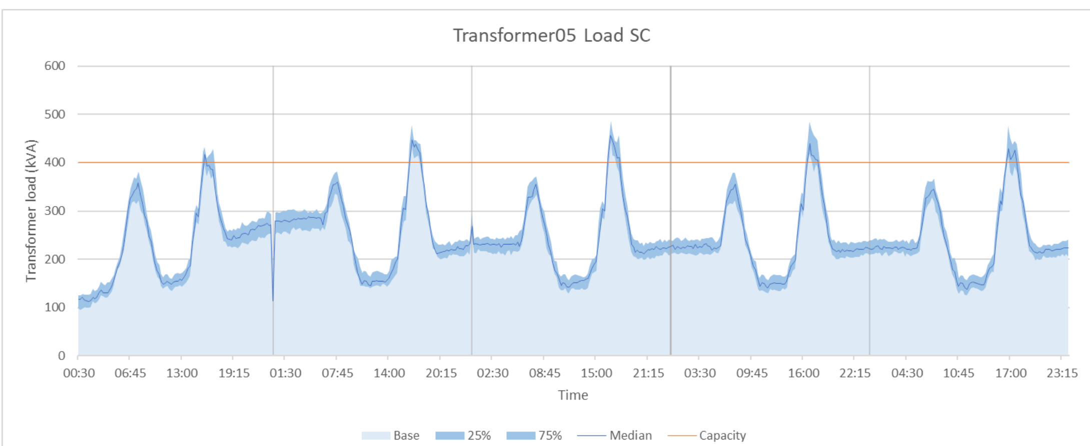
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer05 Load SC
Transformer load (kVA)
600
500
400
300
200
100
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
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16:00
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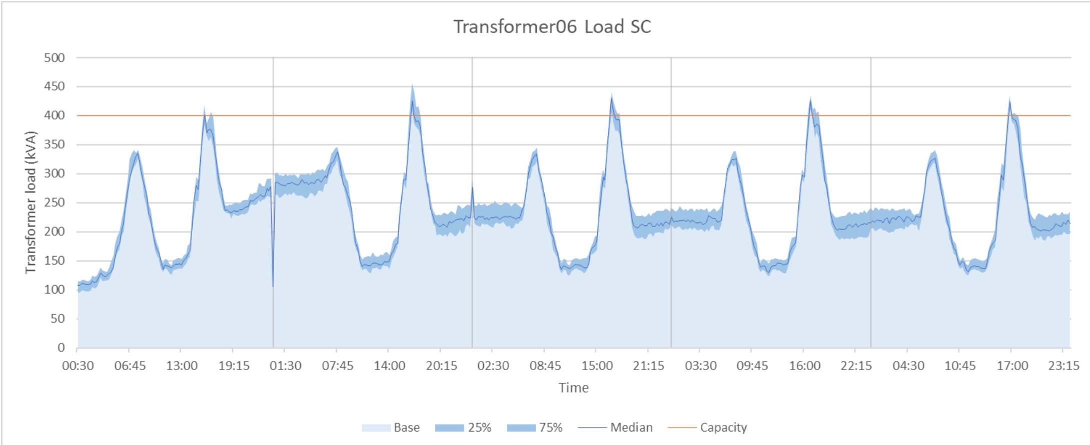
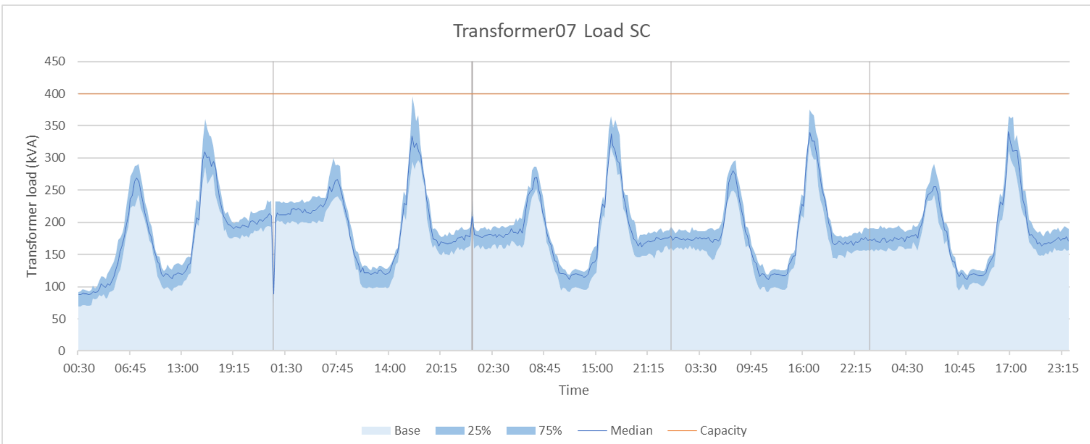
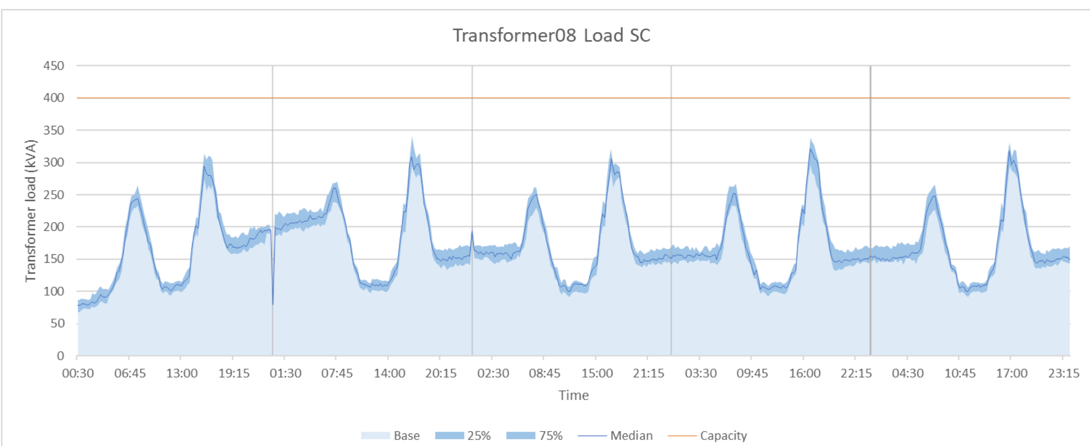
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer06 Load SC
Transformer load (kVA)
500
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
09:45
16:00
22:15
04:30
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer07 Load SC
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
09:45
16:00
22:15
04:30
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer08 Load SC
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
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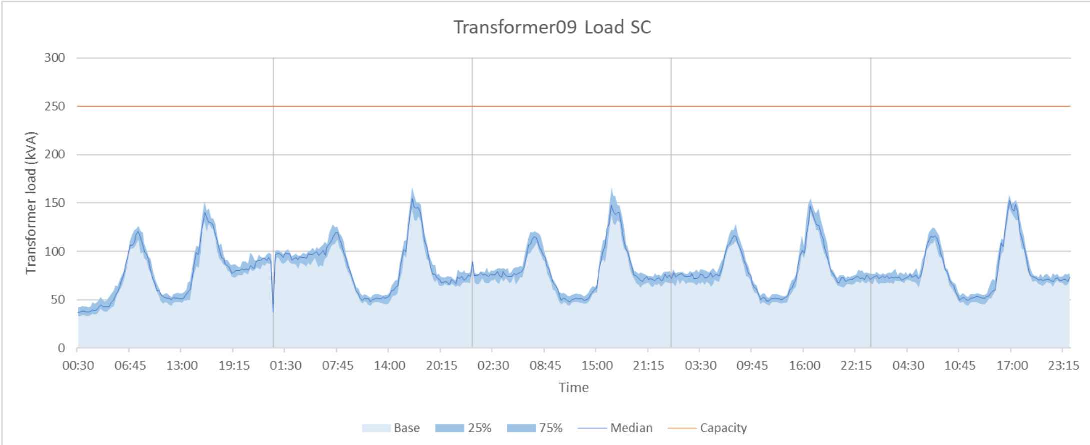
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer09 Load SC
Transformer load (kVA)
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
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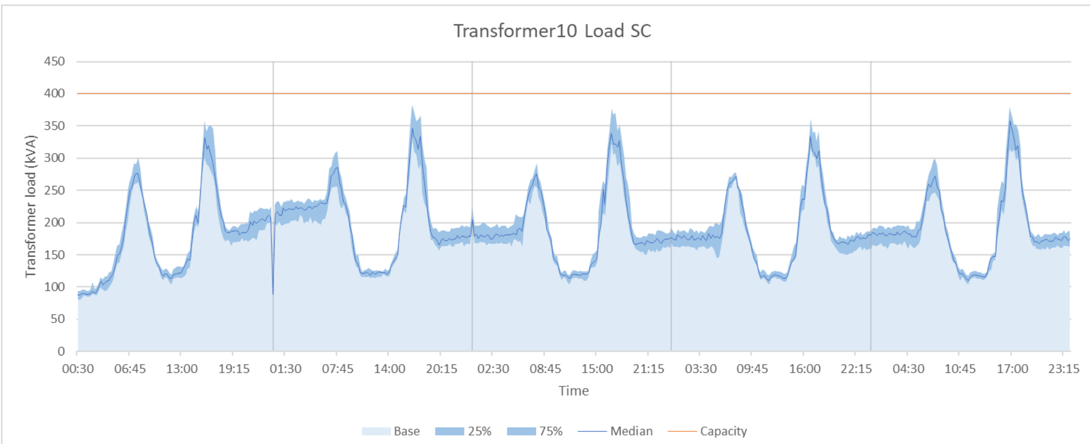
16:00
22:15
04:30
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer10 Load SC
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
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16:00
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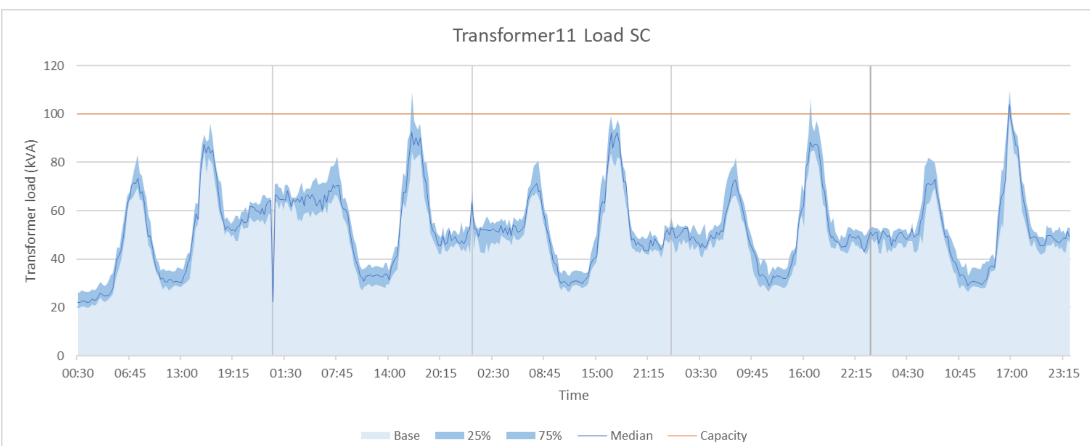
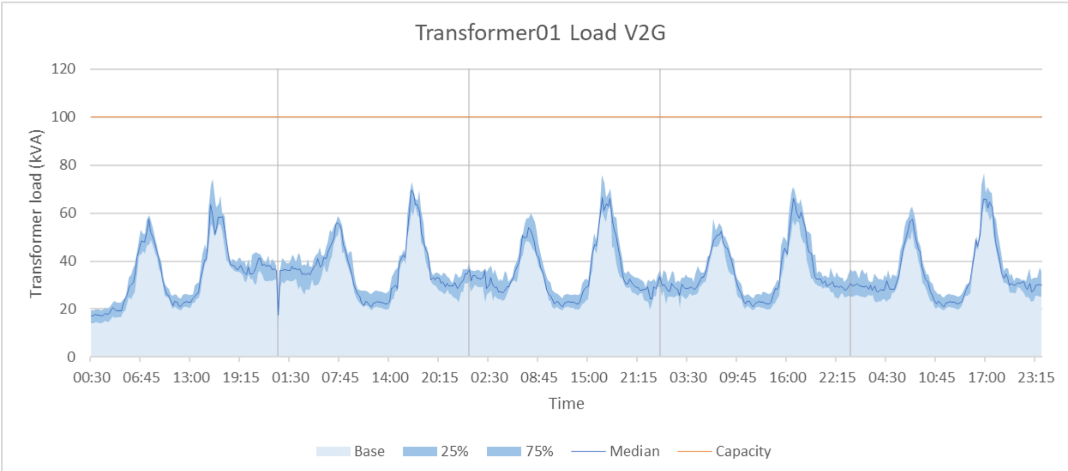
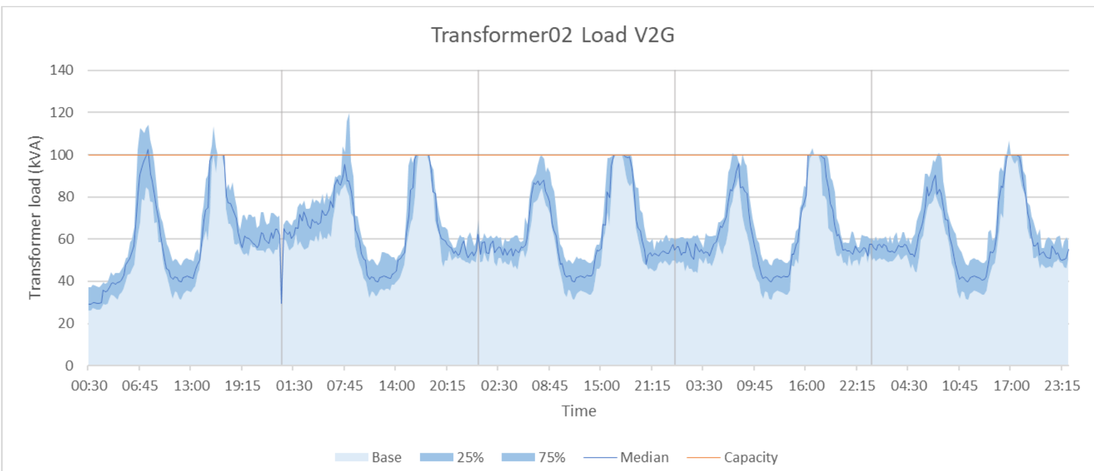
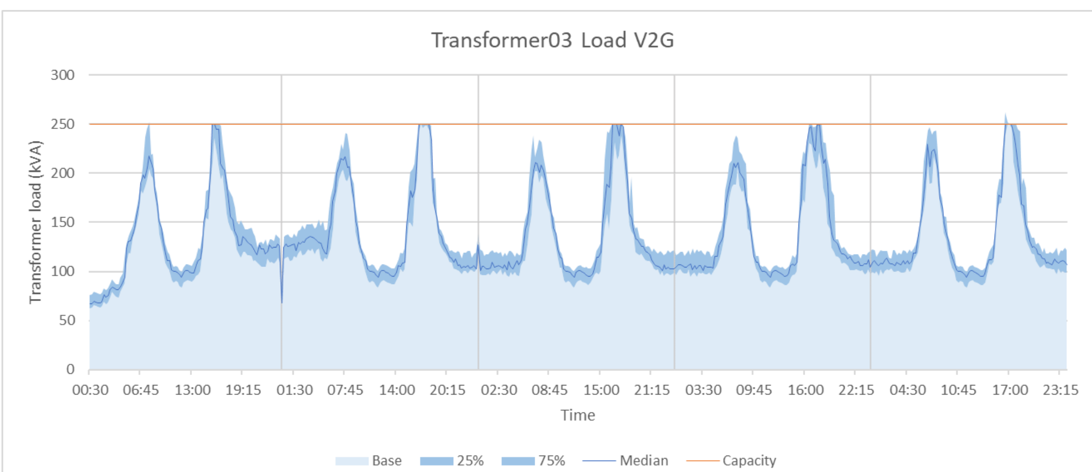
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity

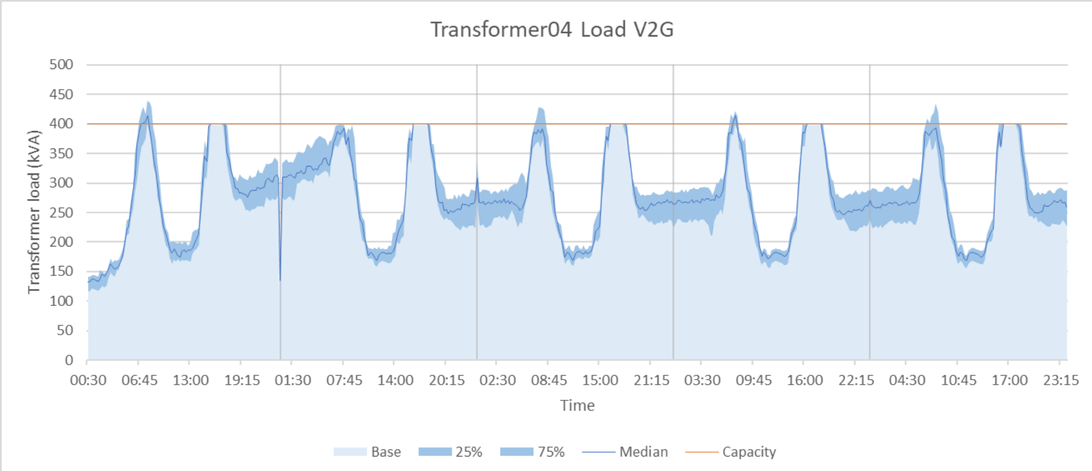

Transformer11 Load SC
Transformer load (kVA)
120
100
80
60
40
20
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
09:45
16:00
22:15
04:30
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity

D.2 Vehicle-to-grid charging transformer loads








Transformer04 Load V2G
Transformer load (kVA)
500
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
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04:30
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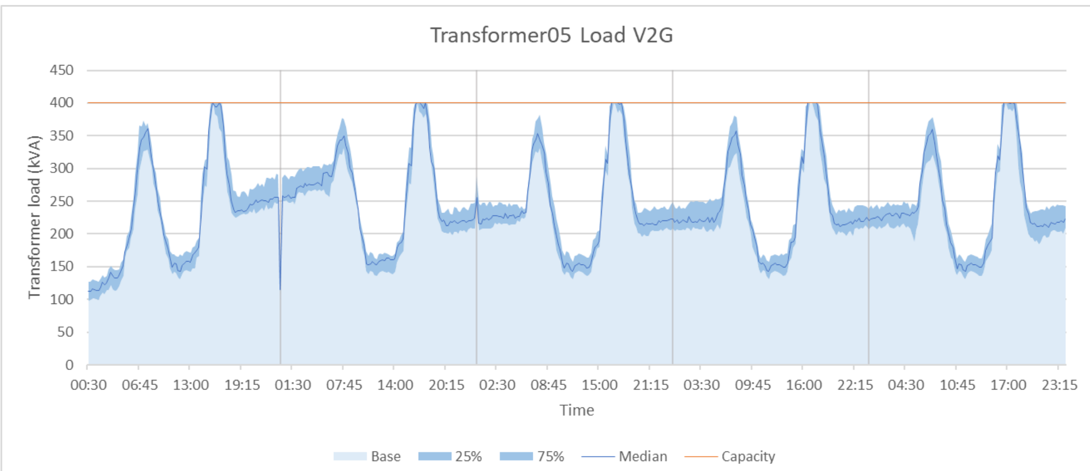
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer05 Load V2G
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
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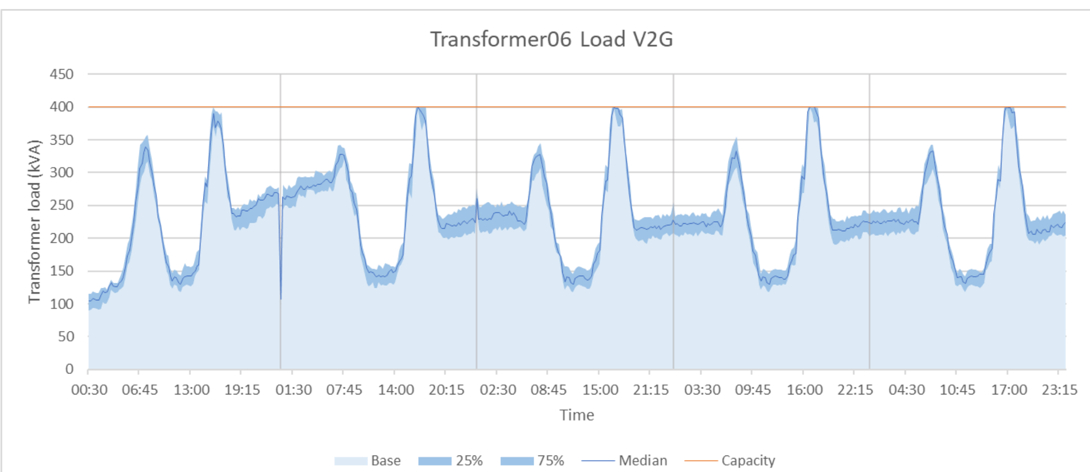
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
09:45
16:00
22:15
04:30
10:45
17:00
23:15
Time
Base
25%
75%
Median
Capacity


Transformer06 Load V2G
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
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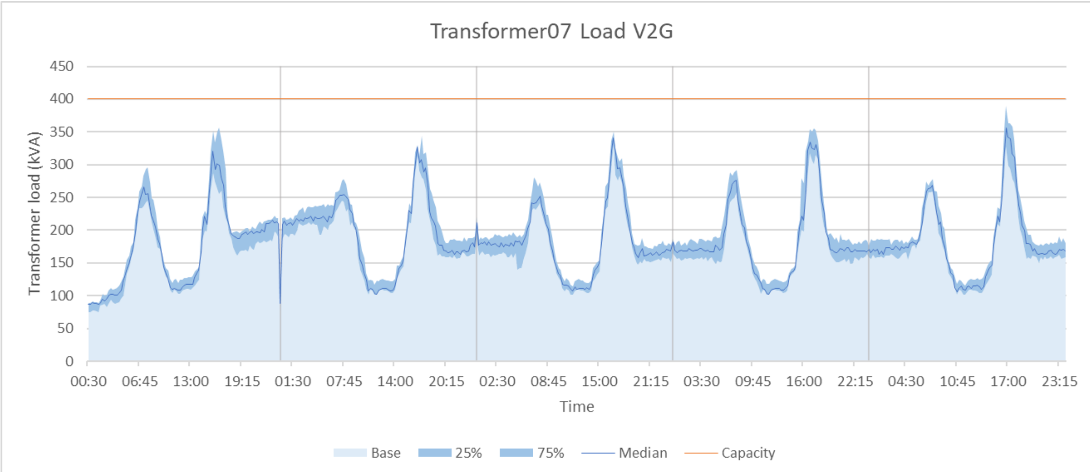
Time
Base
25%
75%
Median
Capacity


Transformer07 Load V2G
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
08:45
15:00
21:15
03:30
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10:45
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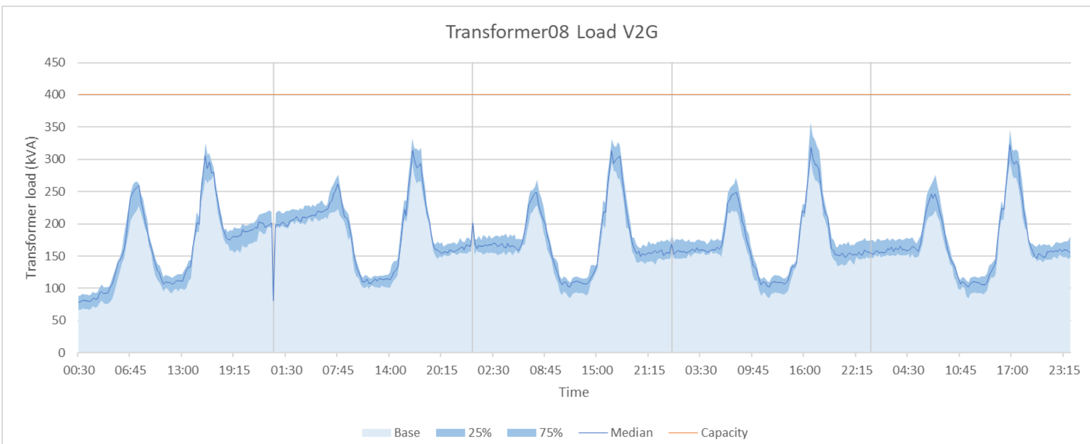
23:15
Time
Base
25%
75%
Median
Capacity


Transformer08 Load V2G
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
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Time
Base
25%
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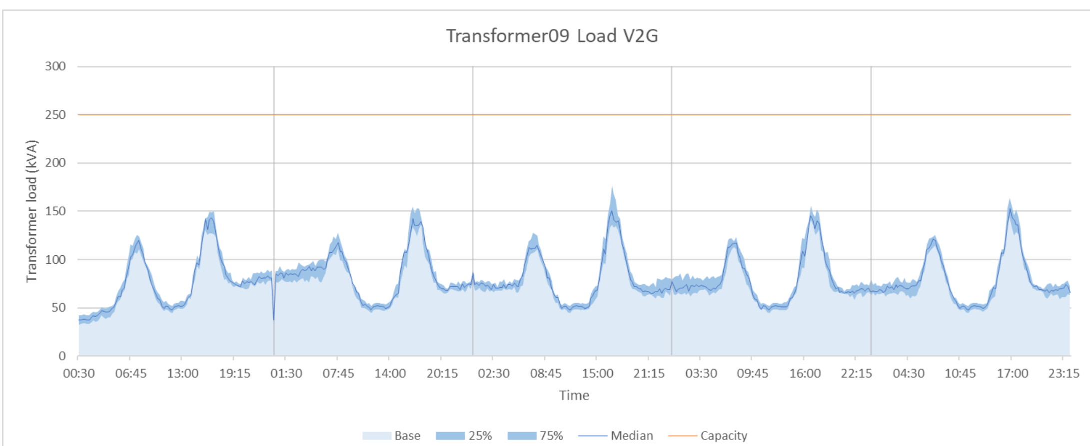
Median
Capacity


Transformer09 Load V2G
Transformer load (kVA)
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
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Time
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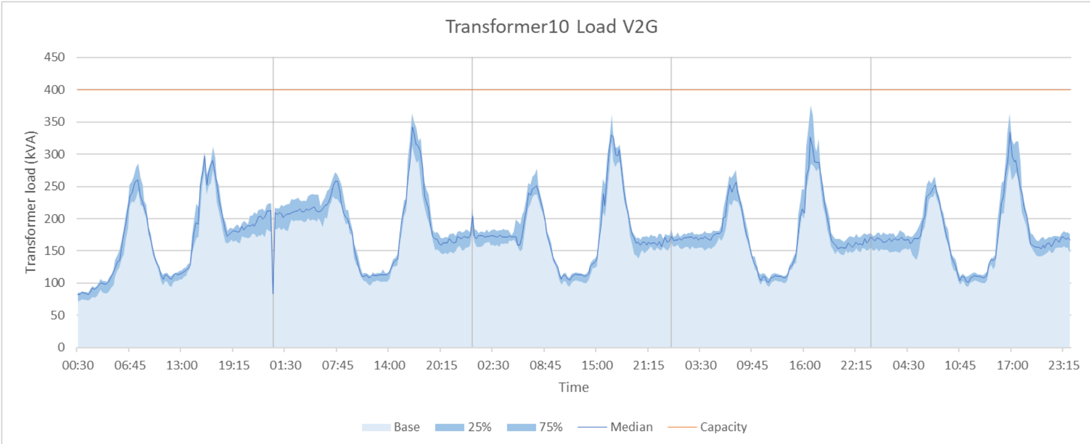
Transformer10 Load V2G
Transformer load (kVA)
450
400
350
300
250
200
150
100
50
0
00:30
06:45
13:00
19:15
01:30
07:45
14:00
20:15
02:30
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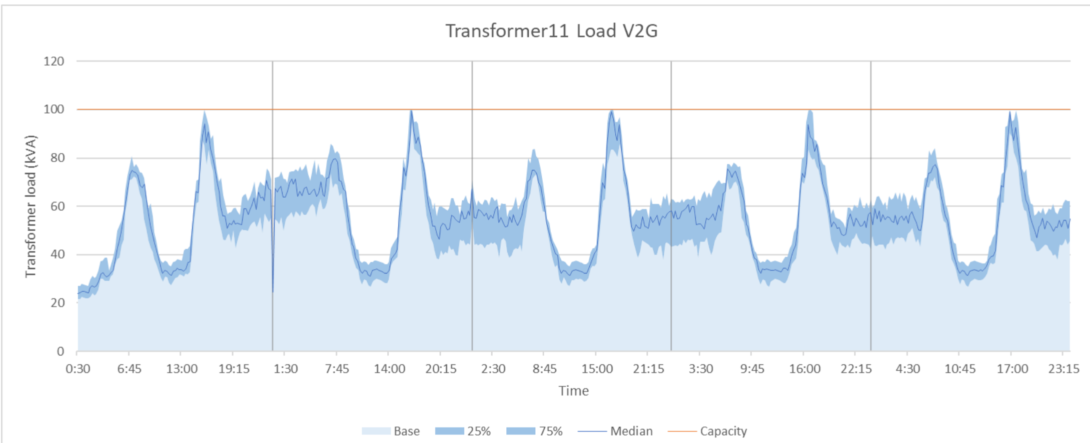
Transformer11 Load V2G
Transformer load (kVA)
120
100
80
60
40
20
0
0:30
6:45
13:00
19:15
1:30
7:45
14:00
20:15
2:30
8:45
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3:30
9:45
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23:15
Time
Base
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Median
Capacity

Appendix E: CoSEM Paper

The paper on the next pages is an adapted version of a paper submitted to the EVS32 symposium by S. Moorman, T. van 't Wel, and T. van Beek.

EVS32 Symposium
Lyon, France, May 19-22, 2019

The value of vehicle-to-grid (V2G) for distribution system congestion management

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Executive Summary

Vehicle-to-grid (V2G) technology has the ability to accelerate the transition towards a more sustainable electricity system. However, a quantification of the value of V2G services is lacking within current research. his paper aims to quantify the value created by V2G for distribution system operator (DSO) congestion management services. Using the SparkCity model, a real-life neighbourhood is modelled to investigate (dis)charging patterns of electric vehicles (EVs) combined with the introduction of solar PV and heat pumps within this neighbourhood. In addition to the previous version of the model, smart charging and V2G algorithms are developed the basis of congestion data within the grid assets of the neighbourhood. The neighbourhood modelled is Lent (Nijmegen, the Netherlands). The observed emerging charging smart charging behaviour lowers peak loads within the grid and could delay investments in grid components potentially necessary due to EV growth. Based on the results presented in this paper, utilizing V2G charging for low voltage congestion management could lower the costs for potential grid reinforcements for the DSO.

Key words: V2G (vehicle to grid), smart charging, EV (electric vehicle), simulation, case-study

1 Introduction

The Netherlands is aiming for a more sustainable energy system, which includes a larger share of electricity within the energy mix and a larger share of intermittent renewable energy sources [1]. The integration of these intermittent sources together with a larger share of electricity within the energy mix will create a greater mismatch between supply and demand and shift generation from a top-down structure to bottom-up[2]. The introduction of electric vehicles (EVs) within this system couldcause potential problems, such as congestion, within the current electricity grid [3]. EVs can mitigate this problem through smart charging mechanisms (V1G) in which the charging of the EV is regulated [3]. Additionally, EVs can provide flexibility for the integration of other measures within the energy transition using vehicle-to-grid (V2G) [4]. V2G has many different applications that could provide valueto different stakeholders[4]. In Table 1, the applications of V2G are presented. The greatest value for V2G could be reached by providing a combination of these services, so called ‘stackedservices’.However, the value of these services remain unclear. The currentbody ofresearch regarding the value of V2G services is mainlyfocusedon national grid and national markets such as the FCR market [e.g. 5].

In order to gain better insight into the value of vehicle-to-grid applications and the value of these services, all these services and their value will need to be quantified. A valuation of V2G congestion management services is currently lacking and therefore this paper will try to answer the following question:

What is the value of V2G for DSO congestion management services?

Table 1: Services of V2G

	Level	Service
V2H/V2B	Home/building	Local storage & use
	Home/building	Peak shaving
	Home/building	Power backup
V2G	Local grid	Local storage & use of energy
	Local grid	Congestion management *(+ power quality and voltage control)*
	National grid	Balancing markets
	National grid	Wholesale energy markets

2 Methodology

A model is created to estimate the impact of V2G on the electrical loads within the distribution grid. After this estimate, the impact on electrical load will be translated to a monetary value.

First, an agent-based model (ABM) is created to estimate the impact of V2G on the loads within the distribution system. This is done through expanding the Sparkcity ABM to include different charging strategies based on driving patterns and geography [6]. While modelling EV charging impact, three main uncertainties are present: driving behaviour, electricity usage and the share of EVs [3]. For this reason, an ABM approach is selected. ABMs allow a model to have a heterogeneity between agents and allow the modeller to capture emergent behavioural patterns within a diverse group of agents [7]. In this case, a more heterogenic driving behaviour could be implemented in comparison to equation-based models. The Sparkcity model, specifically, is an ABM with the objective to study the impact of EVs on the local electricity grid balance and technological developments and will thus be used as the basis of the model [6]. This model is able to estimate the EV charging impact on the electrical load with the usage of GIS-data to make a representation of a real-life neighbourhood (figure 1). This neighbourhood can be divided in three layers: electricity grid, road network and dwellings. The GIS-data is provided by the DSO and the local municipality. To explore the value of V2G congestion management, the electrical load in the low voltage grid is modelled with a V2G congestion management charging strategy and compared to the electrical load combined with a smart charging strategy based on congestion management. In this manner, this paper contributes to the main body of research regarding the impact of V2G. Through developing an ABM and through the integration of solar PV and heat pumps in the electricity demand.

Second, To translate the impact of EV charging and the impact of V2G charging, an grid operator cost benefit analysis is created. The socialized value that is created is based on the load of the transformers within the modelled area. On the other hand, the costs of equipping V2G chargers is calculated. Through the addition of value created for the DSO this paper adds to the current body of research in which the value translation of V2G congestion management remains unclear.

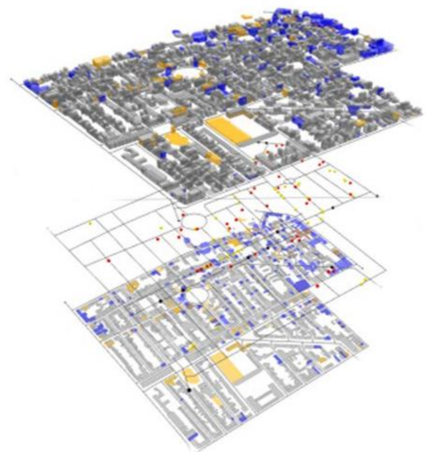

Figure1: Representation of a neighbourhood within Sparkcity [6]

3 Model description

In this section, the adaptations of the Sparkcity model created in [6] are presented. To extract the impact of V2G on the electrical load within a neighbourhood a V2G module and a V1G module for DSO congestion management are created.

3.1 Charging behaviour

Following [1], overloading issues might arise earliest at transformers within the distribution grid. Therefore, the optimization for both charging strategies are based upon the loads within the correspondent transformer. These transformer loads are based on household loads, loads of electrical appliances and EV charging loads. In order to optimize the load in the transformer, the expected load of the transformers for the hours in which the EV is available is calculated. V1G based on valley filling on the basis of expected load within the transformer. In the V2G scenario, first a smart charging optimization is performed for the EV and given this charging schedule, the potential discharge moment and amount is calculated. In order to ensure that the EV owner is not inconvenienced due to a low state of charge (SOC) of the EV, the SOC of the EV battery at the end of the charging session is the same in the V2G and V1G strategy.

3.2 Neighbourhood selection

The neighbourhood that is selected for the model is Lent (Nijmegen, the Netherlands). This neighbourhood is a residential area and is chosen because flexibility solutions are already required within this area. The local DSO and other parties already have a flexibility market for congestion and thus congestion management is recognized as potential solution in this neighbourhood. However, the current flexibility is not provided through EV charging strategies and this paper aims to quantify the potential flexibility and value created through EV charging strategies rather than the sources that are currently in place.

Expected peak loads in the system are expected to be higher than for other neighbourhoods due to the already insufficient grid infrastructure and potential overloads. This overloading allows for a V2G congestion management business case. A future energy scenario is created for 2030 for this neighbourhood. Figure 4 shows the part of Lent that is modelled. Adjusted standard Dutch load profiles are used to represent the electricity usage within the neighbourhood. Solar PV and heat pumps are added to this profile to represent a potential future electricity profile. In order to gain insights in the potential of V2G it is assumed that these loads are not controlled. For the electricity usage per year, real life data per building is used to estimate the height of the electricity demand. In Figure 5 the low voltage electricity grid of this region is described.

Using the parameter settings presented in Table 2 the following connections to the electricity grid can be identified as presented in figure 5.

Figure 4: Lent (Nijmegen, the Netherlands)

Table 2: Neighbourhood input description

Variable	Value
Households (#)	1342
Car ownership *(car/household)*	1
EV share (%)	30
Heat pump share (%)	30
Solar PV share (%)	30
Transformers (#)	11

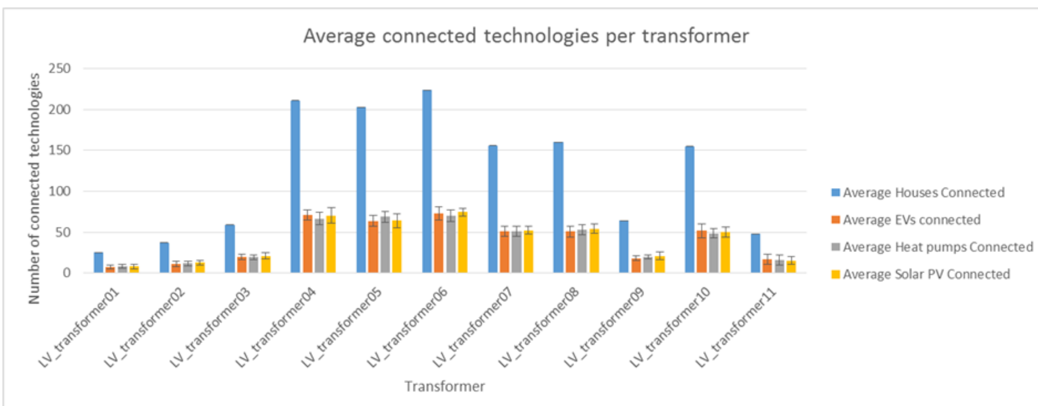

Figure 5: Lent Electricity Grid (Nijmegen, the Netherlands)

3.3 Scenarios

Two different scenarios will be run, starting with a base scenario. This scenario consists of 100% EVs following the V1G charging strategy with all of EVs willing to charge smart. Both scenarios will be under a sensitivity analysis. Within this sensitivity analysis the share of EVs in the overall population of cars as well as the share of charging power and electricity input will be different for both scenarios.

Table 3: EV shares

	Scenario 1	Scenario 2
EV share	30%	30%
Smart charging share	100%	100%
of which V2G capable	*0%*	*100%*

4 Results

The ABM will create different outputs. The following KPIs are identified as most important to identify charging patterns and estimate the impact of EV charging on the electrical load within the neighbourhood:

- Cumulative kWh charged;
- Cumulative kWh discharged; and
- SOC per EV;
- kWh discharged per 15 minutes per EV per charging point.
- Electrical load per 15 minutes per transformer;

To cope with the variability of multiple parameters, such as the distribution of electrical appliances and EVs, the presented results are the results of multiple replications. The number of replications is related to the variability of the set parameters and the following section is based on five replications with different seed values for the random number generators.

First, the results of the smart charging scenario will be presented. Afterwards, the results of the V2G scenario will be presented and compared to the results from the first scenario. In order to understand the magnitude and behaviour of the charging sessions within the neighbourhood, first, the total kW charged will be displayed for the whole neighbourhood.

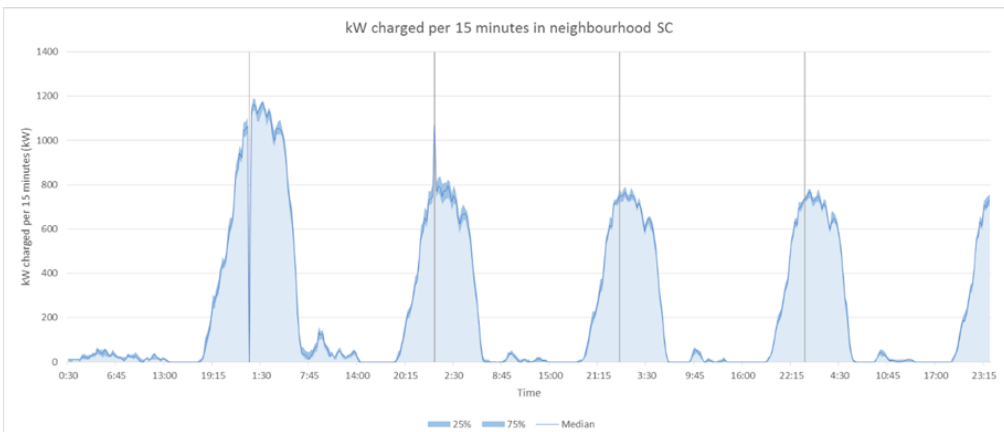

Figure 6: Total kW per 15 minutes charged in neighbourhood during winter week

Figure 6 shows the total amount of kW charged per fifteen minutes over the course of the selected simulation period. This period represents five working days in a winter week. On the x-axis the time is presented and on the y-axis the amount in kW within the fifteen-minute time frame is presented. It can be noted that the amount of kW charged varies per day and follows a day and night cycle. During the day, only a small amount of charging capacity is used while during the night the batteries of the EVs are charged. Five different peaks of electricity usage can be identified in Figure 5. Four of these five peaks are of a similar shape. The last of these peaks, during the night of the fifth day, only represents half of the shape of the previous four peaks. This is because of the ending of the simulation at midnight on the start of the sixth day. It should be noted that a peak is expected during the first hours of the simulation because EVs will be charged during the night before the start of the simulation, but due to the starting conditions of the charging strategy this electricity consumption is absent. Next to the similarity of shape between the peaks during the night, the peak consumption of electricity is around 700 kW per 15 minutes during three of the four nights in the simulation. The first night has a peak of around 1200 kW per 15 minutes. This is partly explained through the absence of charge during the first morning and is also partly explained by the starting conditions in regards to the SOC of the EVs. The effect of charging on the SOC of the EVs is presented in Figure 7.

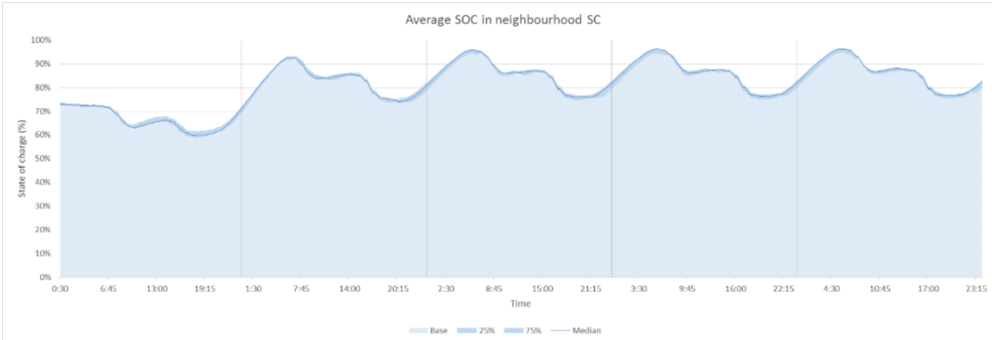

Figure 7: Average SOC of EVs within the neighbourhood

Figure 7 is a graphical representation of the average SOC of all EVs within the neighbourhood. The y-axis represents the SOC as percentage of the battery capacity and the x-axis presents the time within the simulation. The five work days can be identified separately and a similar pattern can be identified over these days. However, it can be noted that the observed behaviour on the first day is different in comparison to the next days. The lower SOC during the first day and the higher increase in SOC during the first night can be explained using Figure 5. A lack of charging during the morning on the first day and the higher total amount of kW charged during the first night cause the difference in average SOC in the neighbourhood. It can also be noted that the SOC peaks are shortly after the peaks in figure 5 which is caused by the cumulative nature of the SOC. Next to this, it can be noted that the peaks of SOC are reducing five percent in the last two nights. Overall it can be concluded that smart charging behaviour with valley filling on the basis of congestion management is highly predictable due to the inelasticity of household electricity usage pattern.

To demonstrate the impact of V2G charging with the purpose of congestion management on the low voltage transformers only transformers with potential overload are of interest. The overload of the transformer is defined as the electrical overload of the transformer. The power factor is assumed to be 1.0. A transformer is overloaded if the electricity demand is higher than the capacity of the transformer load.

For the purpose of this paper, one of the transformers within the neighbourhood is displayed. This transformer is chosen because of the present overload on the transformer. This overload is present during the evening electricity demand peak. The overload is present without the electricity demand for EVs, but additional electricity demand during this period is avoided due to the V1G charging strategy. Figure 8 is graphical representation of this transformer.

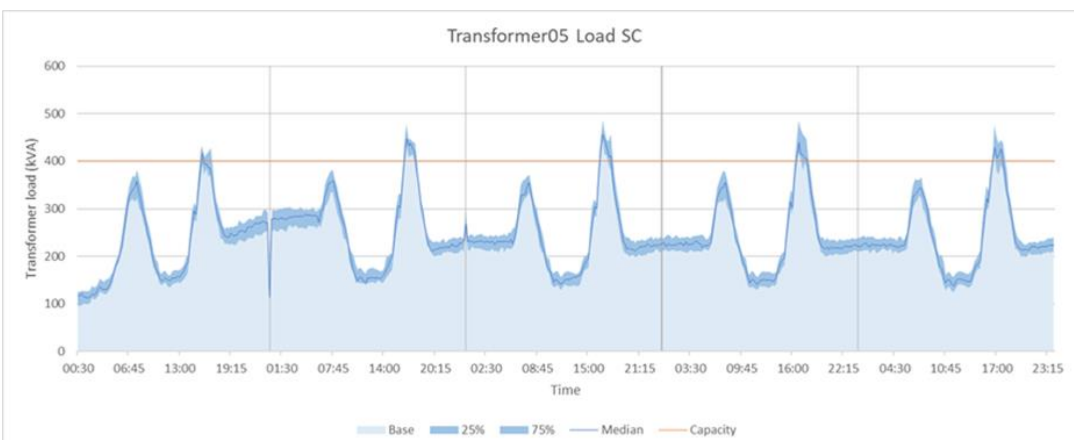

Figure 8: Electricity demand on a 400 kVA transformer with smart charging

On the x-axis, in figure 8, the time is presented. Five days can be identified. On the y-axis the transformer load is presented. The electricity demand for the houses connected to the transformer is plotted over the time. The grey area represents this base demand including non-controllable electric appliances. The yellow area is the electricity demand created by the smart charging of EVs for this transformer. The orange line represents the capacity of the transformer, which is 400 kVA and the blue line represents the total electricity demand for this transformer. The electricity demand generated by the charging of EVs can be described as valley filling. Using this method, the impact of the electricity demand is optimized to be as low as possible. This means that the EVs should not only consider household electricity demand but also electricity demand from other EVs in order to optimize the electricity demand over time below the maximum capacity. Using this smart charging technique, the expected peak demand is decreased. Without smart charging behaviour, EV charging demand would be increased during the evening peak and the total demand would increase further over the capacity of the transformer. This smart charging technique thus mitigates the problems regarding potential additional transformer overload. However, overload still occurs. In order to create additional value for the low voltage electricity grid and thus the DSO the EVs can be used to also provide electricity during peak demand hours and thus lower the electricity demand on the other side of the transformer. Figure 9 is a graphical representation of the same transformer load but with a V2G charging strategy.

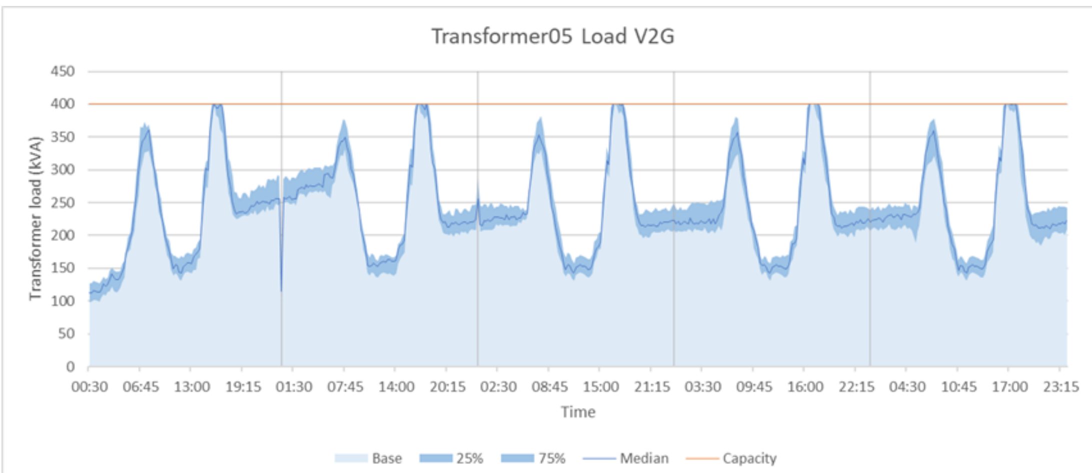

Figure9: Electricity demand on a 400 kVA transformer with V2G charging

The previous graph shows the transformer load based on both a static household demand and a variable EV charging demand with an implemented congestion management V2G charging strategy. It can be recognized that the household electricity demand is higher than the transformer capacity during the evening peak during the whole week. Through the introduction of V2G services however, this demand can be met by utilizing the battery capacity of the EVs present behind this transformer. The discharge starts when EVs are arriving home and utilize the initial SOC left in the EV. During the night, the discharge provided will be charged on top of the V1G charging strategy.

Table 4: Neighbourhood overall transformer load

Transformer	Capacity (kVA)	Max Load (kW)	Overloaded	Load Factor (%)
Transformer 1	100	69,25	No	49
Transformer 2	100	136,52	Yes	47
Transformer 3	250	275,99	Yes	46
Transformer 4	400	549,52	Yes	52
Transformer 5	400	456,80	Yes	53
Transformer 6	400	430,35	Yes	54
Transformer 7	400	341,11	No	54
Transformer 8	400	321,67	No	53
Transformer 9	250	154,08	No	52
Transformer 10	400	357,44	No	53

Transformer 11	100	104,14	Yes	50

In table 4 the transformer loads of the different transformers in the simulated neighbourhood are presented. First, the capacity is presented next to the peak electricity demand of the transformer during the simulations in the smart charging scenario. If this rating is higher than the capacity this rating, overload is expected and V2G might add value to the grid. The load factor is also presented. The load factor is derived from the load profile and allows for an insight in the utilization rate of the transformers. The load factor is an indication of the usefulness for demand control mechanisms, such as the V2G as presented in the second scenario. A low load factor shows a high peak demand and a low average utilization rate. This means that the difference between the highest peak during the simulation and the average electricity consumption is relatively high. In these cases, flexibility solutions might be preferred to grid reinforcements. The simulation shows that V2G charging is able to mitigate all potential overload in Nijmegen, Lent. For the calculation of the costs of V2G in comparison to grid reinforcements only transformers with an expected overload will be taken into consideration.

A sensitivity analysis is performed on the EV share within the neighbourhood, the electricity consumption per household and the charging power of the chargers. From this sensitivity analysis it can be concluded that the resulting charging behaviour is robust for the number of EVs within the neighbourhood. Next to this, the results are robust when considering a higher charging power. However, an increase of 10% of the values within the electricity consumption of the households alters the impact of V2G on the state of certain transformers. A higher electricity consumption within the V2G experiment causes the impact of V2G to be lower as two transformers with overload are not resolved additionally in the case of a higher electricity consumption per household.

In order to calculate the value of the shown flexibility solution, the framework provided by Overlegtafel Energievoorziening is used [8]. This framework is used by Dutch DSO's in order to consider flexibility solutions in comparison to reinforcements. A cost benefit approach specific to grid operators as specified in [8] is used. In order to calculate the net present value (NPV) formula 1 is used.

$$NPV = \sum_{i=1}^{n} \frac{C_i}{(1+r)^t} \qquad (1)$$

The NPV analysis is used to estimate the costs of both alternatives. In order to answer for the main research question, the analyses is performed on the level of the neighbourhood and the calculations for all transformers of interest are combined. Asset value is regulated as well as the WACC, the depreciation, and the discount rate [8] [9]. Differences between operational costs between a reinforced transformer and the current transformer are deemed negligible. The costs of flexible yearly capacity required to mitigate overload is estimated through a rough estimation on the basis of the one simulated winter week. This winter week cannot just be assumed to be representative for all weeks of the year. It is assumed that overload does not occur during the summer. The winter is assumed to last 12 weeks and the amount of flexibility provided in these weeks lowered with a modifier. Next to this, 6 weeks of spring and autumn are expected to have overload. The remuneration of battery degradation to the EV owner is presented as 4 eurocents per kWh and the additional lump sum costs of V2G chargers compared to regular smart chargers is 500 euros per charger [10][11]. Using these values, the NPV of both scenarios are calculated. These results are presented in figure 10.

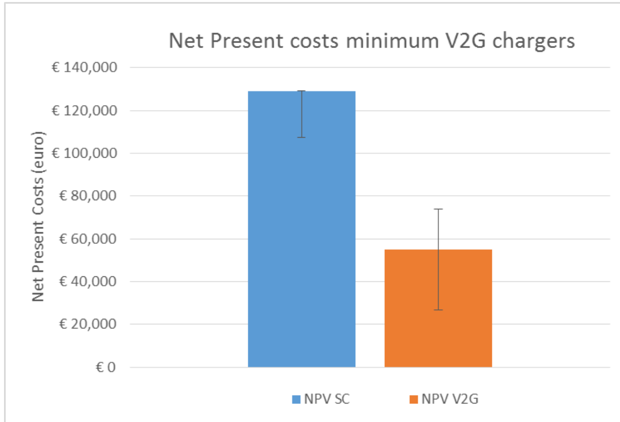

Figure 10: Net present value for 10 years

Figure 10 presents the results of the NPV calculations for both scenarios. It can be concluded from this figure that the flexibility solution has a lower NPV in comparison to the reinforcement alternative. Under the circumstances as described in this paper, the flexibility solution has a lower NPV than the reinforcement alternative. This result could be explained using the electricity load factor as presented in table 4. Average load factors for transformers within a residential area are around 50-60% [12]. The modelled transformers in Lent have a low average load factor. Hence, these transformers are not fully utilized during most of the day and designed for relatively few peak hours. Additional high investments for these relatively scarce peak hours is expensive and a more tailored solution becomes cheaper. Because of the low amount of kWh needed to support the grid with V2G this solution seems more effective. An additional NPV analysis is performed in order to calculate the costs if the DSO deploys V2G chargers for all EV owners in the neighbourhood. If all EVs are connected through V2G chargers, the value of V2G demishes. Therefore, it is important to note that the additional value of V2G is dependent on the amount of V2G chargers deployed. It is expected that the load factor in other neighbourhoods are higher. Next to this, overload issues might not even be present at all in other neighbourhoods. In the latter case, V2G does not provide any additional value in comparison to a V1G scenario. However, V1G might add value in comparison to regular charging. This value is not quantified in this research.

5 Discussion

V2G-charging has shown potential to aid the transition towards a more sustainable energy sector. V2G charging could be used for many different purposes. Currently, the value of these different services are explored. However, the value of V2G charging for low voltage congestion management is yet unclear. Understanding of the value of V2G charging for low voltage congestion management will help stakeholders to make better regarding grid operations and the value of flexibility in order to have a more socialized cost effective transition. The impact of EV charging in a V1G and a V2G setting is modelled in the Sparkcity ABM. The results of this simulations are then translated into a monetary value using the standard cost-benefit analysis for Dutch grid operators in regards to flexibility solutions.

To answer the main research question of this paper: V2G could be a cost effective solution for congestion management in Lent in comparison to grid reinforcements on the LV grid. Comparing these two alternatives, V2G could be up to five times more cost effective. This would create value to the DSO and thus social value. The results in this paper are compared to the results to other another study performed in the Netherlands in regards to the cost effectiveness of flexibility alternatives. The presented cost effectiveness of flexibility as presented in above is high compared to this benchmark study [13]. In [13] only a reduction of 47% is presented. This could be explained due to the low costs for flexibility. In this paper overloading is only expected during the winter period which drastically lowers the amount of flexibility that is needed to be provided. Furthermore, this research focusses on a specific low voltage whereas the benchmark study takes into account all voltage levels with the whole Netherlands as geographical area.

Although V2G charging has different benefits including the aid of the transition towards a more sustainable energy system, multiple barriers for the implementation of V2G exist until this day. Social and cultural barriers towards, implementation of V2G exist [14] as well as business and institutional barriers. One of the challenges for the V2G technology is battery degradation. EV batteries will deteriorate due to the amount of charging and discharging cycles depending on the services provided.

The flexible usage of bidirectional charging options will cause the battery to start ageing faster. Another challenge are the high investment costs for V2G charging hardware. Currently, V2G charging equipment is still in the development phase and upfront costs are thus still high. Next to the technical challenges, social challenges are present for V2G charging. The main social challenge for V2G is the range anxiety as perceived by the EV owner. This is a concern among car owners with regards to EVs in general, but the introduction of V2G and sharing energy from the battery of the EV will create new concerns regarding this anxiety [14].

Following these results a number of recommendations for further research are suggested in regards to the implementation of a V2G charging strategy. If overload in grid assets is expected every day a source of flexibility as provided by EVs might not be desirable due to lower predictability and thus reliability in comparison to other more consistent measures such as a stationary battery. The actual willingness of EV owners to participate in the execution of V2G charging is not considered and might become an issue. The remuneration of EV owner is assumed to be high enough for the EV owner to participate, but this might accumulate to such an extent for which it becomes non-desirable for the DSO to use V2G as a flexible resource. Electricity household demand is assumed to be perfectly forecasted by the DSO and aggregator. Fluctuations in patterns for electricity usage are not accounted for. This may result in a suboptimal scheduling of EVs and might even cause issues regarding security of supply. Actual realization and implementation of high penetrations of solar PV, heat pumps, EVs, smart charging strategies or V2G strategies have many boundaries and are highly uncertain. Next to this, no institutional framework currently exists for the DSO to use flexible resources to balance local LV grid demand. Different pilots are conducted in order to estimate the value of this flexibility, but legal boundaries are currently in place to prevent the actualization of these practices. Furthermore, all electrical loads within the residential neighbourhood are assumed to be static except for EV charging loads. This means that it is assumed that all electrical appliances in the neighbourhood except for EVs are uncontrolled. However, demand response could be provided by, for example, heat pumps [15]. The Sparkcity model could be expanded by including the ability of heat demand or other electrical demand to be responsive and provide a more dynamic environment. Additionally, further research should be conducted in order to obtain electricity consumption data from within the neighbourhood without privacy concerns. As shown in this paper, the value of V2G is dependent on the base electricity consumption and results are not robust for an increase in electricity consumption. Not only will the inclusion of real world electricity consumption data make the model more accurate, it enhances the validity of the results that are obtained.

6 Conclusion

Within the neighbourhood of Nijmegen Lent future electricity demand will most likely exceed the installed capacity within the low voltage grid due to the introduction of electric appliances. A smart charging strategy based on valley filling and congestion management will avoid an increase in peak demand during the evening due to the charging of EVs. However, the smart charging strategy cannot prevent peak electricity demand to be higher than the installed low voltage grid capacity. The proposed V2G charging strategy is able to prevent overloading of low voltage grid transformers and is thus able to delay initial investments in grid reinforcements. Within the area of Nijmegen, Lent V2G congestion management is a viable strategy to avoid overloading of grid assets and the necessity to reinforce transformers in the area. The deployment of a V2G strategy in comparison to a smart charging strategy allows for avoidance of grid reinforcements which account for almost five times the costs in comparison to the V2G charging scenario. This research shows that there is inherent value created for the DSO through V2G charging, and could thus be considered as an alternative to grid reinforcements by the DSO. However, implementation of this strategy is not taken into account in this research and should be further researched.

Acknowledgments

The researchers would like to thank the local DSO, Alliander, for providing information regarding the local electricity grid and the municipality of Nijmegen for providing information regarding demographics and GIS-data.

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