USING ELECTRIC VEHICLES TO STORE SOLAR ENERGY: THE SPATIAL DISTRIBUTION PROBLEM

A QUANTITATIVE ANALYSIS ON THE EFFECTS OF THE SPATIAL DISTRIBUTION OF SOLAR PANELS AND ELECTRIC VEHICLES ON THE COST-EFFECTIVENESS OF THE VEHICLE-2-HOME CONCEPT

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Using Electric Vehicles to Store Solar Energy: The Spatial Distribution Problem

A quantitative analysis on the on the effects of the spatial distribution of solar panels and electric vehicles on the cost-effectiveness on the Vehicle-2-Home concept

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I. PREFACE

This thesis concludes the master program Engineering & Policy Analysis at the Delft University of Technology. With successfully finishing this last assignment, I can officially call myself engineer. The road to obtaining this title lasted six years and led me to The Hague, Rome, and of course Delft. I would like to thank my graduation committee: Zofia Lukszo, Jan-Anne Annema, and Samira Farahani for their time and effort in helping me pass this last hurdle.

Additionally, I want to thank my mother and father for tutoring and preparing me to succeed at the university. I could not have done without their unconditional support. Furthermore, I want to thank my friends for their motivation and distraction from this thesis. Last but definitely not least, I want to thank Maud for her listening, faith, and encouragement. Without her, this process would not have been the same.

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II. EXECUTIVE SUMMARY

The electricity system is in a transition. A transition from a centralized system, where a few large power plants supply all of the electricity, to a decentralized system where many households supply electricity from solar panels. The latter system requires an infrastructure which is able to handle bi-directional flow of electricity. The distribution network operator (DSO) is trying to find a solution since the current electricity distribution grid will not be able to cope with a growing solar energy output. Transitioning to an electricity system which is able to handle large quantities of bi-directional flow is expected to require huge investment costs in the distribution network.

Vehicle-2-Home (V2H) is a concept which can (partly) prevent the need for upgrading the electricity grid. A building can charge an electric vehicle (EV) when it is plugged-in to this building with electricity coming from the grid or the building's solar panels. This charging can be reversed with a bi-directional charger. Now, the EV can discharge, supplying the building with its electricity demand. This technology can relief the strain on the grid in two ways. First, when an EV is connected to a building which produces more solar energy than it consumes, this surplus solar energy can be stored in the battery pack of the EV. Second, the EV can discharge its electricity whenever it is connected to a building and thus levelling out the electricity demand curve from the power grid. However, this requires the EVs to be at the same location as the surplus solar energy or at places where the electricity demand is high. This thesis explores this spatial distribution of EVs and solar panels, and analyses how it impacts the cost-effectiveness of the V2H concept. Furthermore, this thesis sets out to explore how a cost-effective design of this technology should look like. This problem is stated in the following research question:

How will the spatial distribution of solar panels and EVs affect the ability of EVs to store solar energy and return it to the grid via the Vehicle-2-Home concept and how to design a cost-efficient system with this spatial distribution?

This research is an exploratory case study into the grid investments prevented by the V2H concept. Amsterdam, and some large surrounding districts, are subjects of this case study. This study aims to provide insight into whether the V2H concept will be a viable investment option by 2040. This thesis's methodology contains three steps. First, two scenario analysis are constructed into the growth of EVs and solar panels. This is done with datasets from the DSO in Amsterdam, Liander, and the municipality of Amsterdam. Second, commuting trends between the districts are constructed with data from the public transportation company in the Amsterdam metropolitan area. This results in the current and future spatial distribution of solar panels and EVs over Amsterdam. In the last step, these distributions are used in a numerical model which calculates the total system costs of V2H. This thesis also looks into how the costs of the V2H concept can be optimized for the Amsterdam region. To put these costs in perspective, a calculation of the total system costs for upgrading the electricity grid in the traditional manner is done. In this calculation a distinction is made between the day time and the night time. During the day solar panels produce solar electricity which charge the EVs, and during the night time EVs discharge to supply the districts with electricity.

The growth of solar panels in the Amsterdam region is expected to increase. A scenario analysis into this growth shows that the current and future distribution of solar panels is not evenly dispersed over the districts. In 2018, the difference in solar energy output between the districts of Noord and Badhoevedorp is 5,5 MWp. This is the largest relative difference between districts. By 2040, this difference has grown to 9,5 MWp in the low growth scenario and 95 MWp in the high growth rate. Districts with a high solar energy output are Purmerend-Volendam, Noord, and Oost. Districts with a low solar energy output are Centrum, Diemen, and Badhoevedorp. Eight districts are even expected to produce more solar energy than they consume. The surplus solar electricity of these districts will have to be transported to districts with a high electricity demand. Liander expects that between 612 and 2430 transformers and 5625 kilometre of cables will likely overload due to capacity problems of this growth in solar electricity. To allow for the distribution of this surplus solar electricity over the electricity grid, investments in infrastructural components are necessary. This is upgrading the network in the traditional manner. Unfortunately, this traditional solution is an expensive solution requiring investments between 433 and 1408 million euro until 2040, depending on the growth scenario (see table 2).

V2H might offer a solution. This concept stores the surplus solar electricity in the battery packs of EVs. A scenario analysis on the growth of EVs shows that the number of EVs will rise drastically in the Amsterdam region. These EVs can theoretically store all the surplus solar energy of the previously mentioned eight districts. However, this requires the EVs to be in the same location as the surplus solar electricity. Unfortunately, also the EVs are unevenly distributed over the districts in the Amsterdam region and this is expected to grow. In 2018, the highest difference of EVs per district, between Amstelveen and Diemen, is 1460. By 2040, this difference has grown to 44.257 EVs in the low growth scenario and 77.775 EVs in the high growth scenario (Amstelveen – Zuid-Oost).

This uneven spatial distribution of EVs impacts the two potentially positive factors of the V2H concept on the electricity infrastructure. The first factor is the ability to store the districts surplus solar electricity. When incorporating the commuting trends into the scenario analysis, this research found that all but one of the eight districts which have an excess of solar energy, also have enough EV storage capacity. The district of Westpoort is the only district which has a surplus of solar energy but not enough EVs to store it in. Storing the surplus solar electricity in EVs prevents network investments in transformers and cables since the power grid does not need to facilitate bi-directional flow of electricity. This prevents between 1,14 and 60,53 million euros of investment costs into the infrastructure of the distribution grid.

The second factor which positively impacts the electricity infrastructure as a result of V2H is the ability of an EV to use its storage capacity by returning electricity back to the building it is plugged-in to. In total between 1.797.536 and 3.230.363 MWh of electricity can be returned to the districts during the night time electricity demand. This reduces the household dependency on the power grid. However, as a result of the uneven spatial distribution of EVs, this potential is not fully used. The districts surrounding Amsterdam have, on average, a higher storage capacity than the Amsterdam districts. Especially, the districts of Amstelveen, Hoofddorp, and Badhoevedorp have more storage capacity in the form of EVs than they consume during the night time (see figure 1). The surplus EV storage capacity of these districts cannot be transported over the Amsterdam electricity grid in the current centralized system. This decreases the effectiveness of the V2H concept by not being able to match the EV storage capacity supply with the demand in other districts during the night time electricity demand. Still, the V2H concept costs between 387 and 634 million euros, which is cheaper than upgrading the grid in the traditional manner since it only requires investments in bi-directional chargers.

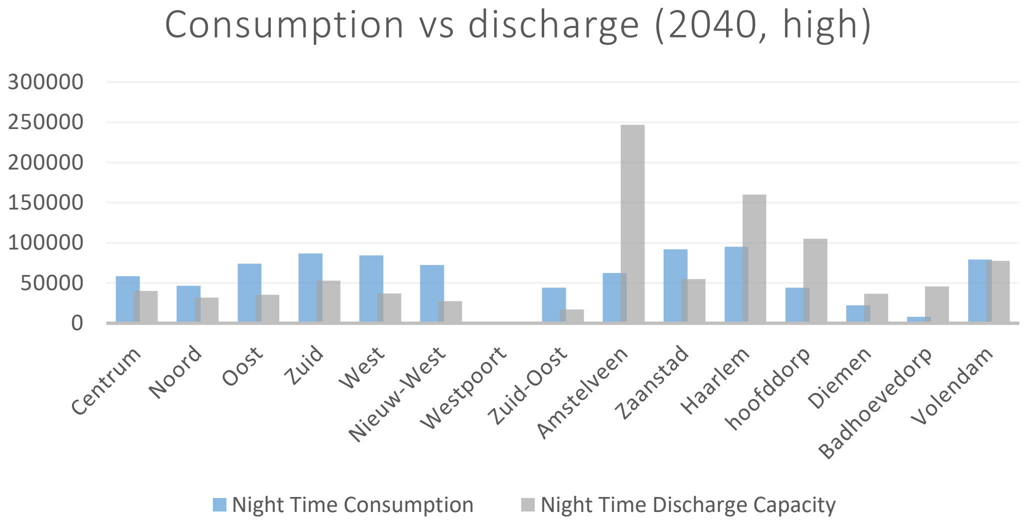

Figure 1, Consumption vs discharge capabilities per district

A compromise between investing in infrastructural components and implementing the V2H concept will counteract the negative effects of the uneven distribution of solar panels and EVs the most. Therefore, this thesis proposes to implement V2H concept and invest in three network links in the Amsterdam region (see table 1). With this design, all surplus solar electricity, except for Westpoort, can be stored in EVs. Furthermore, the proposed network links disperse the surplus EV storage capacity of the districts of Amstelveen, Badhoevedorp, and Hoofddorp more evenly between districts. This results in more districts being able to use the storage capacity in EVs. Now, the number of districts which can be completely independent of the power grid for their night time electricity consumption, has grown from three to eight districts. This reduces the night time electricity demand peak from the power grid significantly. The investment costs for this case is between 700 and 1334 million euros (see table 2). These costs are lower than the costs accompanied by upgrading the power grid in the traditional way (case I), and it reduces the strain on the power grid by capturing (almost) all surplus solar energy and redistributing the EV storage capacity to districts which need it the most.

Table 1, Proposed network links

Network link	District from	District to
Link 1	Amstelveen	Zuid and Zuid-Oost
Link 2	Badhoevedorp	Nieuw-West
Link 3	Hoofddorp	Nieuw-West

Table 2, Total case costs in million euros

Cases	Low growth scenario	High growth scenario
Case I: Upgrade power grid	433	1408
Case II: Vehicle-2-Home (V2H)	387	634
Case III: A compromise	700	1334

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1 INTRODUCTION

The climate agreement, set by the Dutch government, aims to reduce the carbon dioxide pollution by 49% compared to 1990. To achieve this goal the electricity system must transition from a centralized system to a distributed system (Sociaal-Economische Raad, 2018). A distributed electricity system is a system where one centralized power plant is replaced by numerous smaller renewable power plants. In urban areas, solar energy is the preferred renewable source because, unlike windmills, it is quiet and easy to install on roofs. These characteristics of solar panels are the reason that this energy source will grow significantly in urban areas and thus decrease the pollution emitted by environmentally unfriendly coal or gas power plants (Singh, 2013).

Unfortunately, installing solar panels on every roof will only be sufficient if the sun would shine 24/7. The sun doesn't follow human fluctuations in energy demand (Verzijlbergh, 2013). One solution is to give this daytime surplus solar electricity back into the grid and transport it to either a location where the demand for energy is high, or to a centralized storage location. Unforunatly, the transportation of electricity is not easy within the current infrastructure. The Dutch electricity system was designed as a centralized system and not as a distributed system (Wetering, Harmelen, & Gjaltema, 2013). A sunny day with many distributed solar sources giving back to the net can therefore lead to problems (Van Santen, 2017). Liander, the DSO that operates in the Amsterdam region, investigated the resilience of the electricity infrastructure and concluded that it is not ready for the future. The region has seen a large growth in EVs, solar panels, data centers, and heat pumps, and Liander warns that the electricity infrastructure cannot keep up with this growth (Van Zoelen, 2019). Liander expects more blackouts especially as result of the increase in decentralized production of electricity.

Increasing the grid capacity to cope with the growing number of electric vehicles (EVs) and facilitating the bidirectional flow of electricity generated by distributed solar panels throughout Amsterdam, requires tremendous investments (Van Westeringen, Zondervan, Bakkeren, Mijnhardt & Van der Els, 2016). However, a new technology can potentially handle the growth of EVs and solar panels but does not require tremendous network investments. This solution stores electricity locally. In 2035, 3 out of 4 Dutch cars are expected to be electric vehicles (Cuijpers, Staats, Bakker & Hoekstra, 2016). These EVs all have batteries and thus carry a great potential for storing solar energy. New technologies can transform these EVs from just demanding electricity to also supplying electricity. The technology in which EVs give electricity back to the building it is connected to, is called Vehicle-2-Home (V2H). This technology can help facilitate the growth of solar panels and EVs and maintain the stability and quality of the Amsterdam electricity system.

This thesis explores this spatial distribution of EVs and solar panels, and analyses how it impacts the cost-effectiveness of the V2H concept. Furthermore, this thesis sets out to explore how a cost-effective design of this technology should look like. This results in the following research question:

How will the spatial distribution of solar panels and EVs affect the ability of EVs to store solar energy and return it to the grid via the Vehicle-2-Home concept and how to design a cost-efficient system with this spatial distribution?

The rest of this chapter will highlight the literature review, the knowledge gap, the research questions and the scientific and societal relevance. In the subsequent chapter the research method is explained (chapter 2). The next two chapters will contain the scenario analysis into the growth of solar panels (chapter 3) and the growth of EVs (chapter 4). Afterwards, the effects of the commuting trends on the spatial distribution of EVs is incorporated (chapter 5). The next chapter will highlight the cost-effectiveness calculations of the constructed cases (see chapter 6). Finally, the thesis summary and the interpretations of the results are denoted in the last chapter (see chapter 7).

1.1 PROBLEM DEFINITION

The Municipality of Amsterdam wants to transition from fossil-fueled energy sources to renewable energy sources. Amsterdam chose solar energy as one of the predominant solutions to reduce the pollution coming from coal and gas power plants that surround the city (Gemeente Amsterdam, 2019). Since the introduction of solar panels, somewhere in 2012, solar energy has seen a steep rise. In only 6 years, solar energy has grown to account for 3.3 percent of the total Dutch electricity production (Dutch New Energy Research, 2019). In recent years, solar energy has grown by about 40% due to decreasing production costs of solar panels (CBS, 2014). This is more than any other renewable energy source in the Netherlands. Research by Singh (2013) found that solar energy is the preferred choice of urban areas to decrease the pollution by fossil fuel power plants because of the relative ease of installing them on rooftops. The research concluded that installing other renewable energy sources such as wind turbines or a hydro turbine negatively impacts the livability of the urban area. The municipality of Amsterdam acknowledges the importance of solar energy in urban areas.

The Increasing Demand

The rise of electrical appliances such as EVs will cause problems on the electrical infrastructure. Research by Kleiwegt (2011), Verzijlbergh (2013) and by the Amsterdam DSO Liander (Van Soelen, 2017), all conclude that an increase in either EVs or solar panels will lead to capacity problems on the Dutch electricity network. Kleiwegt (2011) investigated the impact of EVs on the electricity grid in Utrecht. This model found that an increase in the number of EVs will cause certain local areas in the grid to overload which leads to blackouts. Also, the current Dutch electricity infrastructure can only handle a certain amount of distributed renewable energy sources (Weterings, et al., 2013). Early research by Richardson (2011) estimated that the ratio of solar energy can increase up to 75% if the electricity infrastructure is not the restraining factor. A more recent study found the same result (Mwalisu, Justo, Kim, Do & Jung, 2014). Niesten & Alkemada (2016) reviewed the literature and found that average Western electricity infrastructures can handle an increase in renewable energy by a factor three. This means that the municipality of Amsterdam is unlikely to reach its 2022 goal of producing 250MW of solar energy. Upgrading cables and transformers requires huge investment costs by the DSO, especially if done in an urban area (Allan, Eromenko, Gilmartin, Kockar & McGregor, 2014).

Facilitating the Growth

The ratio of solar energy can be increased if we match the solar energy supply to the energy demand. This transportation requires grid reinforcements in the Dutch distribution network (Weterings, et al., 2013). These new cables and transformers would allow for a higher capacity of bidirectional electricity flow and thus match the surplus solar energy supply to the demand. This bidirectional electricity network prevents the loss of surplus solar energy during the daytime. This decreases the dependency on fossil fuel power plants. As mentioned above, this is an expensive operation. Another solution is to store the surplus electricity during valley demand peaks locally. This locally stored electricity can then be used whenever demand peaks occur. Storage can be done with numerous techniques such as battery parks, compressed air, flywheel, or pumped hydro (Smith, Steven & Kroposki, 2008). Unfortunately, also these techniques require huge investment costs by the DSO.

A possible solution that does not require huge investment costs by the DSO is the Vehicle-2-Home (V2H) technology. This technology uses EVs to store surplus solar energy. With the use of bidirectional chargers, EVs are capable of not only drawing energy from the power grid but also delivering energy back to the grid (Lui, et al., 2013). This ability enables a car to serve as a transportation tool, but also acts as a distribution source for the (local) power grid (Richardson, 2013). This technology can thus prevent network investment costs. The surplus daytime solar energy of a building is stored directly in the battery pack of the plugged-in vehicle. Hence, no bidirectional electricity infrastructure is needed. The ability of EVs with V2H to deliver back to the grid also impacts the household energy demand peak. Many papers have shown that it can decrease this peak by up to 67 percent (Van der Kam & Van Sark, 2015; Noori, Zhou, Onat, Gardner & Tatari, 2016; Gough, Dickerson, Rowley & Walsh, 2017; Salpakari, Rasku, Lindgren & Lund, 2017). With sufficient numbers of EVs and V2H technology around, no centralized storage is needed, no bidirectional flow is needed, and no solar energy is lost. V2H is therefore, an interesting technology that can mitigate the negative effects that the growing numbers of EVs and solar panels can have on the electricity infrastructure.

1.2 KNOWLEDGE GAP

The V2H concept can be a great method to allow for growth in decentralized solar energy production and at the same time prevent infrastructure investments. However, the literature does not provide for an in-depth analysis of the link between the spatial distribution of renewable energy (including solar panels) and the commuting trends of EVs. The literature largely overlooks the fact that commuting trends accumulate EV's at specific locations and at specific times. Kempton & Tomic (2007) state that the amount of time EVs are on the road, does not significantly impact the economic attractiveness. Green, Wang & Alam (2011) opposes this statement and say that missing accurate and detailed driving patterns is the major issue when investigating the effectiveness of V2H. A detailed model of how the commuting trends disperse the potential electrical storage units over a region is essential to estimate the energy network stability of V2H-technology (Littler, Zhou & Wang, 2013). EVs need to be plugged into the buildings which have a surplus of solar energy in order to capture its full potential.

Modelling this on a detailed level requires extensive EV characteristics such as storage and discharge capacity, current battery level, and battery efficiency. It also requires knowing commuting trends, amount of plugged-in EV's, time, and location. From a computational perspective, it is too difficult to model the driving habits and battery characteristics of each individual vehicle (Richardson, 2013). It is unknown if the spatial distribution of EV due to commuting trends matches the spatial distribution of renewable energy sources (i.e. wind mills and solar panels). This is quite essential information since one of the biggest benefits of using V2H is to store surplus renewable energy. Furthermore, it is unknown whether this match or mismatch is likely to grow in the future. From the existing knowledge gaps identified above, this thesis will focus on what effects the spatial distribution of EVs and solar panels have on the cost-effectiveness of V2H.

1.3 RESEARCH QUESTIONS

This section will briefly explain the sub questions. The main research question (see chapter 1) will be answered with the help of 5 sub questions.

I. How will distributed solar energy production grow and what effect does this have on the current electricity infrastructure?

This question will provide insights into how much distributed solar energy is currently produced in Amsterdam and how this will grow in the future. The municipality of Amsterdam has a dataset with the location and output of all the solar panels in the municipality. Solar panels tend to accumulate in wealthy neighborhoods due to their big price tag (Larson, Viáfara, Parsons & Elias, 2015). Therefore, an uneven spatial distribution of solar energy output is expected.

II. How will the number of EVs grow and what effect does this have on the current electricity infrastructure?

This question will provide insights into number of EVs in Amsterdam and how this is expected to grow in the future. EVs tend to accumulate in wealthy neighborhoods due to their big price tag (Larson, et al., 2015). Again, increasing the chance of an uneven spatial distribution of EVs.

III. How does the spatial distribution of EVs match with the supply distribution of distributed solar energy production?

This question will match the two spatial distribution scenarios constructed in the previous sub questions. Commuting trends of EVs can have a profound effect on the availability of EVs per district. This thesis will develop commuting trends and look into the effects of these trends on the availability of EVs. This will provide insight into how much of the surplus solar energy can be stored in EVs and how this match or mismatch will grow in the future.

IV. What are the costs and (societal) benefits of the V2H-technology and how can these be distributed efficiently between the actors?

In this question the V2H concept will be explored in more detail. The cost-effectiveness is calculated on the basis of sub question *I.* till *III.* This question will also discuss how these potential costs and benefits are allocated between actors.

V. What is the cost-efficiency of upgrading of the Amsterdam electricity infrastructure in order to facilitate the growth of EVs solar panels?

In this question the cost-effectiveness is calculation of making the electricity grid future proof (increasing capacity for decentralized solar energy production) the traditional way. Again, this calculation is on the basis of sub question *I.* till *III.* and the allocation of these costs and benefits are discussed. This sub question is constructed to put the cost-effectiveness of the V2H in perspective.

1.4 SCIENTIFIC AND SOCIETAL RELEVANCE

This thesis sets out to research the possible mitigating effects of the V2H concept on the infrastructure investment costs. The scientific contribution of this thesis is to fill in the knowledge gap of the causal effects between the spatial distribution of EVs and the spatial distribution of decentralized solar panels. By exploring this knowledge gap a more accurate cost-effectiveness calculation of V2H can be done. This cost-effectiveness contributes to the societal relevance because the electrical infrastructure is maintained by (partial) public organizations. Liander is a utility company, paid in full by public money. This means that infrastructural investments are (indirectly) paid for by the public. In Liander's case, all shareholders are municipalities or provinces. The largest shareholders are the province of Gelderland (44,68%), the province of Friesland (12,65%), the province of Noord-Holland (9,16%) and the municipality of Amsterdam (9,16%). The other shares are divided under the municipalities which lie within Liander's distribution grid. Thus, allocating the public investment costs in the most efficient way is therefore valuable to the overall society.

1.5 THESIS OUTLINE

This section visualizes the structure of the thesis. A “flow diagram” is used to help explain the structure (see figure 2).

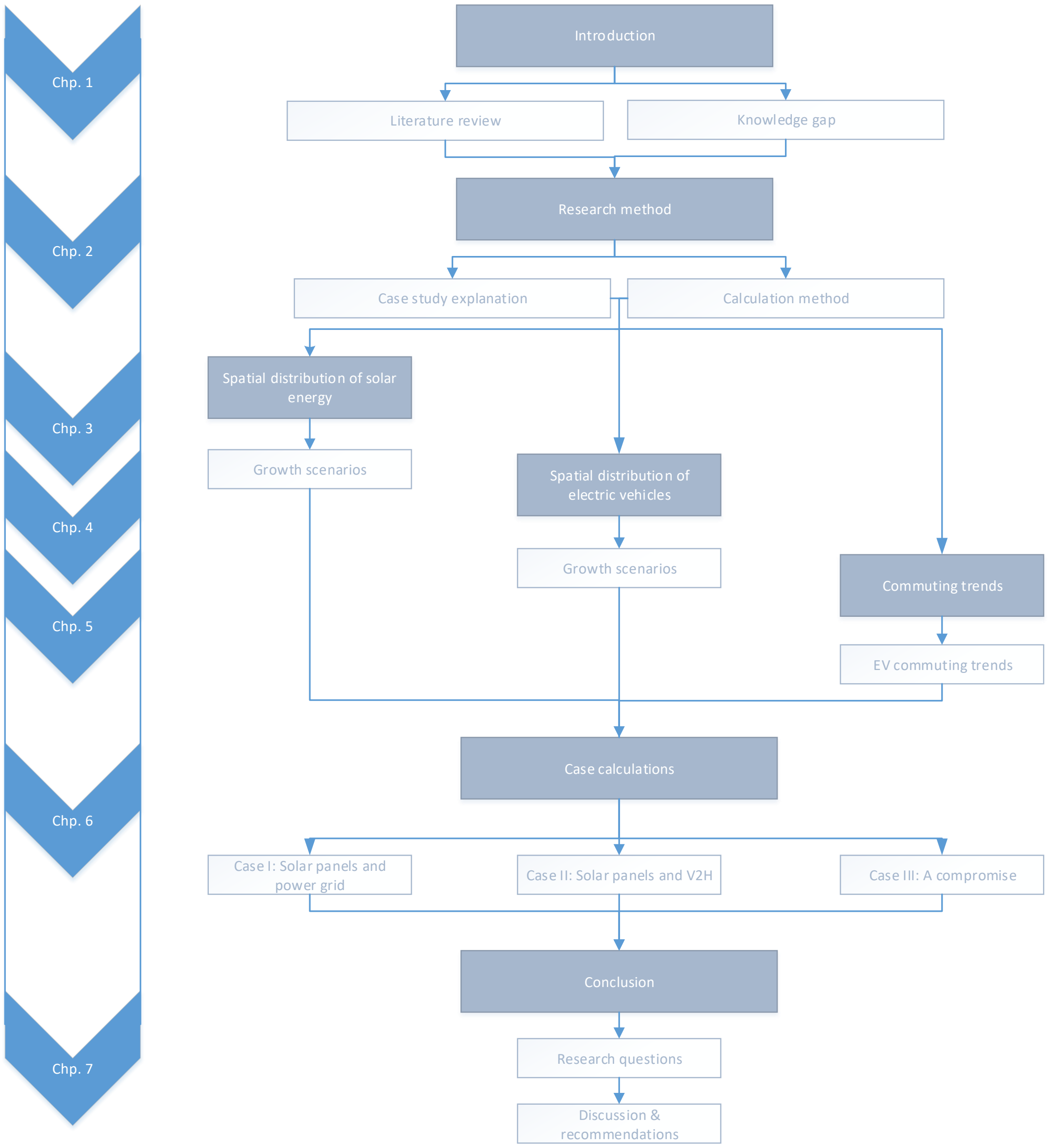

Figure 2, Thesis outline

2 RESEARCH APPROACH

This chapter will explain the research method and methodology used in this thesis (section 2.1). In the following section the exploratory case study is introduced (section 2.2). The scenarios are explained in the following section (section 2.3). The calculations used to estimate the case costs are denoted in section 2.4. Finally, in the last two sections the assumptions are stated, and the general approach of this thesis is presented (see section 2.5 and 2.6).

2.1 RESEARCH METHOD

This research will conduct a quantitative case study using several secondary data sources. Amsterdam and some surrounding districts are subject in this case study (see section 2.3). In this case study, two different cases which “upgrade” the electricity grid are investigated. Also, a third case is proposed and designed. This third case focusses on how the effectiveness of V2H can be increased. Two scenario analysis will provide insights in the possible growth scenarios of EVs and solar panels. These scenarios will provide insights into the adoption of both EVs and solar panels. In order to facilitate these growth scenarios, three cases are constructed (see figure 3). Thus, creating an exploratory case study into the Amsterdam electricity grid (Yin, 1984). The first case centres around traditional improvements in the network such as increasing the capacity of the cables and transformers. The second case centres around the use of EVs to store solar energy in a distributed manner and thus reduce the electricity demand from centralized energy sources. This case uses the V2H technology. This thesis constructs two cost-efficiency numerical models and compares these to gain insights into the height of the investment costs. This cost comparison helps to put the V2H concept costs in perspective (Gusto & Romijn, 2015). Finally, the third case will combine the two previous two cases. Again, this case will also be subjected to a cost-effectiveness analysis.

This thesis will construct two cost-effectiveness analysis with the help of a literature study and a numerical data model where the previously mentioned scenarios are used as inputs (see figure 3). These scenarios, as well as characteristics of EVs, characteristics of solar panels, and what effect this has on the electricity infrastructure, are used in the analysis. This combination of qualitative and quantitative methods will result in a case study with the highest predictive power (Kaplan, Duchon & Study, 1988). The growth of solar energy output, the number of EVs, and the commuting trends between districts are estimated with the help of a literature study and a numerical model (sub question *I.* till *III.*). The cost-effectiveness calculations are performed with the outputs of the previous sub questions and a literature study into the specific characteristics accompanying these calculations (sub question *IV.* and *V.*).

Main research question:

What effect does the spatial distribution have on the ability of V2H to store decentralized solar energy and decrease the power grid dependency and how can it be optimized?

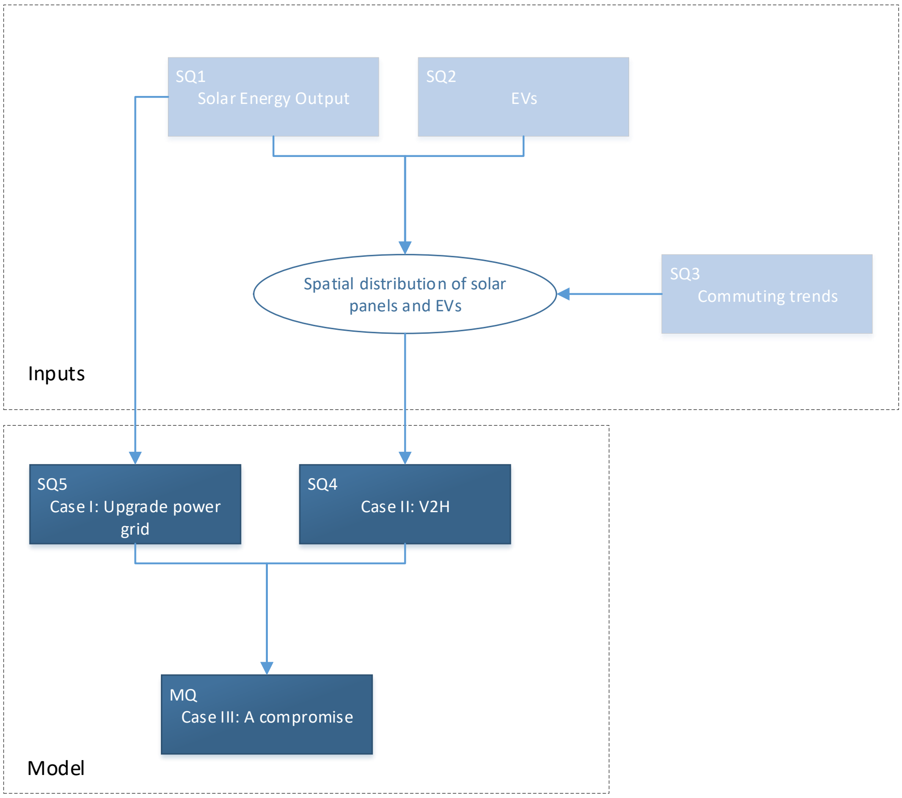

Figure 3, Research method

2.2 Method: Exploratory Case Study

Amsterdam's ambition to transition to an electricity mix with a growing share of solar energy is one reason for choosing this region to explore the cost-effectiveness of V2H. Another important factor is the availability of data. The municipality of Amsterdam has an extensive and detailed dataset of all the solar panels and its output within the 7 city districts. Amsterdam is the only municipality with this accurate dataset. Also, the DSO Liander concluded that their electricity network is not able to handle the future growth of electricity demand (Liander, 2017). The city of Amsterdam is therefore a suitable choice for modelling the effectiveness of V2H to capture surplus solar energy. The Amsterdam metropolitan area also just finished extensive research into the commuting trends within its area.

Districts

The solar energy output, as well as the EV adoption is aggregated to the district level. The city of Amsterdam is divided into 7 districts. These districts are Centrum, Nieuw-West, Noord, Oost, Zuid, Zuid-Oost, West, and Westpoort (see table 3). Amsterdam's electricity demand is connected to surrounding districts and vice versa (Liander, 2017). For this reason, the closest and largest surrounding districts are implemented in the model. Also, there are many commuters which travel between these surrounding districts and the Amsterdam districts. A large district can therefore have a profound effect on the storage availability of V2H on the entire electricity system. The surrounding districts which are incorporated into this research are Amstelveen, Haarlem, Badhoevedorp, Diemen, Hoofddorp, and

Purmerend-Volendam (see table 3). Small surrounding villages are not taken into account because their impact on the electricity system is neglectable compared to these large districts. More district characteristics can be found in appendix 7.2.

Table 3, District characteristics

Region	District	Inhabitants	Number of jobs
Amsterdam Regions*	Centrum	86.400	102.598
	Nieuw-West	146.800	76.718
	Noord	91.000	32.316
	Oost	128.700	62.622
	West	142.800	48.402
	Westpoort	2.000	21.920
	Zuid	141.400	105.642
	Zuid-Oost	84.600	76.770
Surroun-ding districts**	Amstelveen	88.600	43.300
	Haarlem	155.000	52.800
	Badhoevedorp***	12.600	7776
	Diemen	10.000	22.100
	Hoofddorp***	75.000	4600
	Purmerend-Volendam	102.200	27.700
	Zaanstad	155.000	52.800

*Source: Amsterdamse Thermometer voor de Bereikbaarheid (Gemeente Amsterdam, 2019)
**Source: CBS Statline
***Badhoevedorp and Hoofddorp are estimates derived from the data about the municipality of Haarlemmermeer.

2.3 SCENARIOS

This section will briefly explain the growth scenarios and cases. The current number of EVs and solar panels in the Amsterdam region is retrieved from the data sources. From these current adoption rates, two scenario analysis are constructed. Both scenarios will be subjected to a maximum and a minimum growth rate number. A literature study is used in order to estimate these growth rates leading to a worst-case scenario and a best-case scenario. This thesis will perform scenario analysis on the adoption and growth of solar panels (see chapter 4) and a scenario analysis regarding the adoption and growth of EVs (see chapter 5). These scenarios will be used to calculate the cost-effectiveness of the cases further on (see section 6.2-6.3).

Case I: Upgrade power grid

The electricity demand for the household sector is supplied by the grid and decentralized solar panels. This scenario requires to have an electricity infrastructure that is capable of transporting all the decentralized surplus solar energy and has a high-growth scenario and a low-growth scenario.

High: The high-growth scenario. This is a scenario where the solar panel adoption grows according to the highest growth scenario.

Low: The low-growth scenario. This is a scenario where the solar panel adoption grows according to the lowest growth scenario.

Case II: Vehicle-2-Home (V2H)

The electricity demand for the household sector is supplied by the grid, solar panels and with the help of EVs with V2H. In this scenario, the surplus solar energy is stored in EVs during the daytime and at night time the energy stored in EVs is discharged to power the households. Just as in case I, this scenario sees solar panel adoption grow at a certain growth rate. But, because the electricity demand in this case also comes from EVs, the growth rate is also taken into account.

High: The high-growth scenario. This is a scenario where the solar panel installation and the EV adoption grows according to the highest growth scenario.

Low: The low-growth scenario. This is a scenario where the solar panel installation and the EV adoption grows according to the lowest growth scenario.

Case III: A compromise

The last case will explore a design which is more cost-efficient than the case which only implements the V2H concept. This case is designed to work best under the current and future spatial distributions of solar panels and EVs. In order to store more solar electricity and return more electricity back to buildings with a high demand via the V2H concept, investments in several infrastructural components are needed. Therefore, this case is named "a compromise". The scenarios used in this case to calculate this increased cost-effectiveness are the same as in "Case II: Vehicle-2-Home".

2.4 CASE CALCULATIONS

The total cases costs are calculated by summing over the total costs of each districts. However, only knowing the total costs of the V2H for the DSO is not sufficient. Before Liander can decide to change the focus from traditional improvements methods to V2H, we must research the effectiveness of V2H. Can V2H prevent network investments and to what extent? First the total system costs are calculated for V2H from the DSO's perspective. The formulas in 3.4.1 are used to calculate the total costs of both cases (see chapter 6), where the formulas in section 3.4.2 are only used to calculate the V2H effectiveness (Bleeker, 2019).

2.4.1 Total Case Costs

The total case cost (TCC) of both the two cases are calculated with the formulas 1-1 to 1-5. Adding up the costs of all the components result in knowing the total costs related to the system. In this thesis cost-effectiveness is the investments costs which are needed in order to facilitate the growth of decentralized solar energy (see chapter 4).

(1-1) The TCC is the sum of all costs. The TCC is in € / year. Where i, represents the districts.

$$TCC_i = \sum_{i=1}^{n} TC_i$$

(1-2) The Total Cost (TC) of a component is calculated by adding the capital costs (CC) to the Operation and Maintenance Costs (OMC). The TC is in € / year.

$$TC_i = CC_i + OMC_i$$

(1-3) The Capital Cost (CC) is calculated by multiplying the Annuity Factor (AF) with the number of the specific components installed (Q) and the Investment Costs (IC) of the specific component. The CC is in € / year.

$$CC_i = AF_i * Q_i * IC_i$$

(1-4) The Annuity Factor (AF) is used to calculate the costs over a large investment time. This factor allocates these costs over the multiple years. The AF is calculated with the lifetime of components (LT) and the discount factor (r). This thesis assumes a 5% discount factor[1].

$$AF_i = \frac{1-(1+r)^{-LT}}{r}$$

(1-5) The Operational and Maintenance Costs are calculated by multiplying the Operational and Maintenance (OM) with the number of components installed (Q) and the Investments Costs (IC). The OM is a percentage of the IC.

$$OMC_i = OM_i * Q_i * IC_i$$

2.4.2 Effectiveness of V2H

This section focusses on calculating the effectiveness of V2H. The effectiveness of the V2H concept means knowing how much solar energy can be transported from supply to demand locations using EVs. These calculations are done with the data of solar energy output per district, the number of EVs per district, and the traffic flows, as mentioned in chapter 3 until 5.

The effectiveness of V2H is calculated with the formulas 2-1 to 2-5. Adding up total energy supplied (ES) by EVs with V2H and the total surplus solar energy stored (SS) with V2H will result in the total effectiveness of the V2H system.

(2-1) The TSE of the V2H system is in MWh / year. Where i, are the districts.

$$TSE_{V2B} = \sum_{i=1}^{n} ES_{i,V2B} + \sum_{i=1}^{n} SS_{i,V2B}$$

(2-2) The total Energy Supplied (ES) to buildings connected to an EV is calculated by multiplying the availability of EVs per district (A) with the SOC minus the minimum battery charge (M). The ES is in MWh / year.

$$ES_{i,EV} = A_{i,EV} * (SOC_{i,EV} - M)$$

(2-3) The Solar Energy Stored (SS) is calculated by comparing the Surplus solar energy with the Storage Capacity (SC) of the combined EV fleet. Is the combined SC smaller than the surplus solar energy than the solar energy stored (Surplus) is the storage capacity (SC). And vice versa. SS is in MWh / year.

$$if\ SC_{i,EV} < \ Surplus_{i,solar}\ then \quad SS_i = \ SC_{i,EV}$$

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[1] Source: Rapport werkgroep discontovoet 2015

$$if\ SC_{i,EV} > \ Surpus_{i,solar}\ then \quad SS_i = \quad Surpus_{i,solar}$$

(2-4) The Storage Capacity (SC) is calculated with the inverse of the SOC multiplied by the availability of EVs per district (A). SC is in MWh / year.

$$SC_{i,EV} = \left((1 - SOC) * \ A_{i,EV}\right)$$

(2-5) The Surplus solar energy is calculated by subtracting the Total Produced Electricity (TPE) per district with the Total Consumed Electricity per district (TCE). The Surplus solar energy is in MWh / year

$$Surplus_{i,solar} = \ TPE_{i,solar} - TCE_i$$

2.4.3 Time interval

This model is constructed using a time interval of 12 hours. This time interval allows for a distinction between daytime hours and night time hours. This distinction is crucial due to the intermittency of solar energy. The day time interval is used to calculate the surplus solar energy, where the night time is used to calculate the energy supplied from EV to household. The electricity demand of households, as well as the surplus solar energy is evenly distributed over these intervals. The availability (A) in the previous section thus works with these intervals. The Energy Supplied (ES) only makes use of night time intervals, where the Storage Capacity (SC) makes use of the daytime intervals. This abstraction of demand and supply is not a problem because the model is calculated over a yearly basis and into the distant future.

2.5 ASSUMPTIONS

This section lists the major assumptions included in the model. Smaller, less relevant assumptions are denoted in the upcoming sections which specifies where the assumptions came from and how it is used in the model. The major assumptions are listed below:

- Only the electricity demand in the household sector is taken into account. Industry and other major electricity demand players are not incorporated.
- The household electricity demand stays constant.
- The higher prices of EVs with V2H technology is not taken into account. This thesis assumes that future EVs will all be equipped with V2H technology without an extra fee.
- Until 2040 solar energy will only substitute partly the traditional electricity power production. These traditional power plants are flexible in their production capacity in such a way that fluctuations in energy demand due to daytime solar energy is replaced by an increase in traditional power plants. The production of electricity is therefore always in balance with the demand:

$$E_D(k) = \ E_S(k)$$

- Major developments which can increase or decrease the electricity demand significantly (heat pumps, etc.) are not taken into account.
- Electricity can be distributed freely within a district via the LV-cables, these components are therefore not incorporated in this research (see section 6.2).
- Electricity distribution between districts is handled via the MV-cables. The HV-cables are not incorporated into this research (see section 6.2).
- All costs are in million euros, unless denoted differently.

2.6 GENERAL APPROACH

This research will consist of three phases (see figure 4).

- **Phase I**: The first phase will be the data preparation phase. In this phase, two data sources will be used for scenario development. One dataset contains all the solar panels within the municipality of Amsterdam, and the other contains the number of EVs per district. These datasets are used for a scenario development from 2018 to 2040. Furthermore, the commuting trends are constructed and incorporated into the EV adoption scenarios.
- **Phase II**: The datasets from phase I, are combined so they can serve as input for the cost-effectiveness analysis.
- **Phase III**: The cost-effectiveness of two cases are constructed and compared.

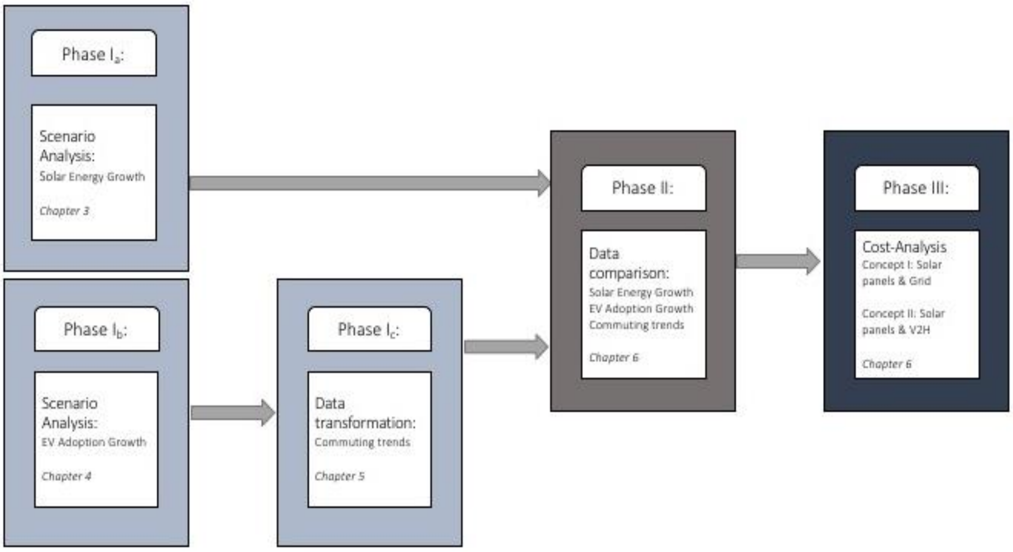

Figure 4, General thesis approach

3 THE FUTURE OF SOLAR ENERGY IN AMSTERDAM

This chapter will first describe the development of the solar panel used in the residential sector (section 3.1). Afterwards the current state of solar energy in Amsterdam is denoted (section 3.2). From this starting point, the scenario analysis is constructed (see section 3.3). These scenarios are later used as inputs in calculating the cost-effectiveness of the cases (see chapter 6). Further information considering the scenario analysis can be found in appendix A.2.

3.1 INTRODUCTION

The International Renewable Energy Agency (IRENA) calculated that 86% of the global energy demand can be replaced with renewable energy by 2050 (IRENA, 2019). Solar energy is seen as one of the predominant renewable energy sources. In the Netherlands, the total installed solar power output has grown from 2,9 GWp to 4,2 GWp in the last year alone (Dutch New Energy Research, 2019). This popularity in solar panels is due to the dropping price of solar panels and the increased solar panel efficiency (Jones & Bouamane, 2012). The Solar Trendrapport by the Dutch New Energy Research initiative identified two reasons for this popularity. First, since 1976 the price for solar panels have seen a yearly decrease of, on average, 28,5 dollar/Wp. In 1976 the solar panels cost almost 100 dollar/Wp. In 2018, this price has dropped to 0,35 dollar/Wp. The main contributor to this price fall is the benefits of economy of scale due to global goals to reduce emissions. Second, the popularity of solar energy is artificially increased by government subsidies. Governments have identified the urgency of climate change. Subsidizing solar energy is a way to reduce emissions and reach a climate-neutral economy. The municipality of Amsterdam has also acknowledged the threat of climate change. In *Routekaart Amsterdam Klimaatneutraal* the municipality set goals to reduce Amsterdam's CO2 emission to zero by 2050. Currently, 52 percent of all CO2 emissions in Amsterdam is coming from fossil fuel power plants (Gemeente Amsterdam, 2019). Because the electricity demand is expected to quadruple by 2050 relative to the current demand volumes, a transition of the energy supply is crucial in drastically reducing the emissions of Amsterdam (Gemeente Amsterdam, 2019).

Unfortunately, two problems prevent the transition to a 100% supply of renewable energy in the Amsterdam electricity system. The first problem is the unidirectional flow of electricity in our current electricity system. Traditionally, the Dutch (and thus the Amsterdam) electricity system is a centralized system where a fossil fuel power plant produces electricity. This electricity is transferred, via the transmission system operator (TSO) and the distribution system operator (DSO), to the consumer. As mentioned above, the electricity system must make a transition to a decentralized system. This allows households and businesses to install solar panels, so they become energy producers, the so-called prosumers. However, having a high number of prosumers within the electricity system requires an electricity infrastructure that allows for bi-directional flow of electricity. The current electricity infrastructure in Amsterdam can only handle a small amount of distributed renewable energy delivered back to the grid (De Haan, 2016). This will become a problem if this growth continues.

The second problem is the fluctuation inherent with solar energy. Solar energy only produces energy during the daytime when the sun shines. In the Netherlands, the sun has often already set when energy demand is highest. In the evening hours, people start cooking, washing and watching television. This creates a peak electricity demand in average households during those hours (Verzijlburgh, 2013). Thus, there is a mismatch between the peak of solar energy supply (daytime) and the peak energy demand (evening). The duck-curve visualizes this mismatch (see figure 5). Also, the surplus solar energy of a household that is produced during the day, must be transported to locations with an electricity demand. However, this transportation is not always possible with the existing infrastructure (De Haan, 2016). This big difference between valley peaks (daytime) and peak demand (evening) increases the stress on the electricity infrastructure (Denholm, O'Connell, Brinkman & Jorgenson, 2015).

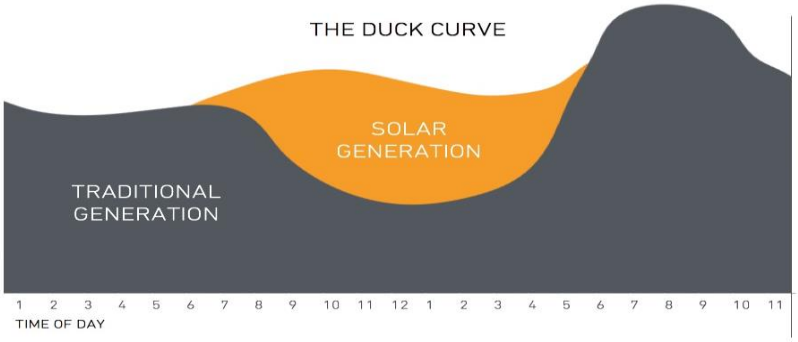

Figure 5, Duck curve

A study done by the PBL and DNV has shown that all the roofs in the Netherlands can be used to produce 70 GWp of electricity. With technological improvements, this number can increase to 150 GWp (Lemmens, et al., 2014). Since 2006 the total electricity demand in the Netherlands is fluctuating around 120 billion kWh, which roughly translates to 100 GWp (CBS, 2019a). PBL and DNV identified the roofs suitable for that installing solar panels. Covering all these roofs with solar panels will almost be sufficient to meet the total Dutch electricity demand. So, solar energy houses great potential. However, the same research concluded that the limit of transporting the distributed solar energy over the current Dutch electricity infrastructure lies between 4 GWp and 20 GWp. Since we have already reached a yearly production of 4,2 GWp of solar energy, monitoring the growth of this distributed solar energy is crucial. This research explores the current and future volumes of distributed solar energy in and around Amsterdam with the help of two data sources. These data sources help to identify the current state of solar panels in Amsterdam. The data comes from the municipality of Amsterdam and Liander, the DSO that operates in the Amsterdam region. The literature on the future growth of the solar energy market will be explored in order to determine the growth of solar energy in Amsterdam.

3.2 THE CURRENT STATE OF SOLAR ENERGY

In the last few decennia, The Netherlands has invested a lot in its national electricity infrastructure. This has resulted in a reliable electricity system with dense infrastructure and clearly defined rules and regulations (Donker, Huygen, Westerga & Weterings, 2015). In 2017, Liander's DSO network was only "down" for an average of 22 minutes (ACM, 2018). This performance is in danger due to the increasing popularity, strengthened by public policy, of decentralized renewable energy. Research from several independent institutions, as well as the local DSO Alliander, have found that the current electricity network is not ready for a highly decentralized energy market (Weterings, et al., 2013; De Haan, 2016; Kleiwegt, 2011; Verzijlbergh, 2013).

Households with solar panels often have a surplus of solar energy during the day. In order to efficiently make use of solar panels, a daytime surplus of solar energy must be matched with daytime energy demand. This requires the bidirectional flow of electricity. Alliander is already experiencing trouble with this bidirectional flow as a result of decentralized renewable energy production (Van Zoelen, 2019; Van Sanden, 2017). Knowing the current and future distribution of solar panels helps Alliander to identify where the bidirectional flow will cause the most problems. This helps the DSO with its investment strategy.

3.2.1 Districts of Amsterdam

The percentage of decentralized renewable energy is still a fraction of the total energy demand of the city of Amsterdam. In 2018, the combined energy demand of households and businesses was 4530 million MWh (Gemeente Amsterdam, 2018). According to the same report, in 2016 only 24 MWp of decentralized renewable energy was produced. The predominant source was solar energy. The municipality aims to have a city-wide solar energy output of 1000 MWp by 2040. They identified 1300 MWp as the maximum amount of solar energy output that can be installed due to the characteristics of the roofs in the city.

Solar Energy Output

*The output of solar panels is measured in Watt peak (Wp). Watt peak is the standard usually used in the photovoltaic industry. A Watt peak is a measurement unit for the capacity of solar cells. The output capacity of solar panels is dependent on factors like brightness of the light, the angle of the light, air mass and temperature. The Dutch environmental agency identifies the Watt peak conversion rate at 0,875 (Van Sark, 2014). This conversion rate allows for the calculation of kilowatt hours. A standard solar panel of 250 Wp per year can therefore produce 250 * 0.875 = 218.75 kWh of electricity.*

The district with the highest cumulative number of solar panels is *Nieuw-West* (see appendix A). This district has a little less than 1200 locations with solar panels. The districts with the lowest number of solar panels are *Westpoort* and *Centrum*. This is to be expected since *Centrum* is the neighbourhood with a high number of monumental buildings and installing solar panels therefore requires an environmental permit. The municipality of Amsterdam cherishes its monumental facades and buildings and is therefore not easy in giving out these permits. This is one explanation for the low number of solar panels in the *Centrum* district. The other district that sees significantly less solar panels is the *Westpoort* district. This is due to the fact that this district houses predominantly industry. In figure 6, the cumulative solar energy output is estimated. Here we see small deviations with respect to the cumulative locations of solar panels. This again can be lead back to the district characteristics. Districts such as *Westpoort,* which do not have many different solar panels locations because this district mainly houses industry, but the number of solar panels per location is quite high. Thus, increasing the output is relative to the number of solar panel locations.

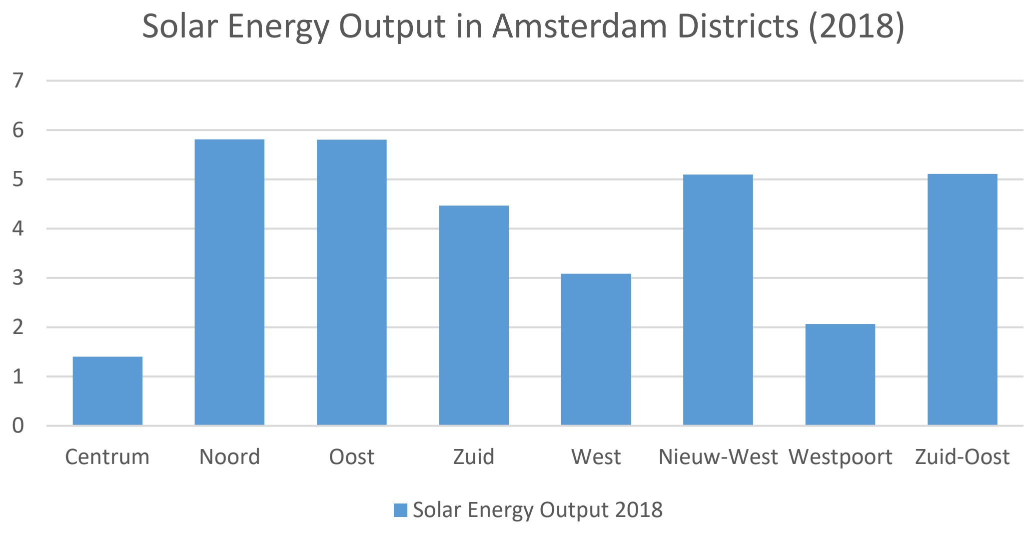

Figure 6, Solar energy output per Amsterdam district

3.2.2 Districts Surrounding Amsterdam

The districts surrounding Amsterdam do not have a detailed dataset about the location and power output of solar panels installed within the district. The solar energy output must therefore be estimated. This estimation is done with two district characteristics. The height of the average income and the number of inhabitants per district are used to match to the Amsterdam districts. Average income is a good predictor for the purchase and instalment of decentralized solar panels (Larson, et al., 2015). After comparing the average income of the districts surrounding Amsterdam with the districts within Amsterdam, the solar energy output is recalculated relative to the number of inhabits the district has.

In table 4, the districts surrounding Amsterdam and the corresponding Amsterdam district are denoted. The districts of Zaandam and Haarlem are given the same solar energy output as the Amsterdam district of West because these districts are both have the same characteristics. Zaandam and Haarlem have an old historic center, surrounded by suburbs and some industrial areas. The Amsterdam districts of *Centrum, Zuid, West,* and *Oost* are also historic centers. But because the average income of Zaandam and Haarlem is most in line with the average income of *West,* this district's solar energy output is used to estimate the solar energy output of Haarlem and Zaandam. Amstelveen and Badhoevedorp are suburbs of Amsterdam with an average income similar to the district *Oost*. Therefore, the solar energy output of Amstelveen and Badhoevedorp is estimated relative to the solar energy output of district *Oost*. The districts Diemen and Purmerend-Volendam are relatively poor districts. Therefore, their solar energy output is similar to the relatively poor district of *Zuid-Oost*. Finally, the district of Hoofddorp, a mainly residential area East of Schiphol, has an average income similar to the district of *Nieuw-West*.

Table 4, Solar energy output conversion table with income and inhabitants (x1000)

District Surrounding Amsterdam	Income	Similar to	Income	Ratio of inhabitants
Hoofddorp	27.9	*Nieuw-West*	27.2	75 / 146.8
Diemen	24.9	*Zuid-Oost*	24.2	10 / 84.6
Badhoevedorp	33.2	*Oost*	34.2	12.6 / 128.7
Zaandam	24.3	*West*	32.0	155 / 142.8
Haarlem	28.3	*West*	32.0	159.7 / 142.8
Amstelveen	31.6	*Oost*	34.2	88.6 / 128.7
Purmerend-Volendam	25.7	*Zuid-Oost*	24.2	102.2 / 84.6

**CBS Statline, 2018 data*

Purmerend-Volendam is the district surrounding Amsterdam with the highest solar energy output (see figure 7). The solar output of this district, 4,75 MWp is surprisingly high, even though the district has a relatively low average income. This is because it is derived from the district of Zuid-Oost, which is equally poor but still has the third-highest solar energy output of the Amsterdam districts. These districts end up having the highest total solar energy output of all the surrounding Amsterdam districts because of the size of the district. Districts with the lowest solar energy output are Diemen and Badhoevedorp. The district of Badhoevedorp has a pretty high average income and is therefore expected to also have high solar energy output, but because this district only houses 12.600 people the overall solar energy output is pretty low. Diemen, a district with a low average income also is a small district with only 10.000 inhabits. These districts therefore have the lowest cumulative solar energy output.

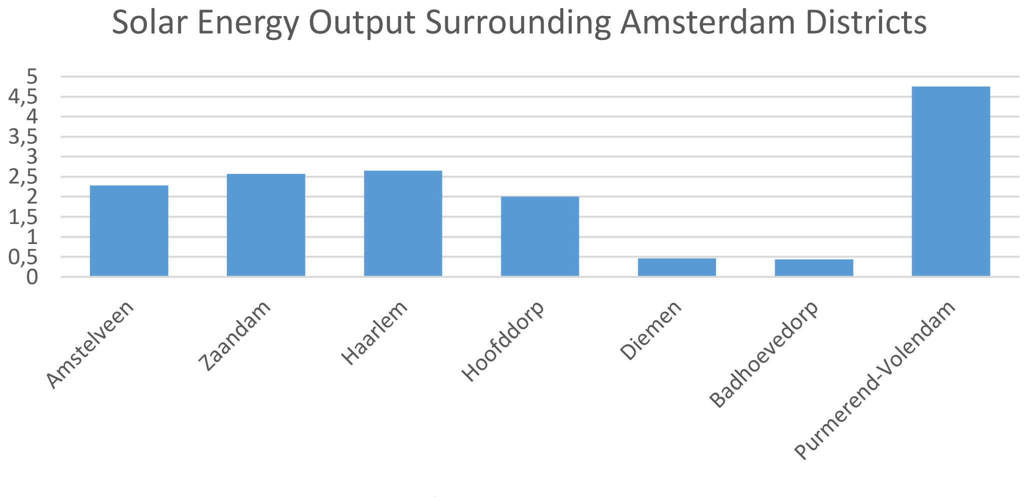

Figure 7, Solar energy output per surrounding district

3.2.3 Validating the Location Data

The data of the municipality of Amsterdam is validated with a dataset of the DSO. Liander operates in the Amsterdam and surrounding area. The DSO kept track of the direction of electricity for every address. The gathered data therefore accurately shows the locations where surplus solar energy is put back into the grid. This dataset was received on the 8th of April 2019 from Liander. Because we are looking at a highly urbanized area, solar panels will be the predominant source of renewable energy. Knowing the volume of distributed produced solar energy that has been given back to the grid, indicates where the capacity problems can arise within the infrastructure. This Liander data is used to determine which district puts a lot of solar energy back into the grid. A connection that gives back to the grid indicates that it produces electricity in a distribution fashion. This is stored in percentages. A building or office with a 100% score only takes in electricity from the grid. A building with a 95% score indicates that this building has sent electricity to the grid 5% of the time over a year. It is important to realize a high average percentage of electricity given back to the net does not necessarily mean that this district has a lot of solar energy panels. This percentage can also indicate that there are a few large producers active in the district. Therefore, this data will only be used as validation.

The Alliander data matches the solar energy output data gathered by the municipality of Amsterdam (see figure 8). The districts West and Centrum show in both datasets to be the district with the lowest solar energy output. A possible mismatch lies in the districts Diemen, Badhoevedorp and Hoofddorp, and Purmerend-Volendam. An explanation for the mismatch of the first three districts is the number of inhabitants of this district. Because these districts are relatively small districts the total solar energy output is also relatively small. However, because these districts are suburbs, the number of roofs suitable for solar panels is higher than the historic Amsterdam city districts. They can therefore install more solar panels per roof and thus give more surplus electricity back to the grid. Purmerend-Volendam is quite a big district. However, this district does not give back the most surplus solar energy. This can be explained by the fact that this district has a relatively low average income which results in the instalment of few solar panels per household.

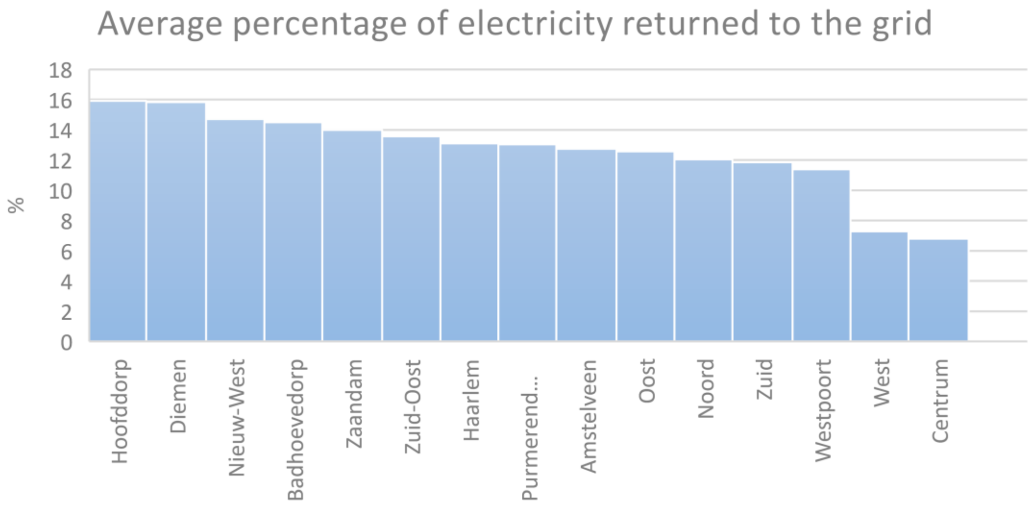

Figure 8, Percentage of electricity returned to the grid per district

3.3 SCENARIO ANALYSIS: SOLAR ENERGY

The ratio of solar energy is expected to increase in the overall energy mix. A lot of research has explored the future energy mix and nearly all researchers conclude that solar energy will continue its growth (McCrone, Moslener, d'Estais & Gruning, 2018). Uncertainty comes from the growth rate. The growth of solar energy depends on many factors such as; energy prices, solar panel prices, governmental subsidies, policy, and many more (Beurskens, 2017). Multiple papers have tried to quantify the growth rate of solar energy (see table 5).

The IRENA identified that renewable energy can provide 86% of the global power demand by 2050 (IRENA, 2019). Alongside wind energy and hydro energy, the IRENA identified solar energy as the three predominant forms of renewable energy in the future. They calculated a global yearly increase of 14% of solar energy output until 2025 (Taylor, Ralon & Ilas, 2016). The European platform for photovoltaics (EUPV), which has been created by the European Commission to bring together the European countries, industries, and researchers in the solar production field, found the same growth rate for the European Union (Vartiaien, Masson & Breyer, 2015). These researches focus on consumer solar panels. Research that looks at solar panels for large scale producers concludes to the same growth number. Agora, a think-tank that guides the German Energiewende (energy transition) found that the price for large scale solar panels keeps dropping resulting in a 5-10% yearly growth rate (Mayer, Philipps, Hussein, Schlegl & Senkpiel, 2015). Experts within the think-tank even estimate the growth rate to 14 percent. Research done by TKI Urban Energy focused on the Dutch solar panel market and found a similar growth rate of 13 (TKI Urban Energy, 2015).

Table 5, Literature review on the growth of solar energy output

Name	Scale	Timeline	Growth	Study
IRENA	World	2013-2025	14%	The Power to Change: Solar and Wind Cost Reduction Potential to 2025.
EUPVTP	Europe	2014-2020	14%	EUPVTP 2015 PV LCOE in Europe 2014-2030.
AGORA	World	2020-2030	5% (low) 10% (high) 14%(expert)	Current and Future Cost of Photovoltaics.
TKI Urban Energy	NL	2020-2030	13%	TKI Urban Energy 2015. Kennis- en Innovatieagenda.

This research focusses on the Amsterdam area. The 13% growth rate would be most obvious because this growth rate was predicted for the society in the Netherlands. However, this thesis chooses for the 14% growth rate because this will increase the solar panel output spectrum. This research tries to provide insights into whether a skewed spatial distribution of solar panels can negatively impact the effectiveness of V2H of storing surplus solar energy. A wider spectrum of scenarios can make the effect of this skewed spatial distribution more explicit. A constant growth rate for each district will increase the cumulative difference of the solar energy output of all the districts. For example, two districts A and B, have a yearly solar energy output of respectively, 1 and 10 MWp. After 10 years of 14% growth, district A will have 3,25 MWp of solar energy output. District B will have 32,5 MWp of solar energy output. The difference in solar energy output has grown from 9 MWp to 29,75 MWp after 10 years. In order to study the effects of large solar energy output differences, this research uses 5 percent as the low scenario and 14% as the high scenario (see table 6).

Table 6, Solar energy output growth rate used in thesis

Thesis scenarios	Growth
Low Growth Scenario	5%
High Growth scenario	14%

3.3.1 Districts of Amsterdam

In 2018, the municipality of Amsterdam collected data of all the installed solar panels within the city. In that year, the Amsterdam districts produced a combined solar energy output of 25,263 MWp. The solar energy output difference between the district with the smallest output (Centrum with 1,077 MWp) and the highest solar energy output (Noord with 4,470 MWp) was only 3,4 MWp. This difference will grow to 7,5 MWp by 2040 if the low growth rate of 5% is maintained. With a high growth rate of 14%, by 2040 this difference will grow to 75 MWp (see figure 9).

Furthermore, we see that the districts of Centrum and Westpoort, and to a lesser extent West, grow at a slower rate. Westpoort lags behind because this district largely houses the Amsterdam port and thus does not house many households. Because the Westpoort district only had 1,558 MWp installed in 2018, this district falls further behind when the growth stays constant over all the districts. Industry located in this area can choose to invest heavily in solar energy and construct large solar energy parks. This will decrease the difference or even overtake the solar energy output compared to other districts. However, the effectiveness of the V2H concept will be limited because the high energy demand of these industries will consume most of the solar energy during the day. The Centrum district also stays behind. This district's characteristics will likely prevent it from developing to a district with large a solar energy output. This district houses multiple historic buildings where solar panels are less likely to be installed onto. Therefore, this district will most likely produce less solar energy than other Amsterdam districts.

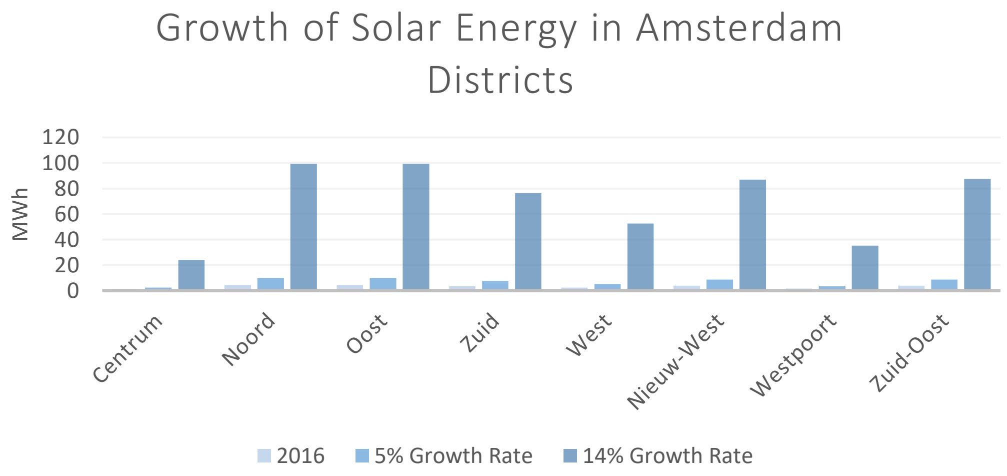

Figure 9, Solar energy output growth rate in Amsterdam districts, 2018 - 2040

3.3.2 Districts Surrounding Amsterdam

The districts surrounding Amsterdam have a combined installment of 15,1 MWp of solar energy. In 2018, the cumulative difference between the district with the lowest (Badhoevedorp with 0,43 MWp) and the highest (Purmerend-Volendam with 4,75 MWp) solar energy output is 4,32 MWp. This difference will grow to 9,5 MWp by 2040 in the low growth scenario and to 95 MWp in the high growth scenario (see figure 10).

Prumerend-Volendam sees the highest increase in solar energy output. It grows from 4,75 MWp in 2016 to 105,5 MWp of solar energy by 2040. The main reason for this high cumulative growth is the fact that the estimated solar energy output of this district is linked to the solar energy output of district Zuid-Oost. These districts have similar average income levels and the solar energy output is therefore, relative to the number of inhabitants, the same as for district Zuid-Oost. Furthermore, we see that the districts Diemen and Badhoevedorp will grow from respectively, 0,46 MWp and 0,43 MWp in 2016, to 10,32 MWp and 9,72 MWp in the high growth scenario. This relatively small solar energy output is because these districts are small with only 10.000 (Diemen) to 12.500 (Badhoevedorp) inhabitants.

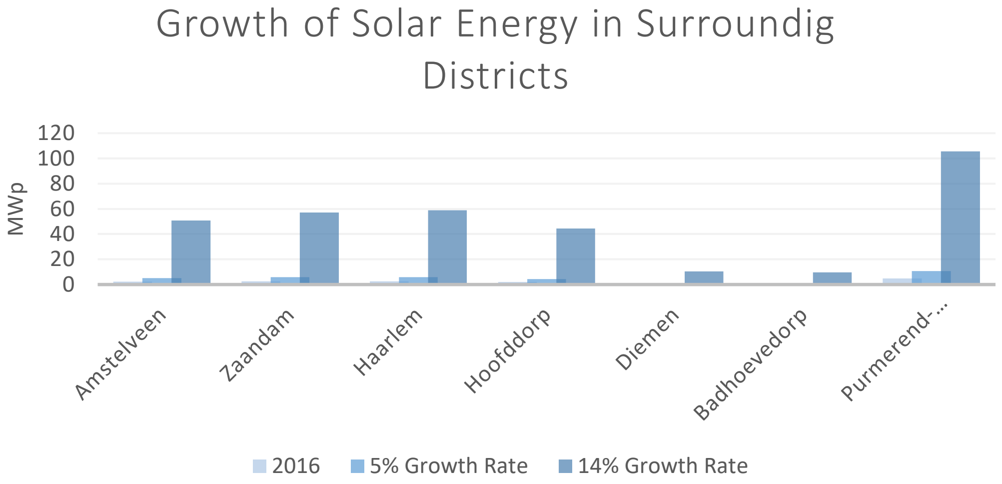

Figure 10, Solar energy output growth rate in surrounding districts, 2018 – 2040

3.3.3 Sensitivity Analysis

The growth in solar energy is set to a constant yearly rate. This means that each year the solar energy output grows with a larger number. This also means that higher growth rates result in higher differences between the solar energy output of districts. Within the Amsterdam municipality we see Centrum, West, and Westpoort stay behind a bit (see figure 11). Higher growth rates within the districts surrounding Amsterdam result that Purmerend-Volendam's solar energy output will increase the highest (see figure 12). At the same time, Diemen and Badhoevedorp's solar energy output will be relatively lower with a higher growth rate.

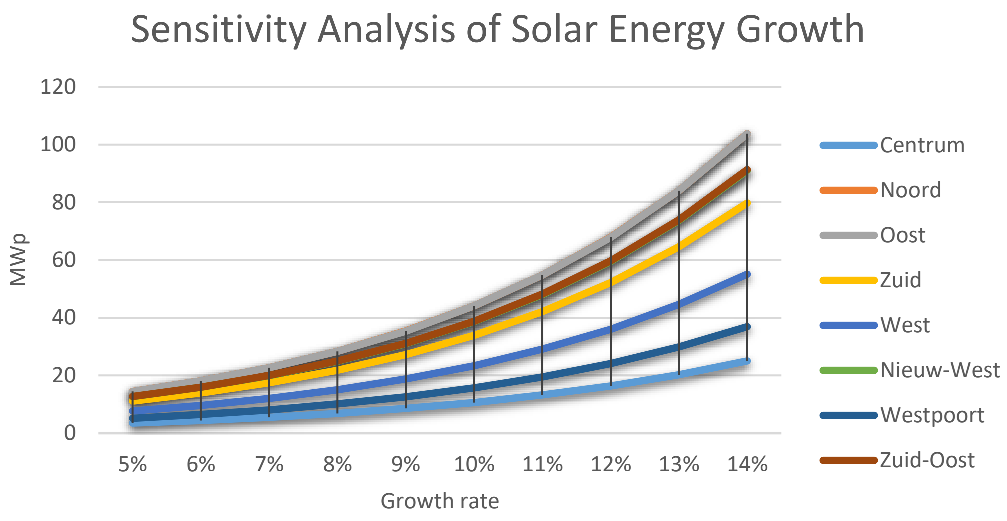

Figure 11, Sensitivity analysis of solar growth rate in Amsterdam districts

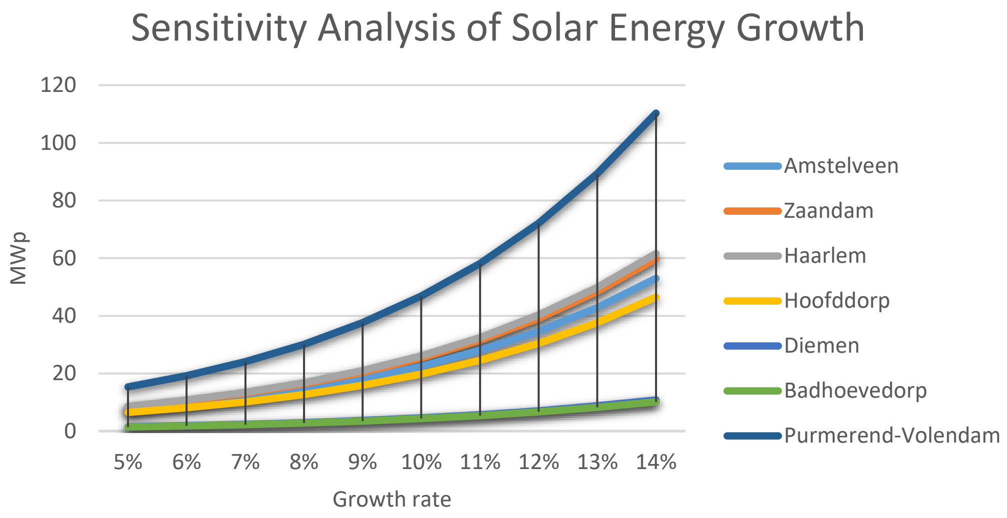

Figure 12, Sensitivity analysis of solar growth rate in surrounding districts

3.4 CONCLUSION

The dataset provided by the municipality of Amsterdam shows that the production of decentralized solar energy is distributed unevenly over Amsterdam and the surrounding districts (see figure 13). The growth scenarios will result in an increase in this uneven distribution. This is true for districts within the Amsterdam municipality boundaries as well as districts outside the Amsterdam municipality boundaries. The districts of Amsterdam will have a higher combined solar output than the districts surrounding Amsterdam. In the lowest growth rate scenario, Amsterdam districts will have a combined solar energy output of almost 100 MWp, where the surrounding districts will produce around 55 MWp combined. The high growth rate scenario will see a solar energy output for Amsterdam districts of almost 600 MWp, where the surrounding districts produce a combined solar energy output of around 350 MWp. These potentially high future differences in solar energy output can greatly impact the effectiveness of the V2H concept.

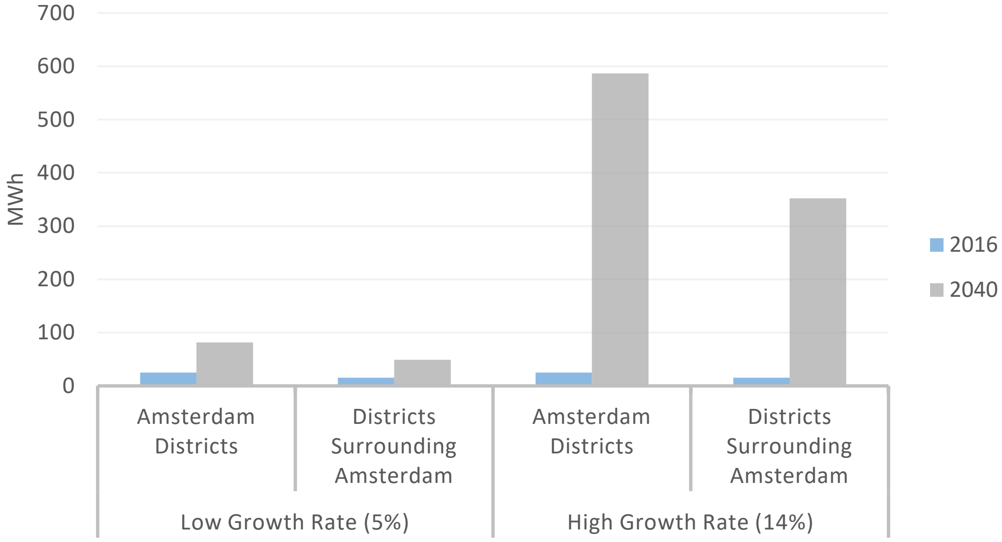

Figure 13, Total solar energy output growth

4 THE FUTURE OF EVs IN AMSTERDAM

This chapter will first describe the development of EVs (section 4.1). Afterwards the current adoption rate of EVs in Amsterdam is researched (section 4.2). From this starting point, the scenario analysis is constructed (see section 4.3). These scenarios are later used as inputs in calculating the cost-effectiveness of the cases (see chapter 6). Further information considering the scenario analysis can be found in appendix A.3.

4.1 INTRODUCTION

By 1925, the hay days of the electric car in the 20th century, many thousands of electrically propelled vehicles drove around the Netherlands (Buteijn, 2018). However, rapid developments of combustion engines led to a dip in commercial electric-powered vehicles in the 20th century. Fortunately, in the 21th century, the electrically powered vehicles re-enter the commercial market. The sales of plug-in hybrids and fully electric vehicles have grown exponentially. Especially the sales of full EV sales. In 2010 only 22 full EV were registered in Amsterdam. This number has grown with 227% to 5014 in 2017 (Gemeente Amsterdam, 2018a). Hybrids have seen the same rapid growth a few years earlier. Currently, their growth is slowly being replaced by the growth in full EVs. The recent rapid development of full EVs is a direct result of the technological improvements in EV technology. Research has shown that the predominant and decisive factors for consumers are range of EV per battery charge, battery degradation rate, the availability of charging stations, and price (Liao, Molin & Van Wee, 2017; Coffman, Bernstein & Wee, 2015). The most recent EVs, such as the Tesla Model S, Jaguar I-Pace, and Nissan Leaf, achieve a driving range of 350+ kilometres (Elektrische Voertuigen Database, 2019). Especially the range per battery charge improved a lot over the recent years and is likely to continue in the upcoming years (Diouf & Pode, 2014). Also, the average price for an EV has dropped and became available to many middle- to high income families.

The Dutch government sees the transition from traditional fossil fuelled cars to EVs as a mean to achieve its climate goals (Social-Economische Raad, 2018). It encourages people to purchase an EV by lowering taxation on retail price, as well as lowering road taxes for EV owners. These financial stimulants, together with the improved technical performances, has led to growth in popularity of EVs. The municipality of Amsterdam also tries to help transition to sustainable transportation by installing public charging stations. The number of EVs is therefore likely to grow exponentially. This thesis uses growth rates from governmental reports which predict the adoption of EVs in the Dutch society (see section 4.3).

4.2 THE CURRENT STATE OF EVs

This section will explore the current number of EVs registered per district in Amsterdam and the surrounding districts. The number of EVs per district is curial in calculating the effectiveness of the V2H technology. The effectiveness largely depends on the availability of EVs per district in order to store the surplus solar energy in the battery packs of the EVs (Liu, Chau, Wu & Gao, 2013). Accumulations of EVs in certain districts can therefore have a profound effect on the effectiveness of V2H technology. The current number of EVs per district is estimated with the number of public charging stations. The grow scenarios are estimated with the help of future scenarios constructed by the Planbureau voor de Leefomgeving (PBL) and Ecofys (Nijland, Hoen, Snellen & Zondag, 2012; Cuijpers, et al., 2016).

4.2.1 Public Charging Stations

Car registration in the Netherlands is done by the Dienst Wegverkeer, formerly known as the Rijkstdienst Wegverkeer (RDW). This institution registers all the cars in the Netherlands. Unfortunately, this data is privacy sensitive information. What is known, are the data about the location of all the public charging stations in The Netherlands. The number of EVs per neighbourhood can be deducted from the number of public charging stations per neighbourhood (Frade, Ribeiro, Goncalves & Antunas, 2011). The number of public charging station (PCS) is documented and listed at www.chargemap.com. This website is a maintained by public users (see table 7). Therefore, mistakes in the data can exist.

Table 7, Public charging stations per district

Region	Districts	PCS*
Amsterdam districts	Centrum	386
	Nieuw-West	327
	Noord	240
	Oost	426
	West	406
	Westpoort	6
	Zuid	752
	Zuid-Oost	112
Surrounding districts	Amstelveen	162
	Badhoevedorp	30
	Diemen	24
	Hoofddorp	69
	Purmerend-Volendam	51
	Zaanstad	36

*Source: www.chargemap.com, 2018

The total number of EVs registered in Amsterdam is known. These are divided over the districts in the next sections. The number of EVs per district is relative to the number of public charging stations (PCS_i) and over the total number of public charging stations (PCS_{total}), times the total number of EVs (see equation 4-1).

(4-1)

$$EV_i = EV_{total} * \frac{PCS_i}{PCS_{total}}$$

4.2.2 EVs distribution over districts

Where the number of EVs in 2018 in the districts within the Amsterdam municipality are known, those of the surrounding districts are estimated. The municipality of Amsterdam documented the total number of EVs registered in the city (Gemeente Amsterdam, 2019). The estimations for the surrounding districts are done with the help of nationwide averages. EVs in use by residents but not officially registered in the Amsterdam districts, such as car-sharing plans and lease cars, are not taken into account.

Public Charging Stations

The number of public charging stations per district is used to divide the EVs over the districts. The total number of EVs in Amsterdam is 10256 in 2017. Of these 10256 EVs, 5014 are full EVs and 5242 are plug-in hybrids (Gemeente Amsterdam, 2018a). The number of EVs have seen a huge rise and will surpass the number of plug-in hybrids by 2018 (see appendix A.1) A literature study into the developments of hybrids, plug-in hybrids and full electric vehicles found that the sales numbers of hybrids and plug-in hybrids will likely be dwarfed by the full EV sales (Al-Alawi & Bradley, 2012). This thesis therefore only incorporates EVs.

The location and quantity of public charging stations is highly correlated with the number of registered EVs per district (Adepetu & Keshav, 2017). This correlation indicates that households in wealthy neighbourhoods have a relative high ownership of EVs. This thesis underlines this correlation. When we focus on Amsterdam, the districts of Zuid has the highest number of registered EVs (806) followed by the district Centrum (614) (see table 8). Not coincidently, these districts also have the highest average income of all the Amsterdam districts. The yearly average income of Zuid is 45.000 euro. Which is a little more than district Centrum, which has an average yearly income of 42.000 euro. This is significantly more than Amsterdam's average income of 36.800 euro per year (Gemeente Amsterdam, 2018b). Districts such as West, Noord and Nieuw-West, with a yearly average income of respectively, 33.000, 32.300 and 33.500 euro, have less EVs registered in their districts. One of Amsterdam poorest neighbourhoods, Zuid-Oost, with an average income of 29.100 euro per year only has 259 EVs. The district of Westpoort only has 3 EVs, but this is due to the fact that this is a mainly industrial area with only 2000 inhabitants. This explains the low number of EVs.

The number of EVs in surrounding districts is estimated with the help of public charging stations (see appendix A.2). According to these public charging stations, Amstelveen and Haarlem have the most EVs registered in their district with respectively, 1715 and 1111 EVs (see figure 14). The Haarlem district houses more than 150.000 inhabitants (see section 2.2.1). A large number of EVs can therefore be expected. A district comparable in size and average income to Haarlem is Zaanstad. Although this district has a high yearly average income of 34.700 euro, only 381 EVs are registered in this district. This low number is explained by the fact that Zaanstad only has 36 public charging station. The EV distribution formula (see section 4.2.1) thus allocates a small number of EVs to this district. A district with a relative high number of EV registration is Amstelveen, although this district is a relatively small district with only 88.000 inhabitants, the distribution formula allocates 1715 EVs to this district. The high number can then be explained by the relative high average yearly income of 42.100 euro. The district of Diemen and Badhoevedorp are both relatively small districts. Subsequently, these districts also have few registered EVs.

Table 8, Current EV distribution over districts

Region	District	Number of EVs (2018)
Amsterdam districts	Centrum	614
	Noord	482
	Oost	538
	Zuid	806
	West	566
	Nieuw-West	421
	Westpoort	3
	Zuid-Oost	259
Surrounding districts	Amstelveen	1715
	Zaanstad	381
	Haarlem	1111
	Hoofddorp	730
	Diemen	254
	Badhoevedorp	318
	Purmerend-Volendam	540

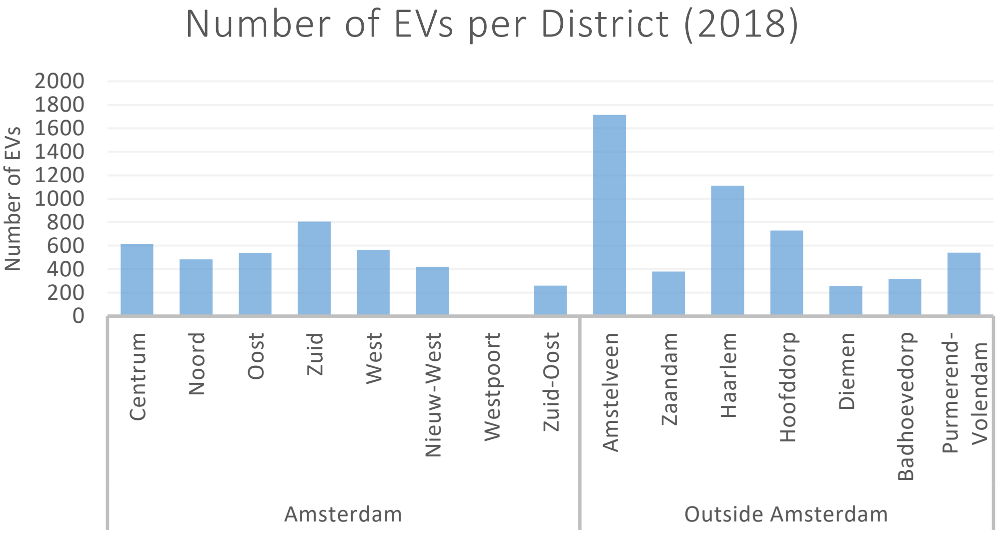

Figure 14, Current EV distribution over districts

4.2.3 Validating the EV data

Regionale Thermometer Mobiliteit from the Metropoolregio Amsterdam studied the modal splits of EVs and (plug-in) hybrids for the surrounding Amsterdam districts. The EVs, derived from this dataset is less than the number of EVs derived from the dataset from the municipality of Amsterdam (see table 9). However, because the Regionale Thermometer Mobilieit from the Metropoolregio was published in 2015 and the dataset from the municipality of Amsterdam was published in 2018, this difference is expected.

Table 9, Validating the EV distribution

Study	Organization	Number of EVs
Regionale Thermometer Mobiliteit (2015)	Metropoolregio Amsterdam	+/- 7.000
Amsterdamse Thermometer voor de Bereikbaarheid (2019)	Municipality of Amsterdam	+/- 10.000

4.3 SCENARIO ANALYSIS: EV

The Dutch automobile fleet has seen a high increase in electrically-propelled vehicles (CBS, 2019b). On 1ste of January, this has led to a complete electrically-propelled car fleet of 184.000 vehicles. The fully EVs and plug-in hybrids account for 1,6% of all the vehicles registered in the Netherlands. The EV market has completely changed the recent years. Since 2014, the plug-in hybrid was the most sold electric vehicle type in the Netherlands. However, since the government decreased the subsidizes for the plug-in hybrids in 2017, the sales have dropped drastically. In 2018, the total number of plug-in hybrids on the road in The Netherlands even decreased slightly (CBS, 2019b). Virtually all research expects that this popularity in EVs will continue to rise in the foreseeable future (Berckmans, 2017; Bloomberg, 2018; J.P. Morgan, 2018; Stanley Morgan, 2016; Cuijpers, et al., 2016).

As mentioned above, the scenario analysis uses growth expectancy rates found by two studies, both performed by a government institute. The first study focuses on the overall growth of the Dutch automobile fleet. A study performed by the Planbureau voor de Statistiek (PBL) explored two future reference scenarios, one high growth scenario, and one low growth scenario, for the Dutch society (Manders & Kool, 2015). This report found that the total car park in the Netherlands will grow between 34% and 10% by 2050. This thesis uses the average growth rate of the total car park. This is 17% by 2040 assuming linear growth.

The second study focusses on the growth of EVs specifically. A lot of research has been done on the adoption rate of EVs (see table 10). The result of these researches varies a lot. This high variance is mainly due to the difference in scope. On a global scale, two papers predict that around 30% of the total car park by 2030 is an EV (or PHEV) (Berckmans, 2017; Bloomberg, 2018). Research by Stanley Morgan shows that this number is more in the range of 15% (Stanley Morgan, 2016). J.P. Morgan explored the European market and predicts that 9% of the cars sold in Europe are EVs or PHEVs (J.P. Morgan, 2018). A study performed on the Dutch automotive market by Ecorys found a number that is significantly higher than the studies performed on a European or global scale. By 2035, Ecofys expects that the number of EVs in the Dutch car fleet is between 40 and 70% (Cuijpers, et al., 2016). This thesis focusses on implementing the V2H technology in the Amsterdam region and therefore uses the ratio of 40% EVs as a low growth scenario and 70% as a high growth rate scenario.

Table 10, Literature review on the growth rate of EV adoption

Organization	Scale	Year	Growth	Source
Free University of Brussels	Global	2030	31.9% of total fleet by 2030	Berckmans, (2017)
Bloomberg New Energy Finance	Global	2040	33% of total fleet by 2040	Bloomberg (2018)
J.P. Morgan	Europe	2025	9% of total sales by 2025	J.P. Morgan (2018)
Ecofys	Netherlands	2035	40 – 70 % of total fleet by 2035	Cuijpers, et al. (2016)
Stanley Morgan	Global	2050	15% by 2030 65% by 2040 80% by 2050	Stanley Morgan (2016)

4.3.1 Districts of Amsterdam

By 2040, the number of EVs in all the Amsterdam districts has grown from 10.256 in 2018 to 47.654 in the low growth scenario, and 84.163 in the high growth scenario by 2040 (see figure 15). The districts with the largest EV adoption are Zuid and Centrum. By 2040, the number of EVs in Zuid is almost twice the number of EVs in 2018. Centrum and Zuid are expected to have the highest number of EVs because these districts have the highest average income, with respectably, 42.100 and 45.500 euros per year. The districts Noord, Oost, West, and Nieuw-West are all estimated to have around 10.000 EVs in the high growth rate scenario by 2040. The district Oost has a significantly higher average income then Noord, West and Nieuw-West, with respectively 37.900 euros per year compared to an average income of 32.800 euros for the other districts. The current number of public charging stations can indicate that the characteristics of this neighbourhood, whether it is the proximity to the city centre, the car accessibility, or the number of jobs in this district, is the reason that the EV adoption of this district is behind Centrum and Zuid. This research does not explore these characteristics in detail. The district of Zuid-Oost is the Amsterdam district with the lowest EV adoption given the two scenarios. This district will accommodate between 3347 EVs in the low growth scenario and 5910 EVs in the high growth scenario. These low numbers are a direct result of the low average income of 29.100 euros per year in these districts.

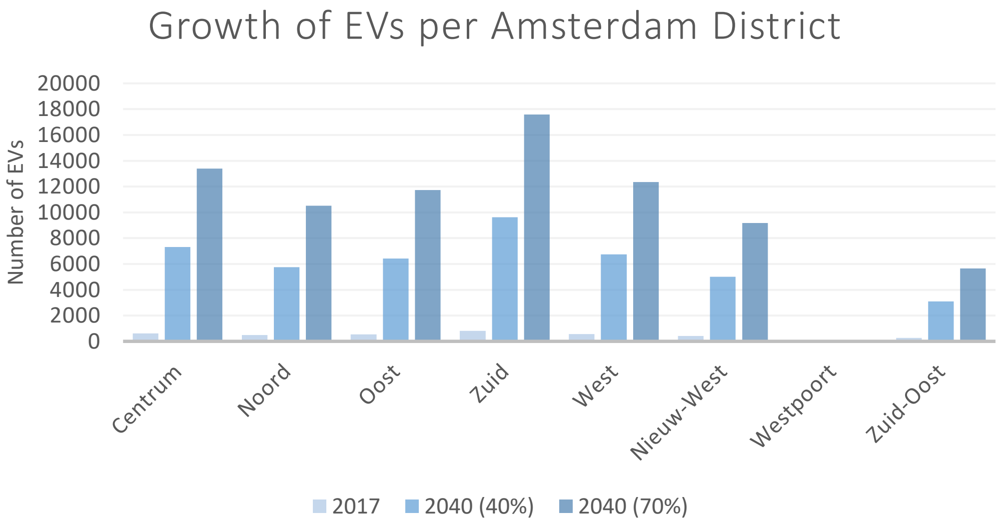

Figure 15, EV growth over Amsterdam districts

4.3.2 Districts Surrounding Amsterdam

Amstelveen is the district surrounding Amstelveen which will have the most EVs by 2040 (see figure 16). The number of EVs in this district will be between 47.604 in the low growth scenario and 83.865 in the high growth scenario. This number is extraordinarily high knowing that Amstelveen is only the fourth largest district (see section 2.2.1). Explanation for these high EV adoption numbers is the fact that Amstelveen is a wealthy suburb from Amsterdam and close to the financial district of Amsterdam. The district of Hoofddorp is about the same size as Amstelveen but is expected to have significantly fewer EVs. In Hoofddorp, about 50% fewer EVs will be registered compared to Amstelveen. Accountable for this high difference is the income gap. Where the average income in Amstelveen is 31.600 euros, Hoofddorp's average income is 29.700 euros. The large districts of Zaandam, Haarlem, and Purmerend-Volendam have a relatively low number of EVs registered in their district. Especially Zaandam and Purmerend-Volendam will likely have a relatively small EV fleet by 2040. Small districts of Diemen and Badhoevedorp are expected to have around 10.000 EVs, which is expected since these two districts are the smallest of the surrounding districts.

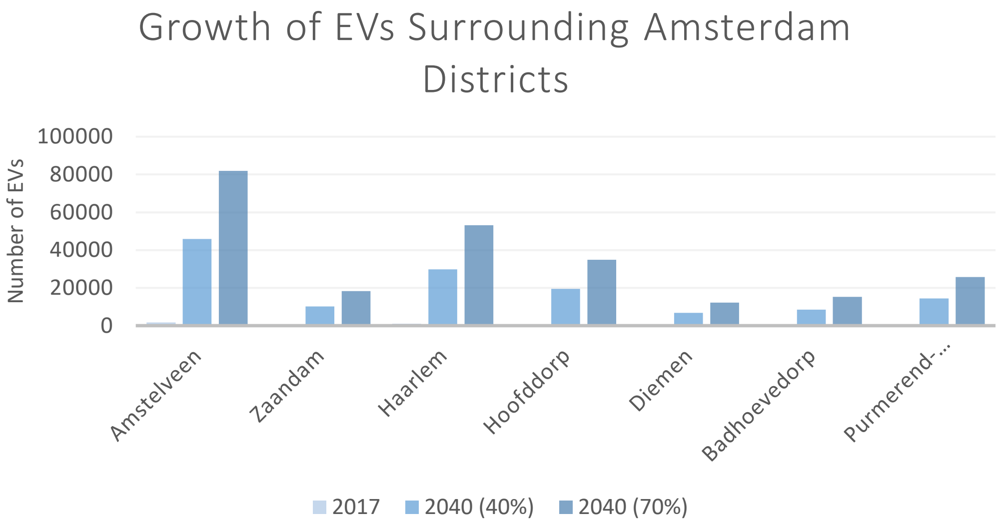

Figure 16, EV growth over surrounding districts

4.4 CONCLUSION

The scenario analysis of the growth of EVs in the districts shows that the uneven distribution of EVs will grow in the future. This uneven distribution can have a negative effect on the effectiveness of V2H. In the districts Zuid, Amstelveen, Haarlem, and to a lesser extent Centrum, potentially have a lot of storage capacity available to store the surplus of decentralized solar energy. The districts Diemen, Badhoevedorp, Purmerend-Volendam, Zaandam, and Zuid-Oost potentially don't have a lot of storage capacity available. The districts with a lot of EVs (and thus a lot of storage capacity) are, in general, the districts which have the highest average income. The opposite effect also exists. Districts without a lot of EVs are the districts with a lower average income. The scenario analysis constructed in section 4.3 is thus in line with the findings of Adeptu & Keshav (2017) which conclude that there is a high correlation between wealth and owning an EV.

This uneven distribution between the districts already exists in 2018. This distribution continues to grow and becomes more uneven by 2040 (see figure 17). The difference between the district with the highest (Amstelveen) and with the lowest (Diemen) EVs in 2018 is 1.461 (excluding Westpoort). This difference has grown to 40.552 in the low growth scenario and 71.287 in the high growth scenario. This gap is 27 times larger than the gap in 2018 (see table 11). This huge gap can negatively impact the effectiveness of V2H because the storage capacity also differs a lot due to this gap.

Table 11, Total growth of EVs in scenarios

Region	District	Number of EVs (2018)	Number of EVs (Low,2040)	Number of EVs (High 2040)
Amsterdam	Centrum	614	7.933	14.011
	Noord	482	6.230	11.003
	Oost	538	6.950	12.274
	Zuid	806	10.419	18.401
	West	566	7.310	12.910
	Nieuw-West	421	5.435	9.599
	Westpoort	3	31	55
	Zuid-Oost	259	3.347	5.910
Surrounding Amsterdam	Amstelveen	1715	47.604	83.685
	Zaanstad	381	10.579	18.597
	Haarlem	1111	30.854	54.240
	Hoofddorp	730	20.276	35.643
	Diemen	254	7.052	12.398
	Badhoevedorp	318	8.815	15.497
	Purmerend-Volendam	540	14.987	26.345

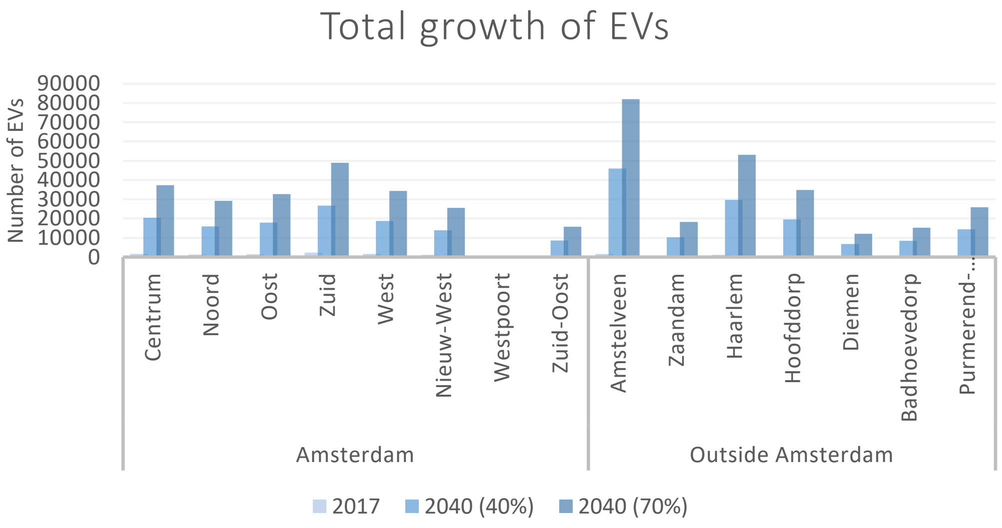

Figure 17, Total growth of EVs in scenarios

5 COMMUTING TRENDS

This chapter will first describe the potential impacts and implications of commuting trends on the effectiveness of V2H (section 5.1). Afterwards the calculations and sources for constructing the origin-destination matrices are explained (section 5.2). The results from these matrices are explained in the next section (see section 5.3). These commuting trends, together with the scenarios (chapter 3 and 4) are used as inputs in calculating the cost-effectiveness of the cases (see chapter 6). Further information considering calculations and assumptions of the origin-destination matrices can be found in appendix A.4.

5.1 INTRODUCTION

As mentioned in the problem definition, the literature into the V2G and V2H concepts do not focus on the effects of commuting trends on the effectiveness of V2G/V2H. Most papers that investigate the effects of V2G on the electricity grid only have two perspectives. They either use a detailed view on the V2G/V2H technology itself or they use an aggregated view (which this thesis also has) and research the potential effects of V2G/V2H. The latter researches assume that a bi-directional electricity system or they do not incorporate the mobility of EVs battery packs (Richardson, 2013). The literature into the effects of moving storage components (EVs) on the effectiveness of V2H is limited. However, a few papers do add to their discussions that commuting trends can have a profound influence on the V2H concept and the electricity infrastructure (Littler, Zhou & Wang, 2013; Green, Wang & Alam, 2011; Richardson, 2013).

Virtually all papers into the V2G/V2H concept identified that the battery packs in EVs can be utilized to store energy coming from decentralized energy production. Littler, Zhou & Wang (2013) identified that the commuting trends within a region with V2H can impact the effectiveness of V2H. This is especially relevant in the early adoption years of the technology, where not every household is in possession of (1) solar panels (or any other intermittent energy source) or (2) an EV (or PHEV). As Adepetu & Keshav (2017) identified, due to the initial high price for an EV, the first adopters of EVs are primarily pretty wealthy households. The same holds true for the instalment of solar panels (Borenstein, 2017). This creates a mismatch between the allocation of both EVs and solar panels between wealthy neighbourhoods and poor neighbourhoods. Commuting trends of EVs affect the V2H in such a way that as a result of a commute to work, the surplus solar energy of solar panels installed cannot be stored in an EV since this commute has left the building without storage capacity (see figure 18).

The distribution of solar panels and EVs is unevenly distributed over the districts now, and in the future (see section 3.3 and 4.3). Districts with a high ratio of households and a low ratio of jobs (and vice versa) can affect the uneven distribution which in its place can impact V2H in a positive or negative way. The commuting trends could reverse the effects of the uneven solar energy distribution if these solar panels are located in districts where many EVs commute to. This affects the uneven distribution, and thus V2H in a positive way. However, the commuting trends can also increase the uneven distribution of solar panels if the commutes from EVs lead mainly to districts without a lot of solar energy output. This can be seen as a negative effect and thus decrease the effectiveness of V2H.

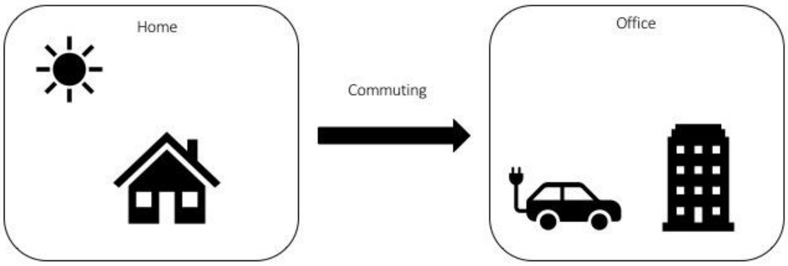

Figure 18, Commuting trends

5.2 COMMUTING TRENDS CALCULATIONS

The commuting trends are calculated with the help of several data/information sources. These data sources contain the origin-destination data of traffic between the Amsterdam districts, between surrounding districts themselves, and between the Amsterdam and surrounding districts (Gemeente Amsterdam, 2019; Vervoerregio Amsterdam, 2017). Furthermore, the open data source (Statline) from the Dutch Central Statistics Office (CBS) is used for district specific information such as the number of inhabitants per district and the number of jobs per districts (see appendix A.1). The information in these datasets is then used to estimate the number of cars which commute between districts.

5.2.1 Input

The data source which contained the data about the traffic between the surrounding district and Amsterdam is highly aggregated. See appendix A.3 for the original data sources and further assumptions. This data source combined all the traffic to the 7 Amsterdam districts into one data point. Also, all the districts north of Amsterdam were combined, as well as all districts south of Amsterdam were combined (see table 13). This aggregated dataset with a low level of detail is transformed to a dataset with a high level of detail. This transformation is done with the help of the district specific characteristics: *inhabitants*, *number of jobs*, and *modal split*. The modal split indicates the ratio of people who take the car for their commute. By multiplying this modal split ratio with the total workforce per district we find the number of cars which leave the district.

The aggregated traffic data is divided over all the districts with respect to the size of the inhabitants and number of jobs of each district (see table 12). In this table we can see that in the district Centrum 7153 people take the car for their working commute. This is a relative low number, compared with the number of inhabitants but this can be explained by the low modal split ratio for cars.

Table 12, District characteristics used in estimating the commuting trends

Region	District	Inhabitants	Work force	Number of Jobs	Jobs (%)	Modal Split (%)	Modal Split
Amster-dam Region	Centrum	86.400	44707	102.598	19	16	7153
	Noord	91.300	47242	32.316	6	50	23621
	West	142.800	73891	48.402	9	13	9606
	Nieuw-West	146.800	75960	76.718	14	43	32663
	Oost	128.700	66595	62.622	12	25	16649
	Westpoort	2.000	1034	21.920	4	50	517
	Zuid-Oost	84.600	43776	76.770	15	33	14446
	Zuid	141.400	73166	105.642	20	25	18292
	Diemen	10.000	5174	22.100	4	33	1708
	Total Amsterdam				1		
Zuid Region	Amstelveen	88.600	45845	43.300	26	43	19714
	Haarlem	159.700	82635	66.300	40	43	35533
	Badhoevedorp	12.600	6520	7776	5	43	2804
	Hoofddorp	75.000	38808	46285,71	28	43	16688
	Total Zuid				1		
Noord Region	Zaanstad	155.000	80203	52.800	66	43	34488
	Purmerend-Volendam	102.200	52883	27.700	34	43	22740
	Total Noord				1		

Table 13, Commuting trends in percentages between aggregated districts

District	Zuid	Noord	Amsterdam
Zuid	0,46	0,03	0,08
Noord	0,03	0,66	0,04
Amsterdam	0,20	0,13	0,63
Other	0,32	0,18	0,25
Total	1	1	1

5.2.2 Calculations

The number of commutes from District *i* to district *j* is calculated by the number of commutes (C) from a district *I* times the percentage of jobs over all the districts *j*. Where the districts are: Zuid, Noord, and Amsterdam. The origin-destination matrix ($OD_{i,j}$) is in commutes per day.

(5-1)

$$OD_{i,j} = C_i * Jobs_j$$

The number of commutes (C) is calculated by number of people within a district that commute by car (ModalSplit) and times the origin destination (OD) of the districts Zuid, Noord, and Amsterdam.

(5-2)

$$C_i = ModalSplit_{car,i} * OD_i$$

See appendix A.3 for the complete constructed OD matrix. Afterwards the number of commutes in the OD matrix is transformed to percentages. These percentages are then multiplied by the number of EVs per district (see section 4.3).

(5-3)

$$EV_{i,j} = OD_{\%} * EV_i$$

5.3 COMMUTING TRENDS

The districts of Zaandam has the most car commuters leaving the district. This district is in size comparable to Haarlem, Zuid, Nieuw-West, and West but has significantly fewer commuters arriving in the district. Also, the district Centrum sees a high number of car commuters arriving in the district (see figure 19). However, this might be an overestimate since this district is not easily accessible by car. This offset is because the modal split data is focused on the mode of choice of the inhabitants living in the districts and not on the mode of choice or workers arriving in districts.

The districts of Badhoevedorp, Diemen, and Westpoort see a very low number of car commuters arriving in these districts. In the case of Diemen and Badhoevedorp, these low numbers can be explained by the fact that these districts do not have many workplaces. The district of Westpoort does not have many arriving commuters with these distribution calculations. Although this district is expected to have more arriving cars due to the fact this is a predominantly industrial area, the number of jobs in this area is not significantly high.

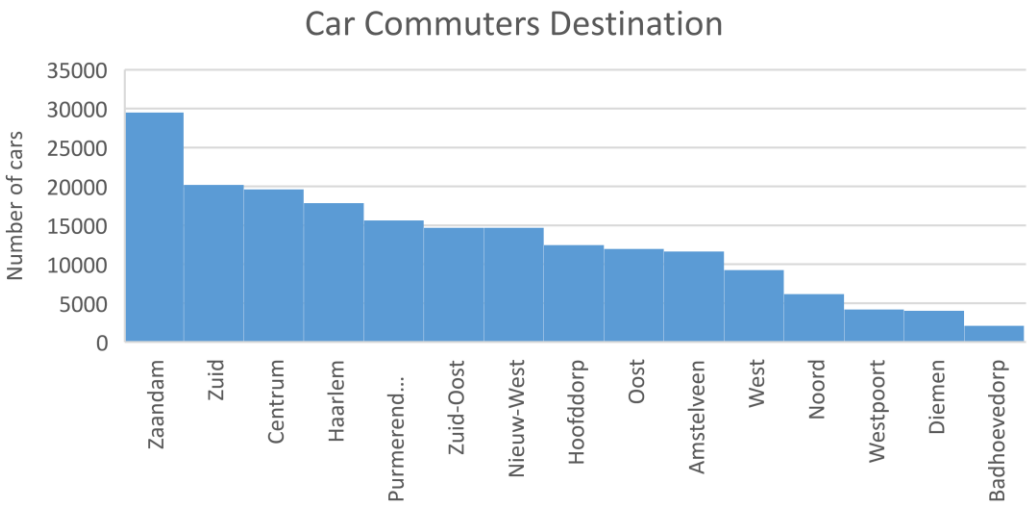

Figure 19, Destination of car commuters per district

Again, the district of Zaandam is the largest when we look at the number of car commuters leaving the districts (see figure 20). We see that the predominantly large districts also have the highest number of car commuters leaving the district. The districts of Zaandam, Nieuw-West, and Haarlem are all districts with many inhabitants and therefore have many car commuters leaving the district. The district of Noord is a smaller district but has many car commuters leaving the district. This can be explained by the fact that this district, relative to the other Amsterdam districts, is fairly accessible by car. Again, the districts of Diemen and Badhoevedorp are the districts with the lowest number of commuters. Because these districts are relatively small, the number of car commuters leaving this district is also among the lowest. The district of Westpoort shows less than 400 car commuters which leave the district. This is by far the lowest of all districts.

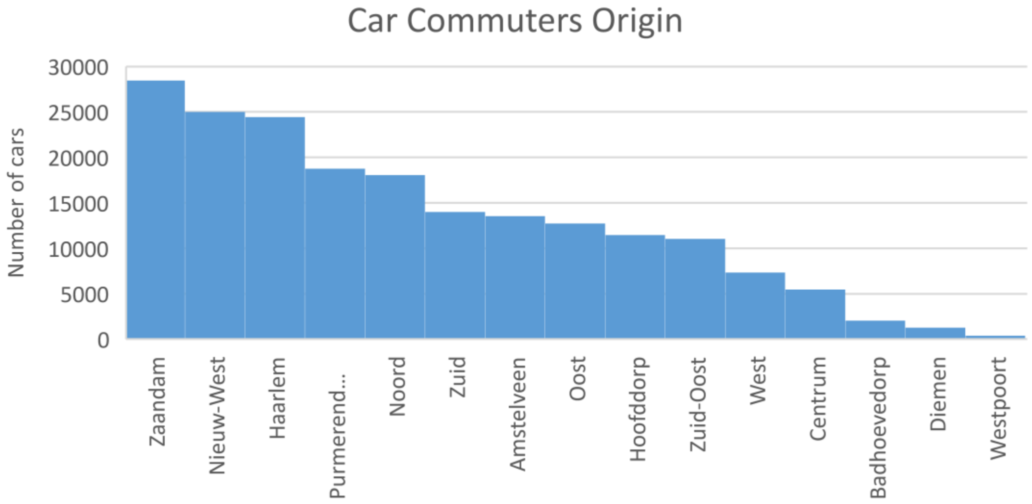

Figure 20, Origins of car commuters per district

When overlapping the data of the car commuter, we see that 8 districts see more car commuters arrive than leave, and 6 districts where the opposite happens (see figure 21). The districts where more car commuters arrive than leave are Centrum, West, Westpoort, Zuid-Oost, Zuid, Hoofddorp, Zaandam, and Diemen. The high arrival rate of car consumers in Centrum probably does not accord completely with the actual car arrivals in this district. The traffic commute calculations divides all the traffic over the districts with the help of the number of jobs and the number of inhabitants. With this reasoning, the district Centrum, which has a lot of jobs should also see a lot of car commuters. However, this district is not easily accessible by car. The distribution method did not take into account other factors which may affect the number of car commuters to a specific district. The high deviation of this districts car commuter data means that the effectiveness of V2H for this district is probably not realistic.

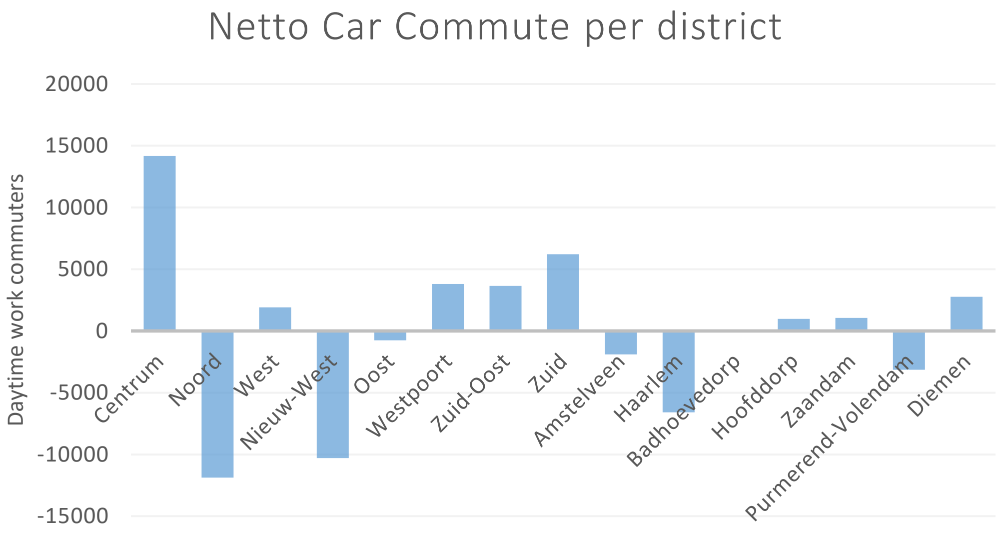

Figure 21, Net car commute per district

5.3.1 EV Commuting Scenarios

The commuting data of all car traffic is used to estimate the number of EVs departing and arriving in the districts (see figure 22). The number of EVs daytime departing and arriving gives insights into the possible storage capacity of these districts during the day and during the night. By 2040, the number of EVs leaving Amstelveen is between 25.000 (low growth scenario) and 50.000 (high growth scenario). This district sees the largest number of EVs departing for the daytime commute. The growth scenarios show that a high growth scenario can almost double the number of EVs leaving the district, compared to the low growth scenario. The districts Centrum, Nieuw-West, Zuid-Oost, and Zaanstad see more EVs arriving than leaving the districts during the daytime. The offset in the number of EVs arriving in the district Centrum is reduced by the fact that this district does not have many EVs registered to its district.

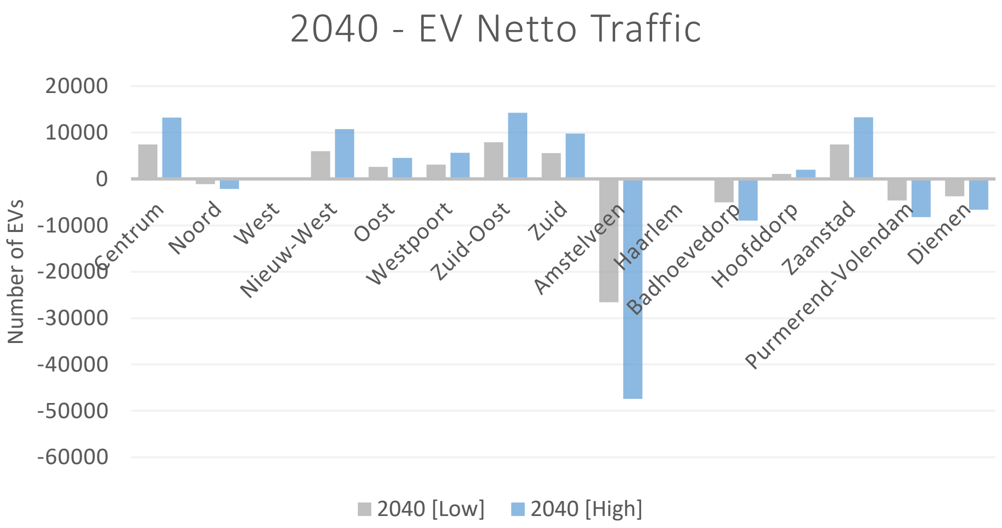

Figure 22, Net EV commute per district by 2040

5.4 CONCLUSION

The commuter traffic is used for estimating the number of EVs in 2018 and the two growth scenarios constructed in the scenario analysis (section 5.3). The commuting data shows that the district of Amstelveen will see a high number of EVs leaving the district. This indicates that this district is a mainly residential area, but this also means that during the day this district loses a lot of its potential storage capacity for surplus solar energy. The districts of Haarlem, Badhoevedorp, Purmerend-Volendam, and Diemen also see their potential daytime storage capacity decrease because the EVs registered in these districts are used for the daily commute. Also, the fact that these districts do not have many jobs results in the fact that not many EVs commute to these districts.

The district with the highest number of EVs present during the daytime is Haarlem (see figure 23). The number of EVs is between 30.000 in the low growth scenario and more than 50.000 is the high growth scenario. Thus, this district potentially has an enormous storage capacity. The districts of Centrum, Zuid, Amstelveen, Hoofddorp, and Zaanstad all have between the 15.000 and 35.000 EVs present during the daytime depending on the scenario. These districts thus have the potential to store surplus solar energy produced during the day. The districts without a lot of storage potential are Westpoort, Badhoevedorp, and Diemen. These districts have around 5000 EVs present in their district during the daytime. These districts do not have a lot of potential storage capacity and thus an fairly uneven distribution of EVs is found. The commuting trends, together with the scenario analysis of EVs and solar panels, can now be used to determine the spatial match or mismatch. In the next chapter this will be used to determine the cost-effectiveness of the V2H concept in the Amsterdam region.

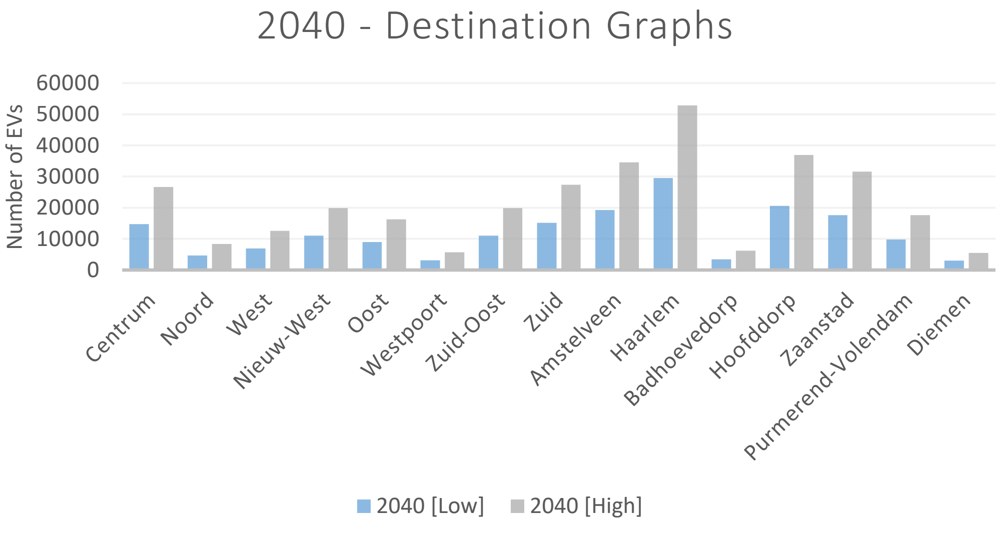

Figure 23, Destination of EVs per district by 2040

6 CASES

This chapter will first describe the potential of the storage capacity of EVs in the specified districts under the spatial distribution settings constructed in the growth scenarios (section 6.1). Then the cost-effectiveness of the first case, upgrading the grid the traditional way, is calculated (section 6.2). The next section calculates the cost-effectiveness of the V2H case, again under the spatial distribution (see section 6.3). Afterwards a new case, which decreases the negative effects of the spatial distributions of solar panels and EVs is proposed (see section 6.4). Further information considering the cost-effectiveness calculations and assumptions can be found in appendix B-D.

6.1 INTRODUCTION

The previous chapters have identified the spatial distributions of solar panels and EVs. The amount of solar energy output coming from the solar panels is not evenly distributed over the districts (see section 3.3). The EV fleet is also not evenly distributed over the districts, where the EV commuting trends further increase this uneven distribution (see section 4.3 and 5.3). These spatial distribution are important factors in assessing the effectiveness of the V2H concept. This thesis calculates the effectiveness by assessing (1) how much surplus solar energy can be stored in EVs and (2) how much electricity can in theory be returned to the buildings to supply for the night time electricity demand (see section 2.4). The first factor requires to match the spatial distributions of solar panels and EVs. The second factor requires to match the spatial distribution of EVs to the household night time electricity demand of each district.

Before calculating the cost-effectiveness of the V2H concept, this thesis first calculates the costs accompanied by upgrading the electricity system in the traditional way. Investing in transformers and cables will accommodate for the growth in decentralized solar. Afman & Rooijers (2018) found that although the consumer price for a kWh will remain roughly the same, the network costs to facilitate this transition to renewable (decentralized) energy production will result in high investment costs. The most expensive scenario in Afman & Rooijers (2018) study is the scenario where decentralized electricity production is the preferred electricity production choice. Currently, the network costs are around 30 billion euro per year to operate and maintain. This will rise, depending on the decentralized production scenario, to roughly 50 – 60 billion euro per year. Other scenarios show a slightly lower total investment cost. The upgrading of transformers in the electricity network is the main reason for these high investment costs. This thesis calculates these investment costs for the Amsterdam region (see section 3.4).

Knowing the costs for upgrading the network in the traditional manner help put the costs for the V2H concept in perspective. V2H is identified as a concept that can potentially prevent parts of these investment costs (see section 2.3). The potential storage capacity of EVs (and plug-in hybrids) is huge, knowing that they are only utilized 4% of the time (Kempton & Tomic, 2005; Ma, Houghton, Cruden & Infield, 2012). Research in Germany found that, as early as 2020, Germany expects to have 1 million EVs driving around on the German autobahn. These vehicles have an aggregated potential storage capacity of 25,3 TWh of energy, roughly the size of Scotland's 5-yearly energy demand (Fournier, Haugrund & Terporten, 2009). This storage capacity enables the V2GH concept to support the electricity demand of a typical building (Pang, Dutta & Kezunovic, 2011). The EVs in the districts in and around Amsterdam have the same potential. In every district, except for Zuid-Oost, the storage capacity of EVs exceeds the solar energy output of these districts (see figure 24). Thus, in theory, every kWh of decentralized solar energy produced during the day can be stored in EVs. However, previous analysis of solar panels and EVs have shown that the distribution of, particularly EVs, is not evenly spread out over the districts. This uneven distribution will likely grow which will result in the accumulation of solar panels and EVs in certain districts (see chapter 3 and 4). The skewed distributions of both EVs and solar panels are used to calculate the cost-effectiveness of the V2H concept.

Furthermore, this thesis will construct a new case in which the previously mentioned cases are combined. Again, this combination is aimed at decreasing the negative effects of the spatial distribution found in the scenario analysis. To calculate this new case, the same scenario inputs and components are used. This new case will try to increase the overall cost-effectiveness by investing in several network links to increase the potential of the V2H concept (see section 3.4). This new case can lie the basis for a smooth transition to implementing the V2H concept in the Amsterdam case study (see section 7.6).

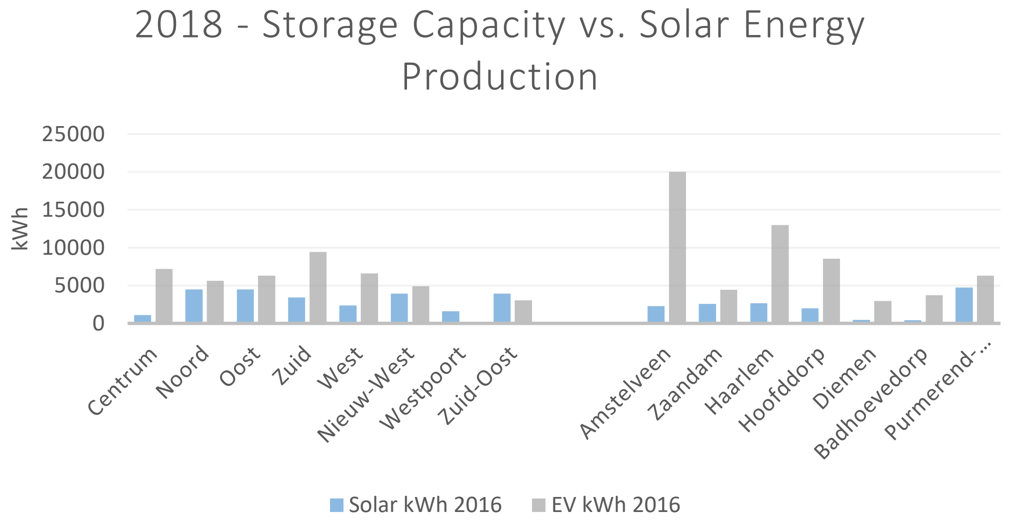

Figure 24, Storage capacity vs. Solar energy output per district

6.2 SYSTEM COMPONENTS

The two cases subjected to the cost-benefit analysis consist of multiple components. Both the V2H cases, as well as the traditional upgrading approach have similar electricity infrastructure components. These are called the grid components. The grid components, transformers and cables are identified both by Liander (2018) and Verzijlbergh (2013). The V2H components, the battery storage system and the bi-directional chargers, are only occurring in the V2H concept. These components are identified by Verzijlberg (2013) and Salet (2018). The system components are:

Grid components:
Transformers:

- HV/MV (High-Voltage / Medium-Voltage): these transformers ‘transform’ the power from high voltage (50 kV) coming from the transmission grid to medium voltage (10 kV) which can be distributed in the medium voltage distribution grid.
- MV/LV (Medium-Voltage / Low-Voltage): these transformers ‘transform’ the power from medium voltage (10 kV) coming from the transmission grid to medium voltage (1,5 kV) which can be distributed in the low voltage distribution grid.

Cables:

- Medium Voltage: These cables transport the medium voltage electricity over the network.
- Low Voltage: These cables transport the low voltage electricity over the network.

V2H components:

Battery storage system:

- State-Of-Charge (SOC): The SOC represents the percentage of electricity in the battery pack of an EV.
- Minimum SOC: The minimum SOC represents the percentage of electricity which cannot be discharged from the EVs battery pack.

Bi-directional chargers:

- Public bi-directional chargers: These chargers are installed in the public space and exploited by public, private or public/private organizations.
- Private bi-directional chargers: These chargers are the chargers which are installed privately, usually in homes of EV owners.

6.3 COMPONENT COSTS

Both cases partially use the same system components. The components in case I are transformers (HV/MV and MV/LV) and cables. These components are also used in case II, in addition to investments costs in bi-directional chargers and transportation costs. These component costs are derived from the literature or are estimated by similar known components costs (see table 14). The costs for a bi-directional charger (BDC) is estimated to be 5000 euro per charger. Currently, a bi-directional charger costs around 10.000 euro (Plötz, Gnann, Kühn & Wietschel, 2013). This price is expected to drop to 3422 euro by 2050 (Grube, Linke, Xu, Robinios, Stolten, 2013). This thesis uses 5.000 euro per bi-directional charger since it only looks to the year 2040.

Table 14, Component costs

Component	IC_i	OM_i [%/year]	LT[2] [years]	Source
HV/MV Transformer	1.200.000	15%	40	Verzijlbergh (2013)
MV/LV Transformer	25.000	15%	40	Verzijlberg (2013) (Klein Entink, 2017)
MV-cables	60 € / meter	3%	40	Verzijlbergh (2013)
Bi-directional charger (BDC)	5.000 € / 2-point bi-directional charger	15%	10 years	Plötz, et al. (2013) Graube, et al. (2013)
Transportation costs	20 €/MWh	-	-	(Grave, et al., 2016)

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[2] Life cycle years are derived from: Net voor de Toekomst (Afman & Rooijers, 2018)

6.4 CASE I: UPGRADING THE POWER GRID

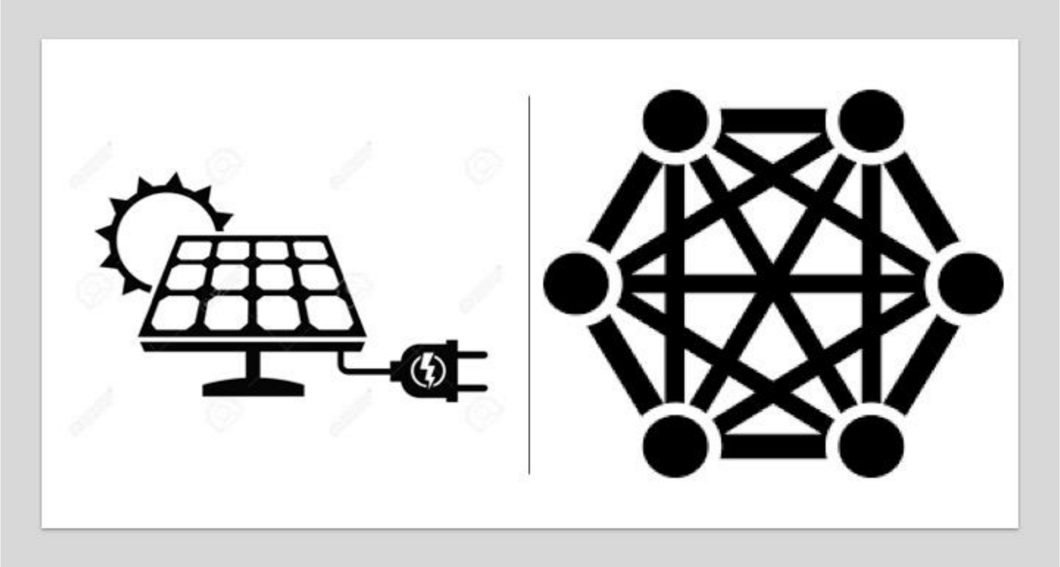

Figure 25, Case I: Power grid and solar panels

The power grid is responsible for the transportation of electricity (see figure 25). In this case, the electricity grid is the only source of electricity for the household sector. This means that the household electricity demand is supplied completely from grid electricity. Also, the surplus solar energy produced during the day is put back into the grid. This requires the electricity to be transported over the network to make sure that the demand is matches with the supply. Unfortunately, the future solar energy output will exceed the capacity limits of the current Amsterdam electricity infrastructure (see section 2.2).

This case requires to change the main design principle of the current electricity network which originates from the 1960s (Weterings, et al., 2013). During these years, the infrastructure was designed as a centralized electricity system which only facilitates a uni-directional flow of electricity. The electricity is distributed solely from one large producer to consumers. However, the current and expected growth of decentralized electricity production (i.e. households with solar panels) reverse this design. A decentralized system with a bi-directional flow of electricity is required to transport the solar energy from the many prosumers (consumers which also produce electricity) to the many consumers (De Haan, 2016). As mentioned before, this requires to update old-fashioned uni-directional transformers and cables to new bi-directional transformers and cables.

In order to assess the cost-effectiveness of this case, a numerical model is constructed. The formulas that make up this numerical model and thus calculate the total case costs can be found in section 3.4.1. This numerical model has as inputs the solar energy output growth scenarios (see section 4.3). In the numerical model, the number of components which need to be updated in the current Amsterdam electricity infrastructure is calculated according to the failure rates identified by Liander (2017) and the investment costs per component. This thesis identifies these components on a district level. The total costs for upgrading the infrastructure in the traditional manner, which will accommodate for solar energy output estimated in the scenario analysis, are calculated by combing the investment costs in all districts (see figure 26).

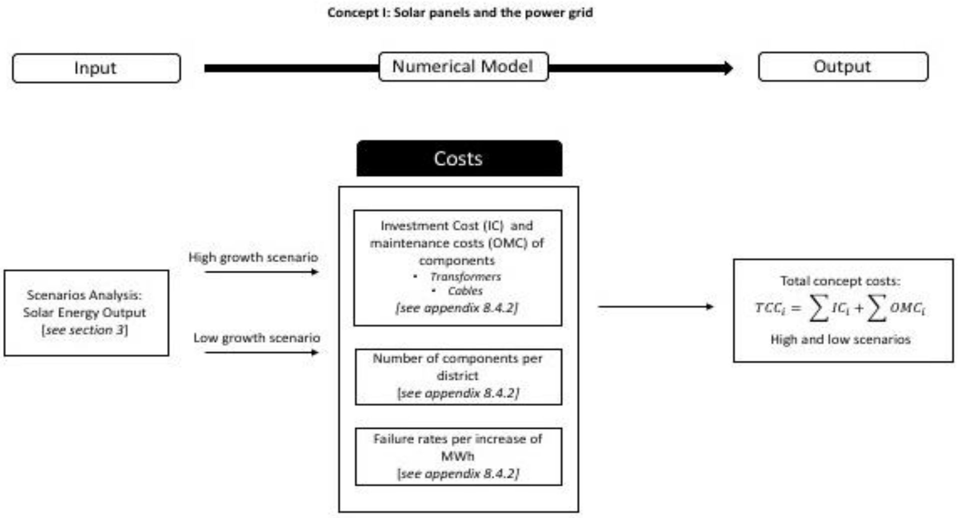

Figure 26, Case I: calculation scheme

6.4.1 Components

This research focuses on the infrastructural components of the electricity network. Liander identified 2 main components in their network (Liander, 2018). These components are either transformers or cables. They also assessed the quality of these components and potential future bottlenecks of these components (see table 15). Liander stated that the failure ratio is a direct result of an increase in solar energy output. However, it did not note to which volume of capacity increase these failure ratios are related to. Therefore, this thesis assumes that an average solar energy output growth of 10% is used to estimate the failure rates in this report. The number of components with future quality issues is recalculated with respect to the solar energy output growth rates constructed in the scenario analysis (see section 4.3). A more detailed description of this transformation can be found in appendix B.

Table 15, Quantity of components

Component Group	Component	Quantity with quality issues[3]	Description
Cables	HV-cables	-	These cables are expected to not overload in the near future.
	MV-cables	5625 km	The old GPLK cables are expected to overload in the near future.
	LV-cables	-	These cables are assumed to be able to handle the distribution of solar energy within the district.
Transformers	Middle-Voltage installation	-	These units are expected to not overload in the near future.

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[3] Components within the Amsterdam region which have a fail rate related to about 10% average increase in solar energy output (Liander, 2018).

HV/MV transformer	50	10% of the total number of MV/LV transformers are expected to overload.
MV/LV transformer	2887	The power switches in the MV/LV transformers are not capable of handling the load variations as a result of decentralized electricity production.

Source: Liander (2017)

6.4.1 Cost analysis

The number of transformers that need upgrading is between 297 in the low growth rate scenario and 1187 in the high growth scenario (see table 16). On average, the number of MV/LV transformers in the high growth scenario which need upgrading quadruples relative to the numbers in the low growth scenario. The number of HV/MV transformers that need upgrading doubles in the high growth scenario, relative to the low growth scenario.

Districts that need to upgrade the greatest number of MV/LV transformers are Zaandam, Haarlem, Purmerend-Volendam, Centrum, and Amstelveen. Not coincidently, these districts are also the largest districts. Furthermore, we see that all the Amsterdam districts need to invest in somewhat equal amounts of transformers. Apart from Zuid-Oost and Westpoort these districts need to invest in between 31 to 55 transformers. Westpoort and Zuid-Oost will need to upgrade significantly fewer transformers. This is to be expected since Westpoort is a mainly industrial area thus having a small household sector. Zuid-Oost is a relatively small district and therefore has a low amount of solar energy output (see chapter 4).

On average, the districts surrounding Amsterdam will need to upgrade more transformers than the districts within Amsterdam. The districts of Zaandam, Haarlem, and Purmerend-Volendam all need more transformer upgrades then the Amsterdam district with the highest upgrade number (Centrum). The districts of Diemen and Badhoevedorp require the least number of transformer upgrades. This is to be expected because these districts are relatively small districts.

The total investments costs in transformers lie between 413,7 million and 1,362 billion euro, the investment costs in cables lie between 6,27 million and 25,09 million euro. The operation and maintenance costs fluctuate between 13,37 and 21,53 million euros. A solar energy output which increases 9% (5% in the low growth scenario and 14% in the high growth scenario) means tripling the total costs associated with upgrading the electricity grid in the traditional manner (see table 17).

Table 16, Case I: number of transformers which need upgrading

District	Low growth scenario (5%) Transformers		High growth scenario (14%) Transformers	
	MV/LV	HV/MV	MV/LV	HV/MV
Centrum	54,80	0,95	219,20	2,00
Noord	38,60	0,38	154,40	0,80
Oost	41,80	0,29	167,20	0,60
Zuid	40,20	0,38	160,80	0,80
West	31,60	0,10	126,40	0,20
Nieuw-West	40,00	0,57	160,00	1,20
Westpoort	11,80	0,95	47,20	2,00
Zuid-Oost	22,40	0,48	89,60	0,90
Amstelveen	49,20	0,38	196,80	0,80
Zaandam	81,20	0,95	324,80	2,00
Haarlem	60,20	0,38	240,80	2,00
Hoofddorp	42,80	0,95	171,20	0,80
Diemen	12,80	0,95	51,20	1,90
Badhoevedorp	8,40	0,38	33,60	0,80
Purmerend-Volendam	68,40	0,10	273,60	0,00

Source: output of numerical model (see appendix B)

Table 17, Case I: total case costs in million euros

Scenario	$\text{IC}_{\text{Transformers}}$	$\text{IC}_{\text{Cables}}$	$\text{OMC}_{\text{Total}}$	Total case costs
2040 – [Low]	413,7	6,27	13,37	433,34
2040 – [High]	1362,1	25,09	21,53	1408,72

Source: output of numerical model (see appendix B).

6.4.2 Cost distribution

The responsibility for the investment costs to upgrade the Amsterdam electricity infrastructure lies at the DSO. In the Amsterdam case study, this actor is Liander. They bear the costs of upgrading the system components and maintaining the new upgraded system. The producers of electricity will likely see a decline in revenue since part of the energy demand is met with decentralized solar energy output. It is important to note that Liander's shareholders are all provinces and municipalities within its operation region (see section 2.6). Furthermore, Liander is a utility company financed by public money. Therefore, the costs lie indirectly with the inhabitants of the districts. The owners of decentralized solar panels benefit from this case by not only decreasing their dependency on the grid but also selling surplus solar energy back to the grid. Also, the intermittency of solar energy can result in the fact that producers may need to install more expensive power plants which can up- and downscale their electricity production whenever the solar energy output decreases. Further research into this effect is advisable.

6.5 CASE II: VEHICLE-2-HOME (V2H)

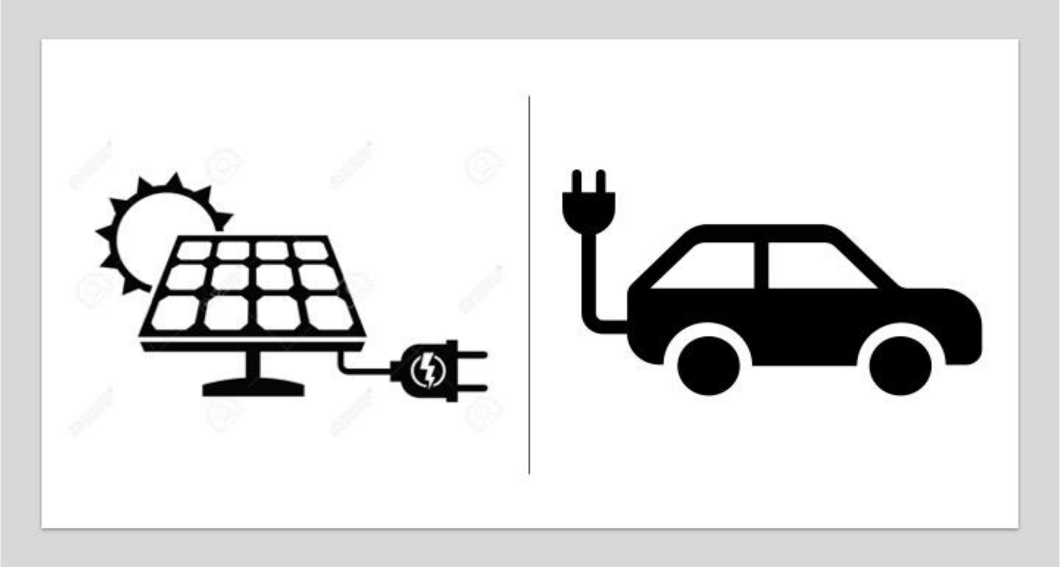

Figure 27, Case II: Solar panels and V2H

V2H can store electricity when the electricity supply is high, and the demand is low (see section 2.3). This electricity is then transferred over the Amsterdam regions, depending on the commuting trend of that specific EV. An EV which is located in a district during the day with a surplus of solar energy can store this electricity in its battery pack and discharge it at night when it is located in a district where the electricity demand exceeds the solar energy output or when the sun has set.

In essence, this case distributes electricity within the districts without using the electricity infrastructure (see figure 27). Thus, less electricity is transported over the grid. This characteristic can prevent expensive network investments into transformers and cables with a higher capacity. However, the growth scenarios and the commuting trends have indicated that EVs will likely accumulate in certain districts (see chapter 4 and 5). As a result of this uneven skewed distribution the V2H concept can potentially not fulfil its full potential. This case incorporates the skewed distribution of EVs and solar panels and calculates the cost-efficiency under these circumstances.

Just as case I, this case is assessed by a numerical model. This model is partly the same as the numerical model in case I. The same formulas are used to calculate the total case costs (see section 3.4.1). However, the V2H concept requires some additional calculations in order to assess its potential benefits (see section 3.4.2.). Both calculations use the growth of solar energy output and EVs. It differs from case I, where only the growth scenarios of the solar energy output are used. In this numerical model, the high scenario solar energy output is combined with the high EV growth rate scenario. Both low growth rate scenarios are also combined. These combined scenarios are used to calculate the cost of this case. The components used to calculate the total case costs differ from the first case (see section 7.5.1). Again, the costs and benefits are aggregated to a district level. The total case is calculated by summing up all the districts costs (see figure 28).

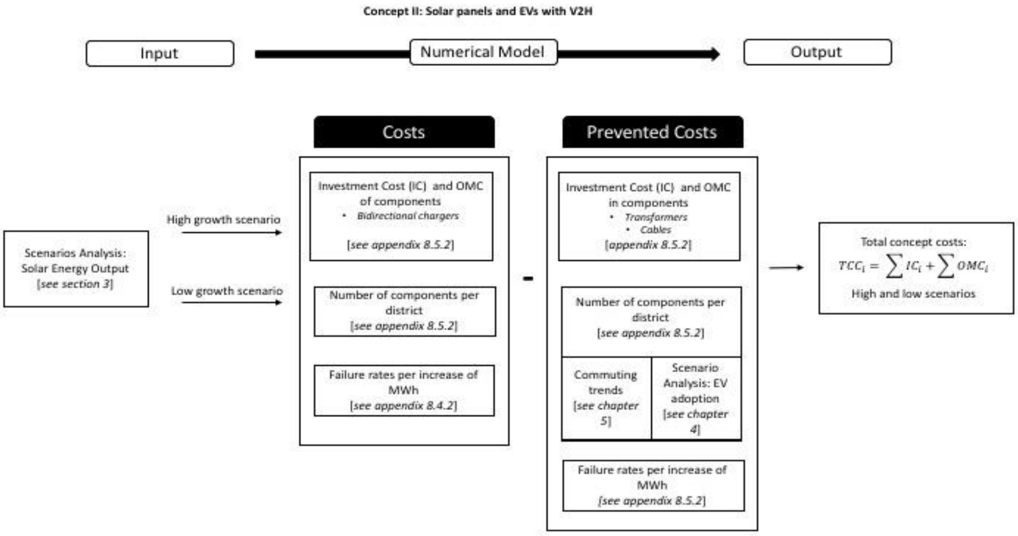

Figure 28, Case II: calculation scheme

6.5.1 Components

The cost-effectiveness of the V2H case is calculated with other system components than the traditional upgrading components. This thesis assumes that no bi-directional charger (BDC) is currently installed. The costs of this case is calculated by the investments in bi-directional chargers (see table 18). The benefits come from prevented network investments due to less electricity which needs to be transported over the network and the reduced electricity peak. For this calculation (see section 3.4.2) the same system components are used to calculate the costs in case I (see section 7.2).

Table 18, Case II: case components

Component Group	Component	Quantity	Description
Bi-directional charger (BDC)	Public*	1 BDC per 10 EVs	Chargers which are located in the public space and exploited by a private, public or public/private organization.
	Private**	0,33 of EV owners	Chargers which are located in the private space. These chargers are assumed to be in households which also own an EV.
Battery**	State-Of-Charge (SOC)	70%	The average SOC is assumed to be 0,7. This is the battery charge percentage of an EV.
	Minimum charge (M)	20%	The battery of an EV cannot be discharged beyond the last 20% of its capacity.

*Source: Mathieu (2018)
**Source: Assumptions made by author

6.5.2 Cost analysis

The total costs for this case is assessed by looking into (1) the height of the investments involved in implementing the V2H concept and (2) the height of the prevented costs as a result of V2H. Subtracting the potential benefits of the investment costs results in the costs associated with this case.

Investment costs

The total costs for installing bi-directional chargers can run up to 1.396 million euros (see table 19). These high costs are mainly due to the investment costs EV owners have by buying and installing their private bi-directional charger. The assumption of this thesis that 33% of all EV owners will install a bi-directional charger have driven the V2H concept costs up. The investments into public bi-directional chargers will be between 90 million and 161 million euros. These costs are reasonable considering the fact that this thesis presumed a public charging station for every 10 EVs. This ratio is assumed to be sufficient in providing EVs with electricity in the public space (Mathieu, 2018).

Table 19, Case II: quantity of components and costs in million euros

Components	Description	2018	2040, low growth scenario	2040, high growth scenario
Private BDC	Quantity	3142	17.908	32.183
Public BDC	Quantity	2913	59.694	107.276
Total	Quantity	6.054	77.602	139.459
Private BDC	Total IC	14,56	298,47	536,38
Public BDC	Total IC	15,71	89,54	160,91
Total	Total IC	30,27	388,01	697,29

Prevented Costs

The costs prevented are quantified in two manners. Cost reductions come in the form of electricity which is not transported over the grid and by preventing investments in the grid components. Electricity which is not transported over the grid is calculated by subtracting the district's daytime electricity consumption of the solar energy output. Eight districts produce more solar electricity than they consume (see figure 29). This electricity can be stored (and redistributed over the network) in EVs. Every MWh which is to be transported over an electricity network is estimated to cost around 20 euro/MWh (Grave, et al., 2016). In the low growth scenario this means that by 2040 the grid benefits 1,14 million euros in electricity which was not transported over the grid. This grows to 57 million euros in the high growth scenario (see table 20).

Infrastructural investments which are prevented due to less electricity which is transported over the network accumulates to, in the low growth scenario, almost 70.000 euro over a year (see table 20). This is insignificantly small compared to the investment costs of bi-directional chargers. However, by 2040, the growth scenario of the V2H concept can potentially prevent around 175.000 MWh being transported over the grid. This can lead to a cost reduction of 3.49 million euros since less transformers and cables need to be upgraded.

Table 20, Case II: total case costs

Cost component	Description	2018	2040, Low growth scenario	2040, High growth scenario
Prevented IC Transportation	Total [million]	-	1,14	57,04
Prevented IC Infrastructure	MWh	9,8	3495,7	174924
Prevented IC Infrastructure	Total [million]	-	69.913	3,49
Total	Total [million]	-	1,14	60,53

Source: output of numerical model (see appendix C).

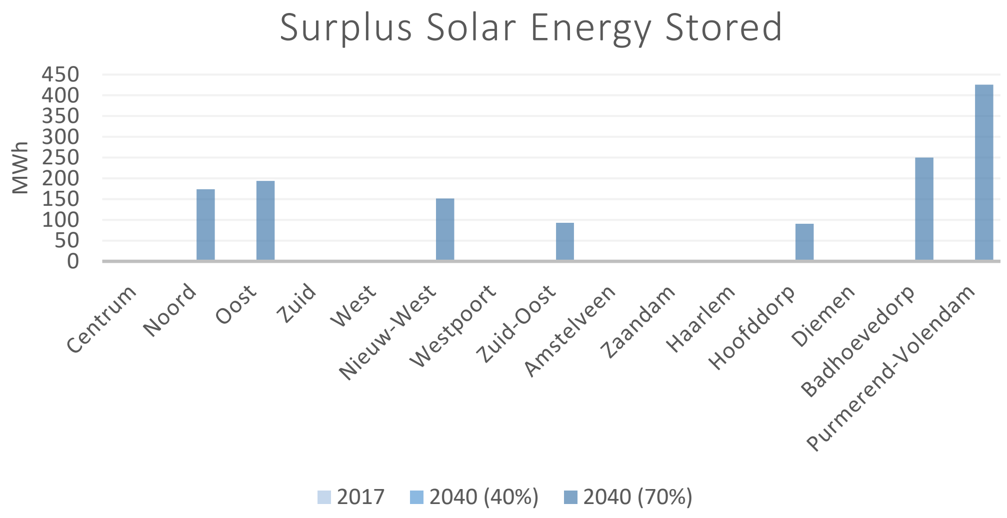

Figure 29, Surplus solar energy stored with V2H

Total case costs

The total costs for implementing the V2H concept is substantially less than upgrading the power grid in the traditional manner (see table 21). In both scenarios the investment costs exceeds the potential prevented costs but this is to be expected. In the low growth scenario, case II would cost around 387 million euros until 2040. In the high growth scenario the cost would have risen to around 637 million euro.

Table 21, Case II: total case costs in million euros

	Investment costs		Prevented investment costs		
	Private BDC	Public BDC	Transportation	Infrastructure	Total case costs
2040 – *[Low]*	298,5	89,5	1,1	0,07	386,8
2040 – *[High]*	536,4	160,9	57,1	3,5	636,8

6.5.3 Reaching its potential?

The height of the cost reduction of the V2H concept in the Amsterdam case study accumulates to 60,53 million euros by 2040 in the high growth scenario (see section 7.5). All but one district, have sufficient EV storage capacity to store their surplus solar energy (see appendix C.1). Westpoort does not have enough EVs located at day time to store the surplus solar energy. In the high growth scenario, 34.992 MWh of surplus solar energy cannot be given back to the grid due to a lack of EVs in Westpoort. Therefore, almost 35.000 MWh which is distributed over the grid could be prevented. This amounts to a 'lost' cost reduction of 60,32 million euros. The same method of calculating the total case costs for V2H has been used (see appendix B.2). The potential total benefits can be doubled. Thus, the total benefits from V2H potential to store surplus solar energy amounts to 120,85 million euros in the case study involving Amsterdam and the surrounding large districts in the high growth scenario.

6.5.4 Additional benefits

Apart from storing surplus solar energy, the V2H concept can reduce network costs in a second manner. In Amsterdam, the V2H concept can, in theory, deliver 51.030 MWh of electricity to buildings in 2018. This grows to 1.797.536 MWh in the low EV growth scenario and 3.230.363 MWh in the high EV growth scenario (see table 22). These numbers can significantly drop the total costs of V2H (Feldman, Tanner & Rose, 2015). This drop is caused by an EV that charges its battery at low demand hours (valleys) and discharges its battery at high demand times (peaks). As a result, the night time electricity peak will decrease (see figure 30). A lower peak demand requires an electricity infrastructure that does not require to handle high peak loads. A case study into the Germany electricity sector found that flattening the electricity peak as a result of demand response decreased the DSO's overall expenditure by 3,52% due to a decrease of 7,74% drop in price volatility (Feuerriegel & Neumann, 2013).

Unfortunately, the overall economic benefits of this decrease in electricity peak demand are very hard to quantify. A rule of thumb to quantify this potential benefit lacks. Although this thesis is not able to quantify this potential benefit, it predicts that this can decrease the total costs for operating an electricity system substantially.

Table 22, Case II: potential reduced peak demand in MWh

	2018	2040, Low growth scenario	2040, High growth scenario
Potential returned EV storage capacity	51030	1797536	3230363

Source: output of numerical model (see appendix B)

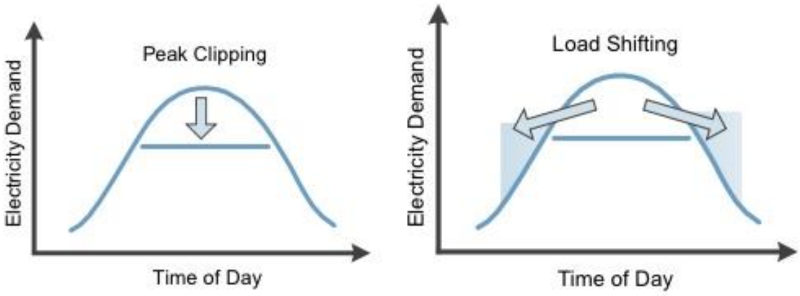

Fig. 2. Comparing peak clipping versus load shifting.

Figure 30, Load shifting

Source: Measuring the financial impact of demand response for electricity retailers (Feuerriegel & Neumann, 2013).

6.5.5 Cost distribution

The cost distribution for the second case is almost opposite to the cost distribution of the first case. The largest part of the costs related to the implementation of the V2H system are the private bi-directional chargers. Installing these chargers are at the account of EV owners which install bi-directional chargers in their home. The benefits of the reduced demand from the electricity grid lie with the DSO. They can invest less in their infrastructure because part of the solar surplus electricity is being stored and redistributed over the grid by batteries in EVs. Households with surplus solar electricity are unable to sell this surplus energy back to the grid because the grid is not sufficiently upgraded. Government subsidies to reduce the investment costs for a private bi-directional charger can help to balance the cost responsibility. However, part of the lower system costs will have to flow back to households who cannot afford an EV and corresponding bi-directional charger.

6.6 CASE III: A COMPROMISE

The case "a compromise" is constructed to increase the effectiveness of V2H by investing in certain infrastructural components. These infrastructural components are aimed at decreasing the negative effects of the spatial distribution mismatch of solar panels and EVs as identified in the previous chapters (see chapter 3-5). This compromise between investing in V2H (see section 6.5) and investing in infrastructural components (see section 6.4) allow for a gradual implementation of the V2H technology in the Amsterdam region.

Apart from storing surplus solar energy, the V2H concept can also be used to reduce the electricity demand from the grid of households during the night time peak. Many papers conclude that reducing the grid peaks and filling the grid valleys will decrease the societal electricity infrastructure costs (Eid, Koliou, Valles, Reneses & Hakvoort, 2015; Albadi & El-Saadany, 2008). Although levelling out the peak demand retrieved from the grid is difficult to quantify, this thesis will layout a design in which the V2H concept can optimally reduce the household peak demand from the grid.

The EV growth scenario analysis (chapter 5) and the commuting trends (chapter 6) have shown that the spatial distribution of EVs is skewed. The spatial distribution of EVs during daytime and night time is unevenly dispersed over the districts (see figure 31). This is a result of the district characteristics and commuting trends. Districts with a high ratio of households and a high average income are expected to have many EVs, this is referred to as the night time location (see section 4.3). Also, commuting trends have a profound effect on the location of EVs. This thesis has calculated the commuting trends which result in the daytime location of EVs (see section 5.3).

In 2018, the night time consumption in the household sector exceeds the electric storage capacity available from EVs in all district. This stays the same for the Amsterdam districts in both the scenarios until 2040. However, in a few districts surrounding Amsterdam, the storage capacity coming from the EV fleet exceeds the districts combined electricity demand. In the districts Amstelveen, Hoofddorp, and Badhoevedorp the night time electricity demand can be supplied fully by the storage capacity available in EVs. Diemen and Haarlem have more storage capacity than electricity consumption in the high growth scenario (see figure 31). Zaanstad consumes more electricity during night time peak than its EV storage capacity in both scenarios. Purmerend-Volendam consumes more electricity than its storage potential in the low growth scenario, but in the high growth scenario, the electricity consumption is roughly the size of the potential EV storage capacity. The storage capacity surplus of the district of Amstelveen can be used to supply 23% of the total night time household energy consumption of all the Amsterdam districts in the low growth scenario. Whereas, in the high growth scenario, the district of Amstelveen has enough surplus EV storage capacity to supply 82% of the night time electricity peak of all the Amsterdam districts combined.

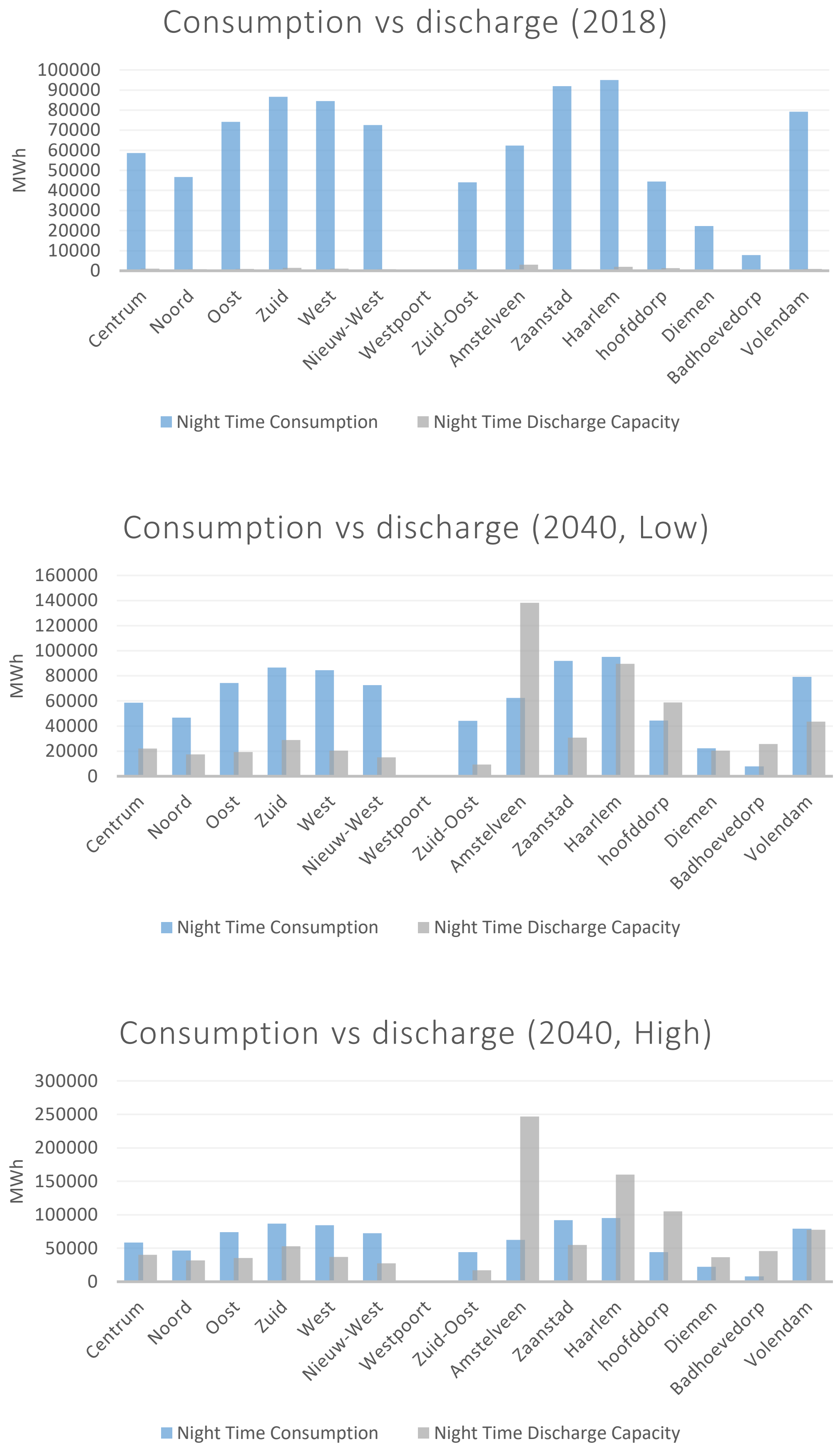

Figure 31, Case II: consumption vs. discharge

6.6.1 A new design

Therefore, this thesis suggests investing in new components that enable the grid to transport electricity during peak hours (night time) from districts with a high discharge capacity to districts without a high discharge capacity peak. These new components are transformers and cables. This new case therefore partially uses case I and case II (see sections 7.4-7.5). V2H is used to store surplus solar energy and to deliver electricity back to the districts (case II). This requires the reinforcement of a few infrastructural components which connect districts (case I). The analysis of the current and future discharge availability per district (see figure 31) is used to design the three network links (see table 23). One link means updating the transformers in both the origin district and the destination district because the electricity must pass through both network districts (see figure 32).

Amstelveen is the district with the highest surplus EV storage capacity. This district must therefore be linked with districts with a deficiency in storage capacity. The nearest districts are the Amsterdam districts of Zuid and Zuid-Oost. The second infrastructural link between two districts is Badhoevedorp to Nieuw-West and Hoofddorp to Nieuw-West. Badhoevedorp and Hoofddorp are chosen because these districts have a surplus of EV storage capacity in both scenarios. Nieuw-West has a deficiency of EV storage capacity in both scenarios (see figure 31).

Table 23, Case III: proposed network links

Network link	District from	District to	Distance	Components
Link 1	Amstelveen	Zuid and Zuid-Oost	15*	Transformers (2x), MV-cable
Link 2	Badhoevedorp	Nieuw-West	5	Transformers, MV-cable
Link 3	Hoofddorp	Nieuw-West	15	Transformers, MV-cable

*Distance from Amstelveen – Zuid, and Amstelveen – Zuid-Oost; one-way trip.
Source: authors proposal

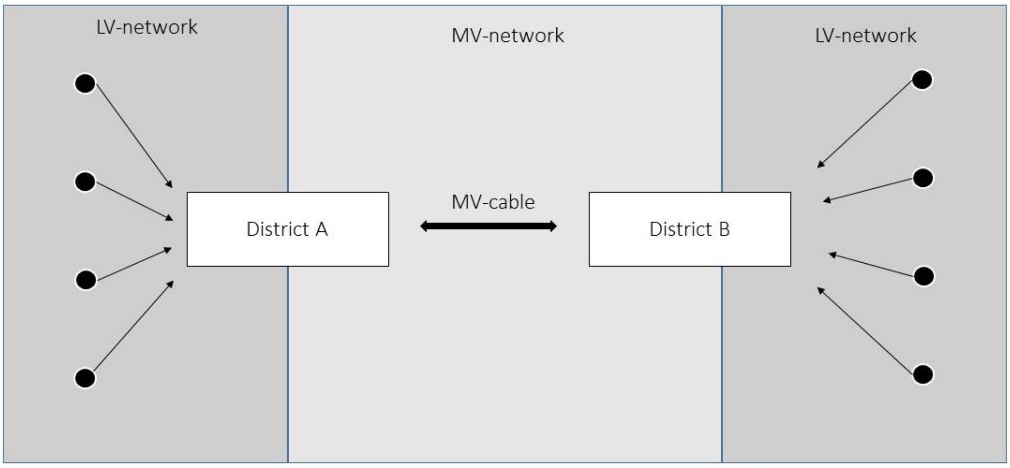

Figure 32, Case III: design of network links

6.6.2 Cost analysis

The costs of this new case are the investments in new components which connect the proposed districts. The new components are the same components as in case I and II, namely cables and transformers. The number of components which need to be reinforced is related to the MWh of electricity which will be transported through them. The same fail ratio is used as in calculating cases I and II. See appendix D for a detailed explanation of these calculations. LV-cables are assumed to be able to disperse electricity within a district and are thus not incorporated in this thesis (see section 2.8). The length of the MV-cables is estimated by measuring the distance between the district's centres.

Also, the transportation costs are taken into effect (Grave, et al., 2016). Upgrading the components and quantifying the costs of electricity transportation gives an overview of the total costs of this proposed new case (see appendix D). The proposed link between Amstelveen and Zuid and Zuid-Oost will be the most expensive link (see table 24). This link will cost between 201,82 and 395,5 million euros. The two other links will cost significantly less. Where Badhoevedorp to Nieuw-West will cost between 62 and 90 million euros, Hoofddorp to Nieuw-West will cost between 5 and 149 million euros. The latter is a bit more expensive due to the long distance leading to higher cable investments. These two districts are further apart from each other.

Table 24, Case III: total case costs

Net work link	Scen ario	Tr*	C**	IC Tr	IC Ca	Total costs
1	Low	430	15	185	15.3	202
	High	883	15	379	15.3	395
2	Low	133	5	57	5.1	62
	High	199	5	85	5.1	90
3	Low	81	15	35	15.4	50
	High	313	15	134	15.4	149

*Tr: number of transformers
**Ca: amount of cables in kilometers

Model outcome: see appendix D

Total case costs

The total costs for implementing the compromise solution is higher than just implementing the V2H concept but less than upgrading the power grid in the traditional manner in the high growth scenario (see table 25). In the low growth scenario the total costs associated with this case amounts to 699,8 million euros. The high growth scenario leads to a total case cost of 1333,8 million euros.

Table 25, Case III: total case costs in million euros

	Investment costs			
	Transformers	Cables	Bi-directional chargers*	Total case costs
2040 – [Low]	277	35.8	387	699,8
2040 – [High]	598	35.8	700	1333,8

*This is the costs for implementing the V2H concept (see section 6.5.2)

6.6.3 Potential Benefits

The proposed network links will balance the night time peak consumption and EV storage capacity. As mentioned before, reducing the night time electricity demand peak can potentially be a huge economic benefit (see section 7.5.4). The three proposed network links lead to 7 districts being self-sufficient in supplying electricity without the help of the grid during the night time electricity peak demand in the low growth scenario (see figure 33-34). By redistributing the surplus storage capacity electricity, the districts of Zuid, Westpoort, Amstelveen, Haarlem, Hoofddorp, Diemen, and Badhoevedorp can become independent from the grid to supply for the night time peak demand. The districts of Nieuw-West and Volendam-Purmerend rely on grid electricity for less than half of the night time peak demand. The districts Centrum, Noord, Oost, West, and Zaanstad still rely heavily on electricity from the grid to meet the night time peak demand.

Within the high growth scenarios of EVs and solar energy output in the Amsterdam region, the proposed network links will lead to a slightly different distribution of storage and consumption. Now, 10 districts will be self-sufficient in meeting the night time electricity demand without grid intervention. These districts are Zuid, Nieuw-West, Westpoort, Zuid-Oost, Amstelveen, Haarlem, Hoofddorp, Diemen, Badhoevedorp, and Purmerend-Volendam. This growth scenario also shows that the overall difference between consumption and storage capacity decreases. The districts Centrum, Noord, and Zaanstad only need a small portion of their night time electricity demand from the grid. Only the districts Oost and West will have a large deficit of electricity coming from the storage capacity of EVs to supply the night time peak demand. However, overall, we see that the high growth scenario leads to an increase in the number of districts being able to completely (or almost completely) rely on electricity coming from the EVs with the V2H technology.

In the low growth scenario, the V2H concept, together with the proposed links can supply for 38% of the total night time peak demand in all districts. In the high growth scenario, this grows to 68%. The V2H concept, together with the proposed network links, can thus significantly reduced the stress on the Amsterdam electricity grid. However, supplying the household electricity demand in the night means that the EVs have to be charged during the night and the day. Further research is required into this EV load time shift. This thesis did not incorporate the effects of this load shift on the power grid.

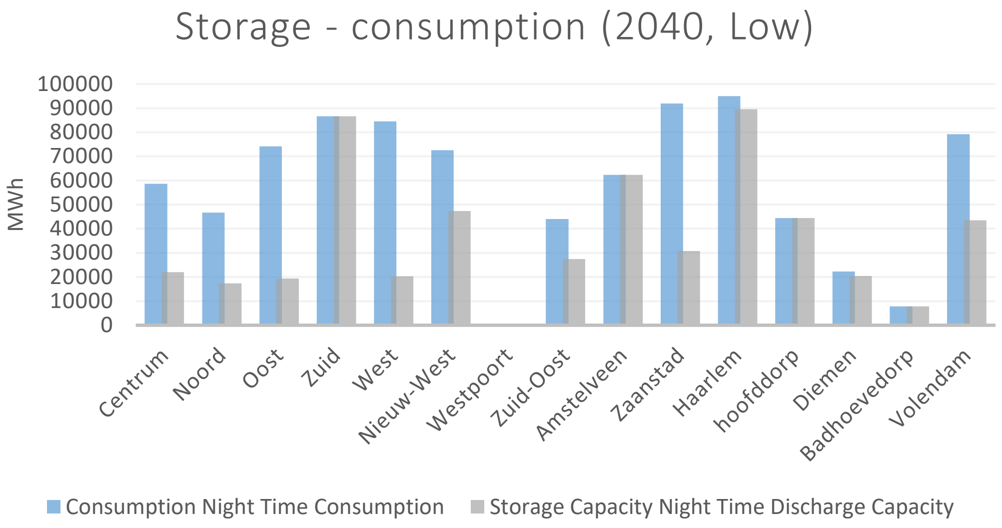

Figure 33, Case III: Effects of proposed network links in low growth scenario

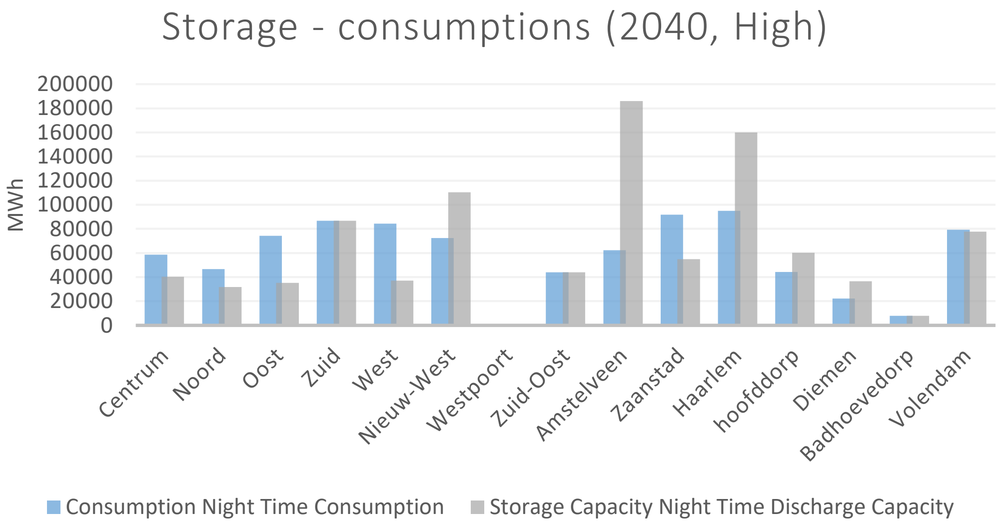

Figure 34, Case III: Effects of proposed network links in high growth scenario

6.6.4 Cost distribution

The cost distribution for the proposed third case is, just as the case name would suggest, in between the cost distributions of case I and II. The investments in the proposed network links lie, just as in case I, at the expense of the DSO. At the same time, the costs for installing bi-directional chargers are for the most part, just as in case II, at the expense of EV owners which install a private bi-directional charger. In case I, the main benefiters are the solar panel and EV owners, wherein case II the DSO is the main benefiter. The financial benefits in the proposed case are both with households and with the DSO. Households can use EVs with the V2H concept to charge at low demand hours, or with solar electricity and thus benefit from the low electricity price. Where the DSO can benefit from the fact that EVs can use the proposed links to balance the deficiencies between districts resulting in a decrease of the stress on the grid in these districts.

6.7 SENSITIVITY ANALYSIS

The investment costs of all the cases are subject to a sensitivity analysis. This sensitivity analysis will provide insights into the effects of changes in the investment costs of the components on the total investment costs of the three constructed cases. Predicting an exact average investment costs of transformers and bi-directional chargers is impossible due to the uncertainty of future developments (see section 6.3).

All transformers currently installed in the Liander distribution network lose electricity (Liander, 2017). This electricity loss happens inside the transformers when the voltage is changed. Future transformers are expected to be more efficient and thus reduce the electricity loss (StatPlan, 2019). Increasing the efficiency can result in a lower investment cost per transformer than the investment price of 25.000 euro per transformer (see section 6.3). The investment cost for a bi-directional charger is estimated to be 5.000 euro per transformer. This is an estimate coming from two sources (Plötz, et al., 2013; Graube, et al. 2013). Unknown future developments can increase or decrease this investment cost. Therefore, this thesis uses an increase and decrease of 5% of the investment costs per transformer and bi-directional chargers to map out the uncertainty effect on the total investment costs per case. Cables are not taken into account because the literature lacks a clear view on whether future developments can increase or decrease the investment costs for cables.

Case I: Power Grid and Solar Panels

The investment costs in the case where the surplus solar energy is distributed via the electricity grid is estimated at 413,7 million euro in the low growth scenario and 1362,1 million euro in the high growth scenario (see figure 35-36). If the investment costs in transformers decrease by 5% from 25.000 to 23.750 euro per transformer, the total case investment costs decrease to 409,6 million euro in the low growth scenario. If the investment costs of transformers increase with 5%, the total case investment costs increases to 434,4 million euro. When we look at the high growth scenario, the total investment costs of this case ranges between 1294 million euro and 1430,2 million euro.

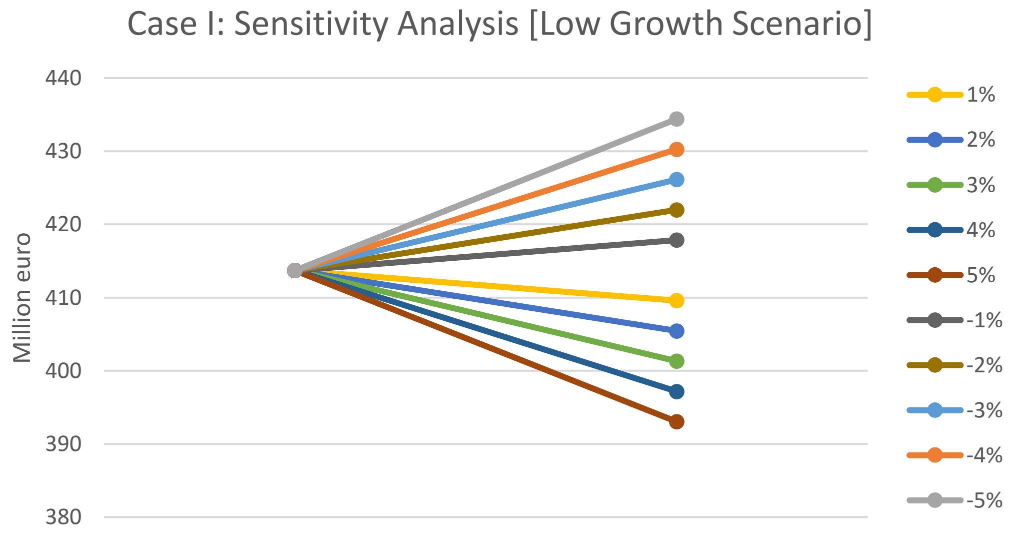

Figure 35, Case I: Sensitivity Analysis, low growth scenario

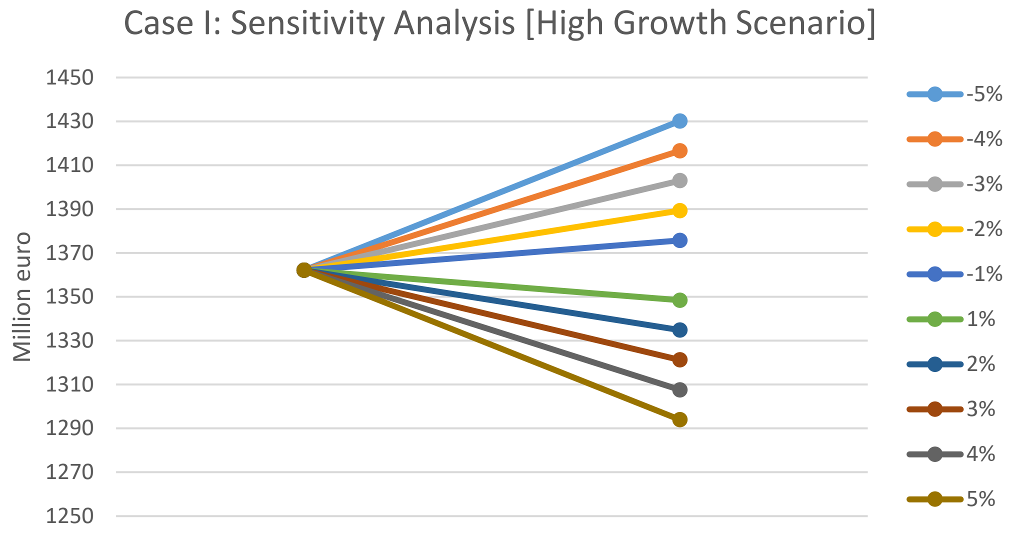

Figure 36, Case I: Sensitivity Analysis, high growth scenario

Case II: Solar Panels and V2H

The investment costs in the case where the surplus solar energy is stored and redistributed via the V2H concept is estimated at 388 million euro in the low growth scenario and 679,3 million euro in the high growth scenario (see figure 37-38). This is the direct result of investing in bi-directional chargers. If the investment costs in bi-directional chargers decrease by 5% from 5.000 to 4.750 euro per charger, the total case investment costs decreases to 368,6 million euro in the low growth scenario. If the investment costs of transformers increases with 5%, the total case investment costs increases to 407,4 million euro. When we look at the high growth scenario, the total investment costs of this case ranges between 662,4 million euro and 732,2 million euro.

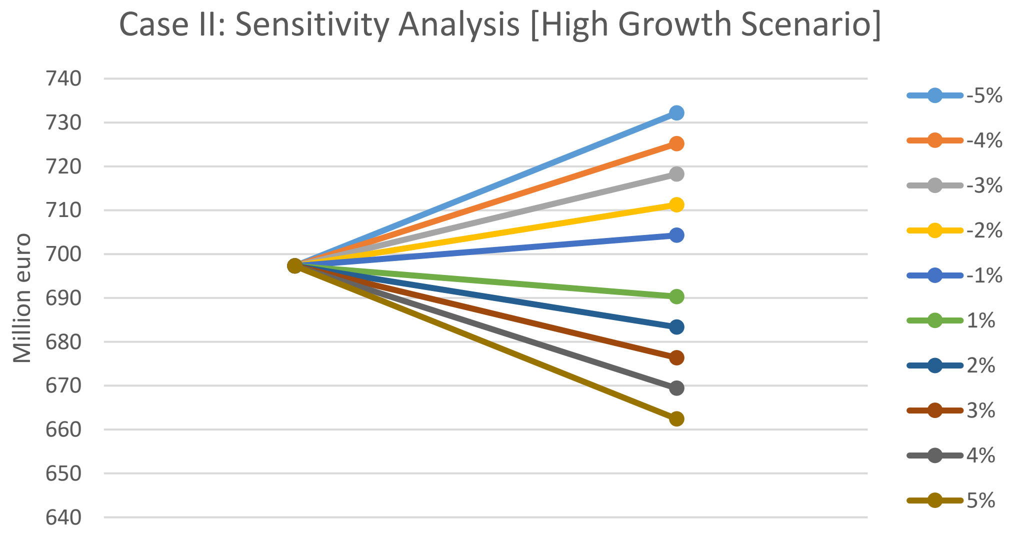

Figure 37, Case II: Sensitivity Analysis, high growth scenario

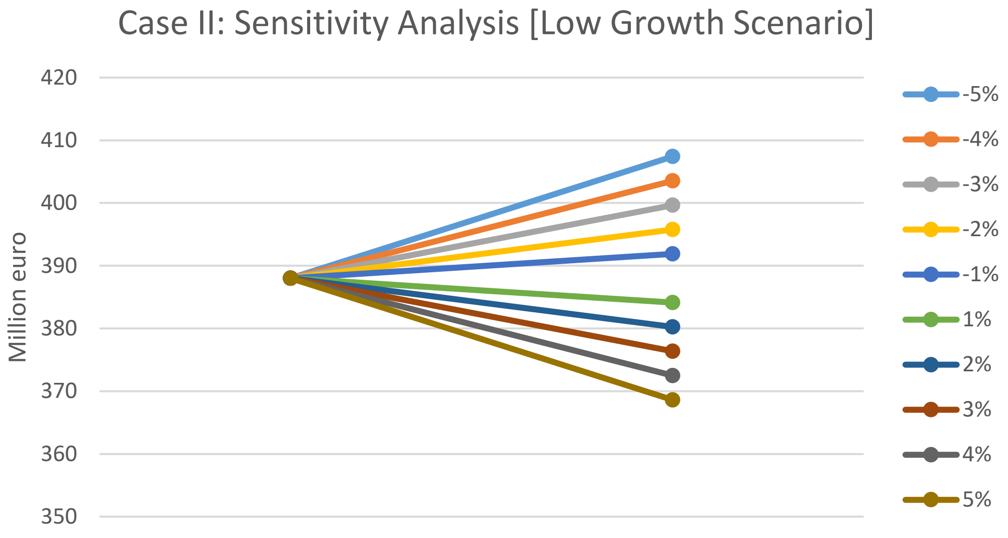

Figure 38, Case II: Sensitivity Analysis, low growth scenario

Case III: A Compromise
The investment costs in the final case is estimated at 666,8 million euro in the low growth scenario and 1295,6 million euro in the high growth scenario (see figure 39-40). This case requires investments in bi-directional chargers and transformers. If the investment costs in bi-directional chargers and transformers decrease by 5%, the total case investment costs decrease to 633,5 million euro in the low growth scenario. If the investment costs of transformers increases with 5%, the total case investment costs increases to 700,1 million euro. When we look at the high growth scenario, the total investment costs of this case ranges between 1230,8 million euro and 1360,4 million euro.

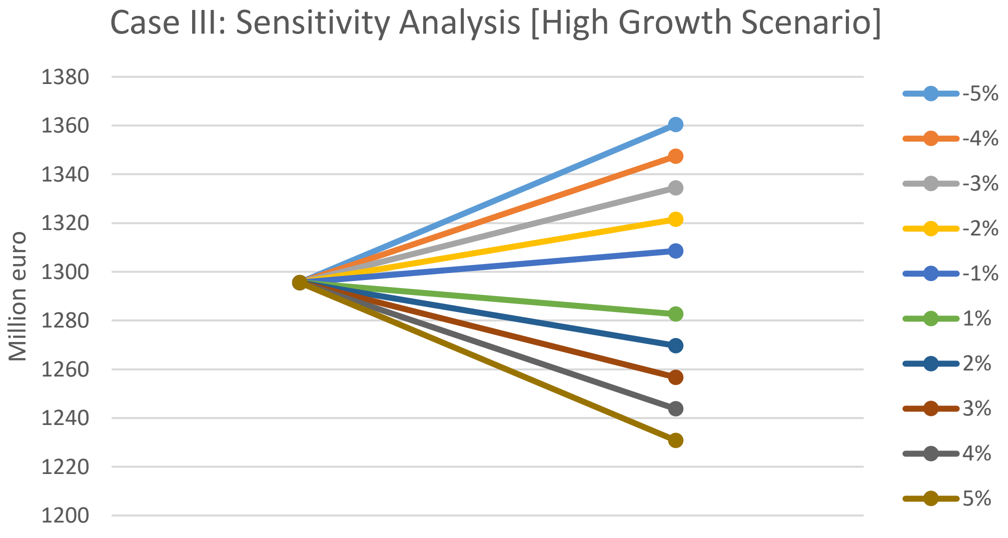

Figure 39, Case III: Sensitivity Analysis, high growth scenario

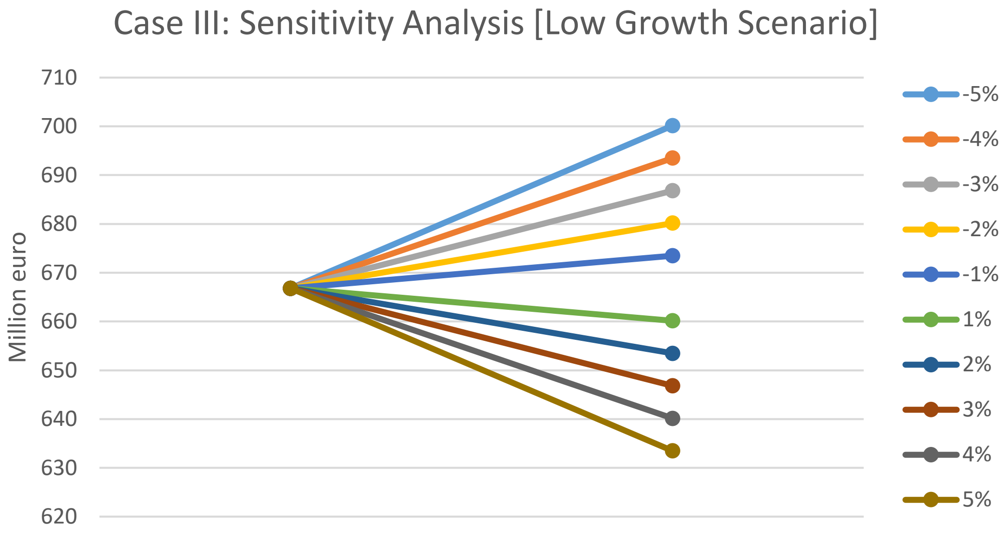

Figure 40, Case III: Sensitivity Analysis, low growth scenario

7 CONCLUSION AND RECOMMENDATIONS

In this section the research questions will be answered. The five sub questions are answered subsequently in section 7.1. In the next section, the main research question is answered (see section 7.2). The results are discussed in the following section (see section 7.3). Finally, the limitations and recommendations for further research are denoted in the last section (see section 7.4). The main research question of the thesis is:

How will the spatial distribution of solar panels and EVs affect the ability of EVs to store solar energy and return it to the grid via the Vehicle-2-Home concept and how to design a cost-efficient system with this spatial distribution?

7.1 SUB QUESTIONS

Sub question I. [SQ1]: *How will distributed solar energy production grow and what effect does this have on the current electricity infrastructure?*

The growth of solar energy output of all districts is estimated on the basis of a detailed dataset provided by the municipality of Amsterdam. In 2018, the solar energy output of the districts within the Amsterdam municipality was distributed relatively even over all the districts. Only the districts of Centrum and Westpoort (+/- 1,5 MWp) have a substantially lower amount of solar energy output than the Amsterdam average (+/- 4 MWp). The characteristics of these districts explain these low quantities. While Westpoort is a mainly industrial area without many households, Centrum is home to many historic buildings which often do not provide for a suitable option for the installment of solar panels. The surrounding districts have on average a lower solar energy output but higher variances between districts. Purmerend-Volendam is the district surrounding Amsterdam with the highest solar energy output (+/- 4,5 MWp) and Diemen and Badhoevedorp are the districts with the lowest solar energy output (+/- 0,5).

The scenario analysis shows the spatial distribution of 2018 will increasingly grow uneven. The districts with an already high solar energy output in 2018 will see a relatively higher increase in solar energy output than districts with a low solar energy output in 2018. In 2018, the solar energy output difference between the highest and lowest district (Noord – Badhoevedorp) is 5,5 MWp. By 2040, this difference has grown to 9,5 MWp in the low growth scenario and 95 MWp in the high growth scenario (Purmerend-Volendam – Badhoevedorp).

The current distribution network in the Amsterdam region is not able to accommodate this growth. The DSO investigated the failure rates of transformers and cables in their network. The growth rates in solar energy output lead to 612 transformers to overload in the low growth scenario and 2430 transformers to overload in the high growth scenario. The DSO estimates that in both scenarios 5625 kilometers of MS-cables overload.

Sub question II. [SQ2]: *How will the number of EVs grow and what effect does this have on the current electricity infrastructure?*

The growth of EVs in the Amsterdam region is estimated by data from the public transport system operating in the Metropolitan area of Amsterdam. The number of EVs in the districts within the municipality of Amsterdam are evenly distributed, with an average of 500 EVs per district. In the district of Zuid significantly more EVs (806) are registered, where Westpoort only has 3 EVs registered since this is a mainly industrial area. The EV distribution in the surrounding districts is less evenly distributed. The districts of Amstelveen and Haarlem have respectively, 1715 and 1111 EVs registered in their districts, where Diemen only has 254 registered EVs. Wealthy districts like Zuid and Amstelveen have a significantly more EVs registered in their districts than poorer districts like Diemen and Zuid-Oost.
The scenario analysis shows that, just as in the solar energy output, the uneven distribution of EVs between districts grows. In 2018, the difference between the number of EVs registered to the highest and lowest district (Amstelveen – Diemen) is 1460 EVs. By 2040, this difference has grown to 44.257 EVs in the low growth scenario and 77.775 EVs in the high growth scenario (Amstelveen – Zuid-Oost).

The electricity peak demand for households is highest at the night time. The scenario analysis on the growth of EVs, as mentioned above, are used to determine how much of this night time energy peak demand can potentially be supplied with electricity coming from EVs. The night time electricity consumption of households is higher than the EV storage capacity in every district in 2018. However, rapid growths of EVs have changed this balance quite substantially. While all Amsterdam districts still consume more electricity than they have storage capacity available, in several districts surrounding Amsterdam the storage capacity will exceed the night time electricity consumption. In the high growth scenario, Amstelveen's night time surplus storage capacity is so high, it can supply 82% of all the Amsterdam districts' night time electricity demand. The scenario analysis indicates high differences in the location of EVs. The EVs are distributed unevenly over the Amsterdam region. In the future this can potentially lead to a substantial decrease of effectivity of the V2H concept.

Sub question III. [SQ3]: *How does the spatial distribution of EVs match with the supply distribution of distributed solar energy production?*

In order to store surplus solar energy via the V2H concept, the location of EVs must match with the location of the solar panels. However, commuting trends lead to a substantial redistribution of EVs during the day time. The districts within the Amsterdam municipality all see an increase in EVs coming to these districts during the day due to work commutes. The opposite effect happens in the surrounding districts. Among all the surrounding districts, Amstelveen is the district which sees more EVs leaving than arriving. By 2040, 50.000 EVs leave this district for their daily work commute. Districts that see a high increase in EVs due to commuting trends are Zaanstad, Zuid-Oost, and Centrum. These increases are around 10.000 EVs daily. These high differences can potentially lead to an insufficient storage capacity to store surplus solar energy. The surplus solar energy of each district is calculated by subtracting the daytime electricity consumption of the total solar energy output of each district. Fortunately, all districts but one district have sufficient EV storage capacity available to store all surplus solar electricity. The districts, Noord, Oost, Nieuw-West, Westpoort, Zuid-Oost, Hoofdorp, Badhoevedorp, and Purmerend-Volendam are all expected to produce more solar electricity than the total households sector demands and are able to store this in EVs in their district. The EVs disperse over the Amsterdam region in such a manner that all districts, except for Westpoort, will have sufficient storage capacity in the form of EVs to store their surplus solar energy.

Sub question IV. [SQ4]: *What are the costs and (societal) benefits of the V2H-technology and how can these be distributed efficiently between actors?*

The spatial distribution of decentralized solar electricity over the grid will require heavy investments (see section 2.2). An EV connected to a building can serve as a storage facility to surplus solar electricity using the V2H concept. When the sun sets and the building's demand surpasses the solar energy production, the storage capacity of an EV can be used to meet the electricity demand of the building. This technology prevents the flow of the surplus solar electricity to the grid during day time and it reduces the grid dependency of households during the night time peak demand.

These above-mentioned benefits can prevent infrastructural investments in transformers and cables. Sub questions I. till III. have shown that currently an uneven spatial distribution of solar panels and EVs over the Amsterdam region exists. This uneven distribution will continue to grow to an even more uneven distribution by 2040. Fortunately, this does not affect the ability of EVs to store the surplus solar electricity. There is no spatial mismatch between the district's surplus solar energy and the storage capacity. The surplus solar energy of all 8 districts (see SQ3) can be stored in EVs. This electricity does not need to be transported over the grid, thus preventing between 1,14 and 57,04 million euros depending on the growth scenario. Not having to transport the surplus solar electricity to the power grid also prevents investment costs in the distribution grid's infrastructure. The V2H concept stores surplus solar energy and thus prevents investments in transformers and cables amounting to between 70.000 euro and 3,49 million euros depending on the growth scenario. These prevented costs can double if Westpoort will have sufficient EV storage capacity.

Unfortunately, these prevented costs dwarf the investment costs into bi-directional chargers which facilitate the bi-directional flow of electricity. The costs of bi-directional chargers are expected to drop in the future due to technological developments. Bi-directional chargers are expected to have an average cost of 5.000 euros per charger until 2040, which will lead to a total investment cost of 387 million euros in the low growth scenario and 634 million euros in the high growth scenario. These investments costs are, for the most part, for EV owners which install a bi-directional charger in their homes. About one third of the investment costs go the public bi-directional chargers. The DSO benefits in this case from not having invest in upgrading the distribution grid infrastructure to facilitate the surplus solar energy. Furthermore, the V2H concept can potentially return between 1.797.536 and 3.230.363 MWh yearly to buildings it is connected to. However, quantifying this effect lies outside the scope of this thesis. Still, this effect can increase the attractiveness of this case even further.

Sub question V. [SQ5]: *What is the cost-efficiency of upgrading of the Amsterdam electricity infrastructure in order to facilitate the growth of EVs solar panels?*

The growth of decentralized solar energy production will lead to high costs. Infrastructural upgrades of transformers and cables will have to be made to keep up with the growth of solar panels in the Amsterdam district (see SQ1). The low and high growth scenarios will lead to investments of, respectively 433 and 1334 million euros. The districts which will see the most infrastructural upgrades are Zaandam, Haarlem, and Purmerend-Volendam. The districts with the least infrastructural upgrades are Westpoort, Diemen, and Badhoevedorp. The responsibility for these investments lies completely at the DSO. However, the DSO is a utility company, paid in full by public money. Therefore, the costs of upgrading the grid in the traditional manner is completely at the expense of the society.

7.2 ANSWER TO THE MAIN RESEARCH QUESTION

Main research question [MQ]: *How will the spatial distribution of solar panels and EVs affect the ability of EVs to store solar energy and return it to the grid via the Vehicle-2-Home concept and how to design a cost-efficient system with this spatial distribution?*

Some districts are expected to have a higher solar energy output than others. 8 districts in the Amsterdam region are expected to produce more solar energy than the household sector in these districts consumes. To prevent the loss of this surplus solar energy, this electricity must be transported to districts with a demand for electricity which is higher than their own production of solar electricity. Unfortunately, the transportation of this electricity will cause capacity problems in the current Amsterdam distribution grid. To prevent these capacity problems in the distribution grid either the power grid infrastructure must be updated or the electricity needs to be stored in EVs via the V2H concept.

The surplus solar electricity in the Amsterdam region can be stored in EVs. The V2H concept is able to store the surplus solar energy in EVs since these are sufficiently available in all districts except Westpoort (see SQ2). Storing this surplus solar energy in EVs with V2H is significantly cheaper than upgrading the distribution grid to transport this surplus solar electricity. Implementing the V2H concept would cost between 387 and 634 million euros, where upgrading the traditional manner would cost between 433 and 1334 million euros over a time span of 22 years (see SQ 4 and 5).

The uneven spatial distribution of EVs has a negative impact on the cost-effectiveness of the V2H concept. As mentioned above, Westpoort is the only district with a surplus of solar energy but not sufficient storage capacity in the form of EVs. Due to the uneven spatial distribution of EVs, Westpoort's surplus solar energy has to be transported to the distribution grid. If sufficient EVs were available in this district, the costs for the V2H concept could be decreased by between 1,14 to 60,53 million euros. Apart from storing the surplus solar energy in the Amsterdam region, the uneven distribution of EVs also has a negative effect on the ability of the V2H concept to return electricity to buildings. This thesis has explored the ability of EVs with V2H-technology, to reduce the dependency of the power grid for the night time electricity demand. All Amsterdam districts consume more electricity during the night than they have available in the EV storage capacity. A few surrounding districts have more EV storage capacity available than they consume during the night time electricity demand. Amstelveen alone can supply between 23% and 82% of the nigh time electricity peak of the Amsterdam districts combined. In this situation, Amstelveen and the other districts, rely less on the power grid for their night time energy demand. Although many papers have identified this as a great potential benefit, this thesis did not have the resources to quantify this shift in demand loads.

To address the negative effect of the uneven spatial distribution of EVs, one options is to build a network which is able to facilitate the bi-directional flow of electricity between all districts. However, this choice is accompanied by very high investment costs (see SQ5). Therefore, this thesis suggests to only upgrade several network links. The surplus EV storage capacity of Amstelveen, Hoofddorp, and Badhoevedorp can supply many districts with electricity and hence, it will decrease the dependency and fluctuations of the power grid (see SQ2). This requires an exchange of electricity between the previously mentioned three districts, and districts which consume more electricity than they have available in the EV storage capacity. This reduces the night time electricity peak demand from the grid and the fluctuations in the electricity system in the Amsterdam region.

By investing in transformers and cables in three network links, the dependency on the power grid for the night time electricity peak demand can be reduced. These network links connect the districts of Amstelveen with Zuid and Zuid-Oost, and Nieuw-West with Badhoevedorp and Hoofddorp. As a result of these network links, seven districts can be completely supplied by electricity coming from EVs via the V2H concept. The investment costs in transformers and cables are between 316 and 637 million euros for all network links (see table 26). The EV storage capacity is now distributed more evenly between all the districts in the Amsterdam region. Thus, by investing in the infrastructural components connecting these districts, the uneven distribution of EVs will be decreased.

Table 26, Costs of proposed network links in million euros

Network link	District from	District to	Total costs
Link 1	Amstelveen	Zuid and Zuid-Oost	202 – 396
Link 2	Badhoevedorp	Nieuw-West	63 - 91
Link 3	Hoofddorp	Nieuw-West	51 - 150

7.3 DISCUSSION

This thesis found an uneven spatial distribution of solar panels and EVs which will continue to grow more uneven by 2040. Three electricity system cases were constructed which mitigate the negative effects of these uneven distributions in the Amsterdam region. Solely investing in the electricity infrastructure (Case I) or investing in a combination of V2H and (partially) the electricity infrastructure (Case III) require heavy investments (see table 27). As shown in the table below, only investing in V2H (Case II) is substantially cheaper.

Table 27, Total case costs

Cases	Low growth scenario	High growth scenario
Case I: Upgrade power grid	433	1408
Case II: Vehicle-2-Home (V2H)	387	634
Case III: A compromise	700	1334

The first case involves upgrading the infrastructure to facilitate the bi-directional flow of electricity and thus distributing the surplus solar energy via the power grid over the Amsterdam region. This case requires heavy investments in transformers and cables. As a result of these investments, the decentralized produced solar energy can move freely throughout the network. Thus, evading the negative effects of the uneven spatial distributions of solar panels and EVs. The second case explored the cost-effectiveness of the V2H concept. This case is significantly cheaper than the previously mentioned case. Still, the rapid growth of EVs result in the fact that almost all surplus solar energy can be stored in EVs in the Amsterdam region. Thus, the daytime spatial distribution of solar energy output and EVs match. However, at night time, the spatial distribution of EVs accumulates, leading to a few districts (Amstelveen, Badhoevedorp, and Hoofddorp) which have more EV storage capacity than they consume during the night time. These districts can supply their night time electricity demand via the V2H concept with electricity coming from the storage capacity in EVs. Thus, being less dependent, and reducing the fluctuations on the power grid.

In order to decrease the negative effect of the uneven spatial distribution of EVs during the night time, this thesis proposes to invest in three network links. The three network links are supplementary to the V2H concept. This innovative solution combines upgrading the infrastructural components with the V2H concept. With these network links the surplus solar energy of Amstelveen, Badhoevedorp, and Hoofddorp can be transported to districts with a low EV storage capacity. These are in this case Zuid-, Zuid-Oost, and Nieuw-West. By implementing these links, the night time electricity demand of seven districts can theoretically be supplied with electricity solely coming from EVs via the V2H concept. This leads to a reduction of the grid dependency by between 1.797.536 and 3.230.363 MWh of electricity during the night time peak demand, which is beneficial to both the DSO and the electricity consumer. Besides reducing the grid dependency, this case also results in lower investment costs in the high growth scenario compared to case I. As such, the DSO benefits from a distribution grid with lower fluctuations and the consumer benefits from a lower electricity price.

This thesis has shown that the spatial distribution of EVs is an important factor to incorporate when assessing the effectiveness of the V2H technology. The research approach constructed in this thesis can be adopted to find the spatial match or mismatch of solar panels and EVs in other cities or regions. Identifying the spatial match or mismatch between solar panels and EVs will help in constructing an efficient electricity design which includes mobile storage components such as, V2G, V2H or V2N technologies.

7.4 LIMITATIONS AND RECOMMENDATIONS

This thesis did not encompass all factors which influence the cost-effectiveness of V2H. This thesis suggests incorporating 4 extra factors. The first factor, and arguably the most important factor, entails an immediate financial benefit of the decrease in night time peak demand due to the V2H concept. Further research into the effects of decreasing the household night time electricity demand peak is required. Several technologies such as Demand Response, Vehicle-2-Grid, and Smart Charging aim to have, among other things, spread out the electricity demand coming from the grid more equally over a day. All researches conclude that this will decrease the overall electricity grid costs. This thesis suggests that the V2H concept experiences the same benefits. Analysing the possible economic effects of this load shifting might make the V2H a more financially viable option than investing in the grid the traditional way.

Secondly, the energy market is left out. The transition from a centralized to a decentralized energy system with a V2H, or comparable system, can greatly impact the price of electricity. Subsequently, this also impacts the supply and demand curve. This thesis did not dive into the possible impacts which the V2H concept has on the price of electricity. Also, an aggregator is needed in order to efficiently and effectively redistribute electricity over a specific area. How this aggregator is designed and how the electricity is redistributed between several households in a street requires further research.

Thirdly, the characteristics of districts are set as constants. Characteristics such as, the number of inhabitants and average income, heavily define the spatial distribution of EVs and solar panels per district. In practice, these characteristics change over time. For example, the district of Noord in Amsterdam was, for many years, a mainly industrial area. In a decade, this district has evolved to an upcoming neighbourhood which not only sees an increase in households moving to Noord but also sees a steep growth in the average income. It is to be expected that more districts can change by 2040. These changes can then lead to a different distribution of solar panels and EVs within these districts. The electricity demand of these districts is also set as constant. This thesis does not incorporate the increase in demand due to the charging of the EVs. Also, other developments which are expected to increase the electricity demand of households, such as heat pumps, are not incorporated. Further research on the effects of this increased electricity demand on the effectiveness of V2H is advised.

Fourthly, this thesis estimated the total costs for the V2H concept with currently known technologies. For instance, this thesis calculated the storage capacity by looking into the developments of currently used lithium-ion batteries. Developments in other battery types, such as solid state batteries and it performances are not taken into account. Also, developments in other technologies are not taken into account. Car-as-a-Power-Plant technologies, often with a hydrogen power source can also profoundly impact the storage capacity and thus the effectiveness of V2H. This thesis did not include other electricity resources, other than solar energy and the grid. Research on the effects of a more diverse electricity system is recommended.

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APPENDIX A: SCENARIO ANALYSIS

This appendix contains all the information about the construction of the scenario analysis. Also, the districts characteristics are denoted in this appendix.

A.1 DISTRICT CHARACTERISTICS

The table below has data containing several district characteristics. These characteristics are the number of inhabitants, the number of jobs, and the average income per district (see table 28). This data originates from 2018. This data is used: to distribute the solar panels over the surrounding districts (see chapter 3), to distribute EVs overall the districts (see chapter 4), and it is used to compute the commuting trends (see chapter 5). The size of the districts are used to distribute the previously mentioned factors. For example, a large district and wealthy district, such as Amstelveen, is assigned a large number of EVs. A small number of EVs is assigned to a small and poor district, such as Diemen.

Table 28, Extensive district characteristics

	Districts	**Inhabitants**	**Number of jobs**	**Average personal income (x1000 euro)**
Amsterdam districts*	Centrum	86.400	102.598	41.7
	Nieuw-West	146.800	76.718	27.2
	Noord	91.000	32.316	26.1
	Oost	128.700	62.622	34.2
	West	142.800	48.402	32.0
	Westpoort	2.000	21.920	22.0
	Zuid	141.400	105.642	44.8
	Zuid-Oost	84.600	76.770	24.2
Surrouding districts**	Amstelveen	88.600	43.300	31.6
	Haarlem	155.000	52.800	28.3
	Badhoevedorp***	12.600	7776	33.2
	Diemen	10.000	22.100	24.9
	Hoofddorp***	75.000	4600	27.9
	Purmerend-Volendam	102.200	27.700	25.7
	Zaanstad	155.000	52.800	24.3

*Source: Onderzoek, Informatie, Statistiek, Gemeente Amsterdam
**Sources: Statline (CBS)
***This data is estimated with the help of Haarlemmermeer data

A.2 SCENARIO ANALYSIS: SOLAR ENERGY

The municipality accurately kept track of the number solar panels in Amsterdam. This data was gathered from the open data portal of the municipality. This is publicly available via https:/data.amsterdam.nl. Data about solar panels comes from 2018. The dataset contains:

- Geolocation (latitude and longitude coordinates)
- Estimated solar energy output (Wp)
- Type of dwelling (housing or non-housing)

The dataset contained in total 4616 locations with solar panels. These locations were spread out over the Amsterdam districts (see figure 41). The information about the location of these solar panels are stored in latitude and longitude coordinates. These latitude and longitude coordinates were converted to address information. This conversion process is called reverse geocoding. This research made use of the reverse geocoding script made by Stephen P. Morse. This script enabled the conversion of large batches of longitude and latitude coordinates. This script uses the Google Maps API for the geo-coordinates and the address information. The data is then clustered over the Amsterdam districts. This is done with the help of postal codes. Every district has its own postal code which enables a quick clustering of the data over the districts.

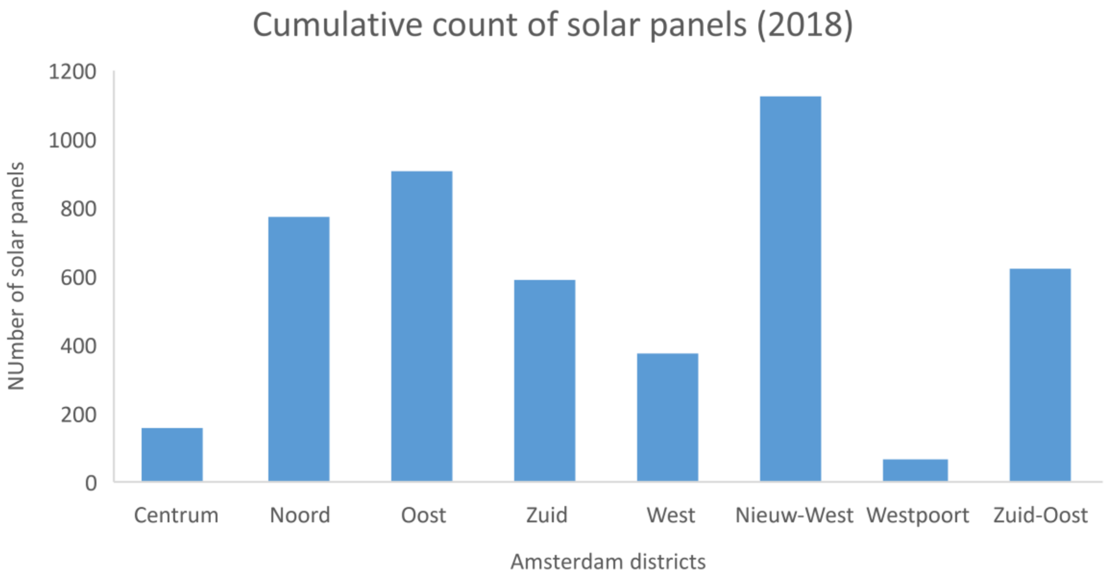

Figure 41, Cumulative number of solar panels in Amsterdam districts

The other districts do not have a detailed dataset of the number solar panels per district. Therefore, the solar energy output in these districts needs to be estimated. This estimation is done with the district characteristics. The districts surrounding Amsterdam are matched with an Amsterdam district with similar characteristics in average income (see table 29). The solar energy output of the comparable district is then recalculated for the difference in inhabitants between districts (see figure 42). This method results in Purmerend-Volendam to have the highest estimation of solar energy output in 2018. The district with the lowest solar energy output are Diemen and Badhoevedorp. This is high difference is mainly due to the big size difference between these districts.

Table 29, Amsterdam districts comparable to surrounding districts

Surrounding district	Comparable to Amsterdam District
Amstelveen	Oost
Haarlem	West
Badhoevedorp	Oost
Diemen	Zuid-Oost
Hoofddorp	Nieuw-West
Purmerend-Volendam	Zuid-Oost
Zaanstad	West

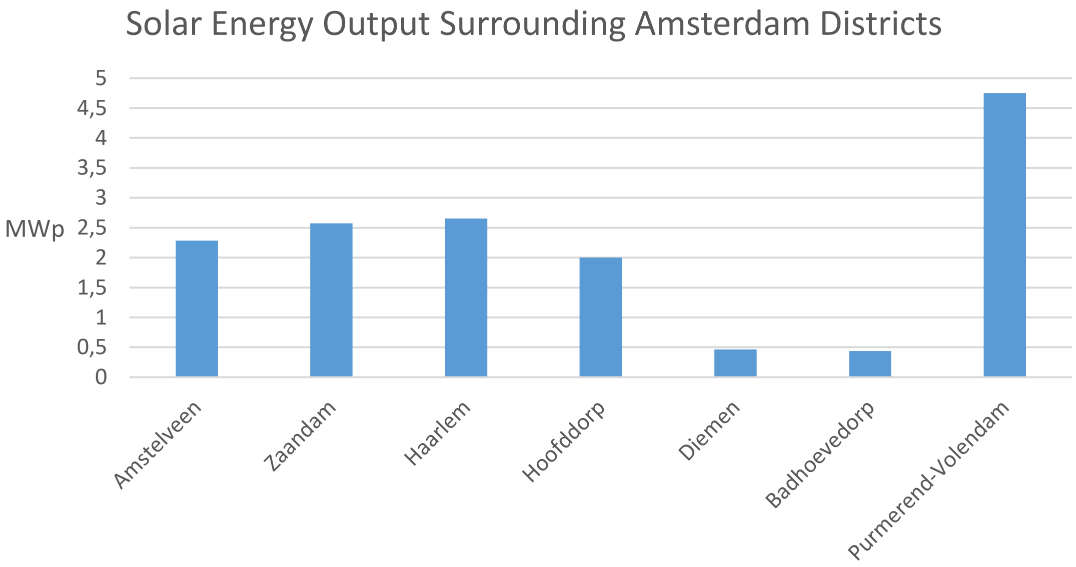

Figure 42, Solar energy output of Amsterdam districts

Solar Energy Scenario Analysis

The growth scenarios are constructed with either a 5% growth rate of a 14% yearly growth rate. The outputs are in MWh per district per year.

Table 30, Complete solar energy output table, low growth scenario

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Centrum	1,19	1,25	1,31	1,37	1,44	1,52	1,59	1,67	1,75	1,84	1,93	2,03	2,13	2,24	2,35	2,47	2,59	2,72	2,86	3,00	3,15	3,31	3,47
Noord	4,93	5,17	5,43	5,70	5,99	6,29	6,60	6,93	7,28	7,65	8,03	8,43	8,85	9,29	9,76	10,25	10,76	11,30	11,86	12,45	13,08	13,73	14,42
Oost	4,93	5,17	5,43	5,70	5,99	6,29	6,60	6,93	7,28	7,64	8,02	8,43	8,85	9,29	9,75	10,24	10,75	11,29	11,85	12,45	13,07	13,72	14,41
Zuid	3,79	3,98	4,18	4,38	4,60	4,83	5,08	5,33	5,60	5,88	6,17	6,48	6,80	7,14	7,50	7,87	8,27	8,68	9,11	9,57	10,05	10,55	11,08
West	2,62	2,75	2,88	3,03	3,18	3,34	3,50	3,68	3,86	4,06	4,26	4,47	4,70	4,93	5,18	5,44	5,71	5,99	6,29	6,61	6,94	7,29	7,65
Nieuw-West	4,32	4,54	4,76	5,00	5,25	5,52	5,79	6,08	6,39	6,70	7,04	7,39	7,76	8,15	8,56	8,98	9,43	9,91	10,40	10,92	11,47	12,04	12,64
Westpoort	1,75	1,84	1,93	2,03	2,13	2,23	2,35	2,46	2,59	2,72	2,85	2,99	3,14	3,30	3,47	3,64	3,82	4,01	4,21	4,42	4,65	4,88	5,12
Zuid-Oost	4,34	4,55	4,78	5,02	5,27	5,53	5,81	6,10	6,41	6,73	7,06	7,42	7,79	8,18	8,59	9,01	9,47	9,94	10,44	10,96	11,51	12,08	12,68
Total Amsterdam	27,8	29,2	30,7	32,2	33,8	35,5	37,3	39,1	41,1	43,2	45,3	47,6	50,0	52,5	55,1	57,9	60,8	63,8	67,0	70,3	73,9	77,6	81,4
Amstelveen	2,52	2,64	2,77	2,91	3,06	3,21	3,37	3,54	3,72	3,90	4,10	4,30	4,52	4,75	4,98	5,23	5,49	5,77	6,06	6,36	6,68	7,01	7,36
Zaandam	2,84	2,98	3,13	3,29	3,45	3,62	3,80	3,99	4,19	4,40	4,62	4,85	5,10	5,35	5,62	5,90	6,20	6,51	6,83	7,17	7,53	7,91	8,30
Haarlem	2,92	3,07	3,22	3,39	3,55	3,73	3,92	4,12	4,32	4,54	4,76	5,00	5,25	5,51	5,79	6,08	6,38	6,70	7,04	7,39	7,76	8,15	8,56
Hoofddorp	2,21	2,32	2,43	2,56	2,68	2,82	2,96	3,11	3,26	3,43	3,60	3,78	3,97	4,16	4,37	4,59	4,82	5,06	5,31	5,58	5,86	6,15	6,46
Diemen	0,51	0,54	0,57	0,59	0,62	0,65	0,69	0,72	0,76	0,80	0,83	0,88	0,92	0,97	1,01	1,07	1,12	1,17	1,23	1,30	1,36	1,43	1,50
Badhoeve-dorp	0,48	0,51	0,53	0,56	0,59	0,62	0,65	0,68	0,71	0,75	0,79	0,82	0,87	0,91	0,95	1,00	1,05	1,11	1,16	1,22	1,28	1,34	1,41
P-R[4]	5,24	5,50	5,78	6,06	6,37	6,69	7,02	7,37	7,74	8,13	8,53	8,96	9,41	9,88	10,37	10,89	11,43	12,01	12,61	13,24	13,90	14,59	15,32
Total other	16,7	17,5	18,4	19,3	20,3	21,3	22,4	23,5	24,7	25,9	27,2	28,6	30,0	31,5	33,1	34,7	36,5	38,3	40,2	42,2	44,3	46,5	48,9

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[4] Purmerend-Volendam

Table 31, Complete solar energy output table, high growth scenario

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Centrum	1,40	1,60	1,82	2,07	2,36	2,69	3,07	3,50	3,99	4,55	5,19	5,92	6,74	7,69	8,76	9,99	11,39	12,98	14,80	16,87	19,24	21,93	25,00
Noord	5,81	6,62	7,55	8,61	9,81	11,19	12,75	14,54	16,57	18,89	21,54	24,55	27,99	31,91	36,37	41,47	47,27	53,89	61,43	70,03	79,84	91,02	103,76
Oost	5,81	6,62	7,55	8,60	9,81	11,18	12,75	14,53	16,56	18,88	21,53	24,54	27,98	31,89	36,36	41,45	47,25	53,86	61,41	70,00	79,80	90,98	103,71
Zuid	4,46	5,09	5,80	6,61	7,54	8,60	9,80	11,17	12,73	14,52	16,55	18,87	21,51	24,52	27,95	31,86	36,33	41,41	47,21	53,82	61,35	69,94	79,73
West	3,08	3,51	4,01	4,57	5,21	5,94	6,77	7,71	8,79	10,02	11,43	13,03	14,85	16,93	19,30	22,00	25,08	28,60	32,60	37,16	42,37	48,30	55,06
Nieuw-West	5,09	5,81	6,62	7,55	8,60	9,81	11,18	12,75	14,53	16,57	18,89	21,53	24,54	27,98	31,90	36,36	41,45	47,26	53,87	61,42	70,02	79,82	90,99
Westpoort	2,06	2,35	2,68	3,06	3,49	3,97	4,53	5,16	5,89	6,71	7,65	8,72	9,94	11,34	12,92	14,73	16,79	19,14	21,82	24,88	28,36	32,33	36,86
Zuid-Oost	5,11	5,83	6,64	7,57	8,63	9,84	11,22	12,79	14,58	16,62	18,95	21,60	24,63	28,07	32,00	36,48	41,59	47,42	54,05	61,62	70,25	80,08	91,29
Total Amsterdam	32,8	37,4	42,7	48,6	55,5	63,2	72,1	82,2	93,7	106,8	121,7	138,8	158,2	180,3	205,6	234,4	267,2	304,6	347,2	395,8	451,2	514,4	586,4
Amstelveen	2,97	3,38	3,86	4,40	5,01	5,71	6,51	7,42	8,46	9,65	11,00	12,54	14,29	16,29	18,57	21,18	24,14	27,52	31,37	35,76	40,77	46,48	52,99
Zaandam	3,35	3,81	4,35	4,96	5,65	6,44	7,34	8,37	9,54	10,88	12,40	14,14	16,12	18,38	20,95	23,88	27,23	31,04	35,38	40,34	45,99	52,42	59,76
Haarlem	3,45	3,93	4,48	5,11	5,82	6,64	7,57	8,63	9,83	11,21	12,78	14,57	16,61	18,93	21,59	24,61	28,05	31,98	36,46	41,56	47,38	54,01	61,58
Hoofddorp	2,60	2,97	3,38	3,86	4,40	5,01	5,71	6,51	7,42	8,46	9,65	11,00	12,54	14,30	16,30	18,58	21,18	24,14	27,52	31,38	35,77	40,78	46,49
Diemen	0,60	0,69	0,79	0,90	1,02	1,16	1,33	1,51	1,72	1,96	2,24	2,55	2,91	3,32	3,78	4,31	4,92	5,60	6,39	7,28	8,30	9,47	10,79
Badhoeve-dorp	0,57	0,65	0,74	0,84	0,96	1,09	1,25	1,42	1,62	1,85	2,11	2,40	2,74	3,12	3,56	4,06	4,63	5,27	6,01	6,85	7,81	8,91	10,15
P-R	6,17	7,04	8,02	9,15	10,43	11,89	13,55	15,45	17,61	20,08	22,89	26,10	29,75	33,91	38,66	44,07	50,24	57,28	65,30	74,44	84,86	96,74	110,29
Total other	19,7	22,5	25,6	29,2	33,3	38,0	43,3	49,3	56,2	64,1	73,1	83,3	95,0	108,3	123,4	140,7	160,4	182,8	208,4	237,6	270,9	308,8	352,0

Scenarios with low growth scenario (4%)

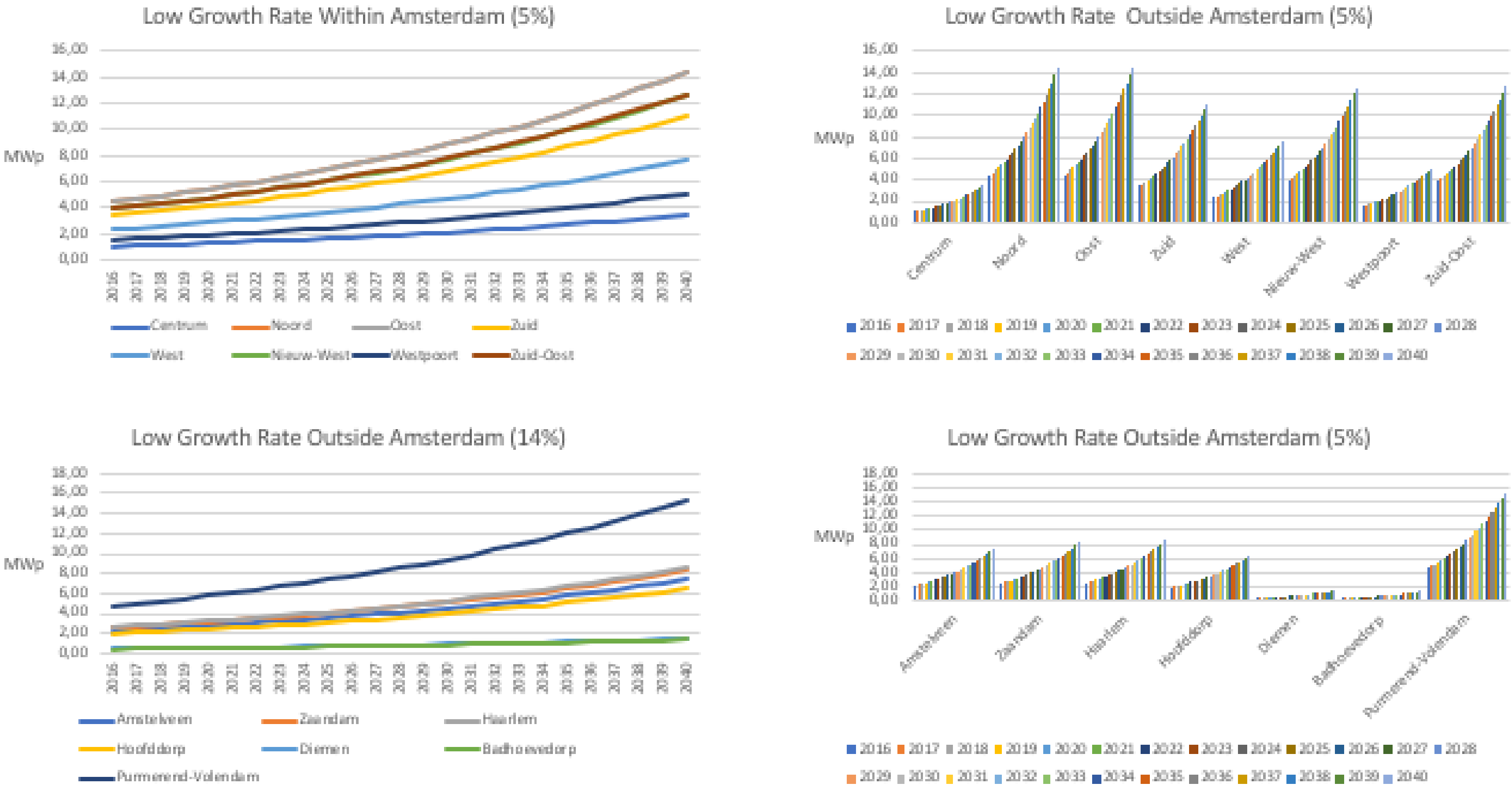


Figure 43, Complete sensitivity analysis of solar panel growth in low growth scenarios

Scenarios with high growth rates (14%)

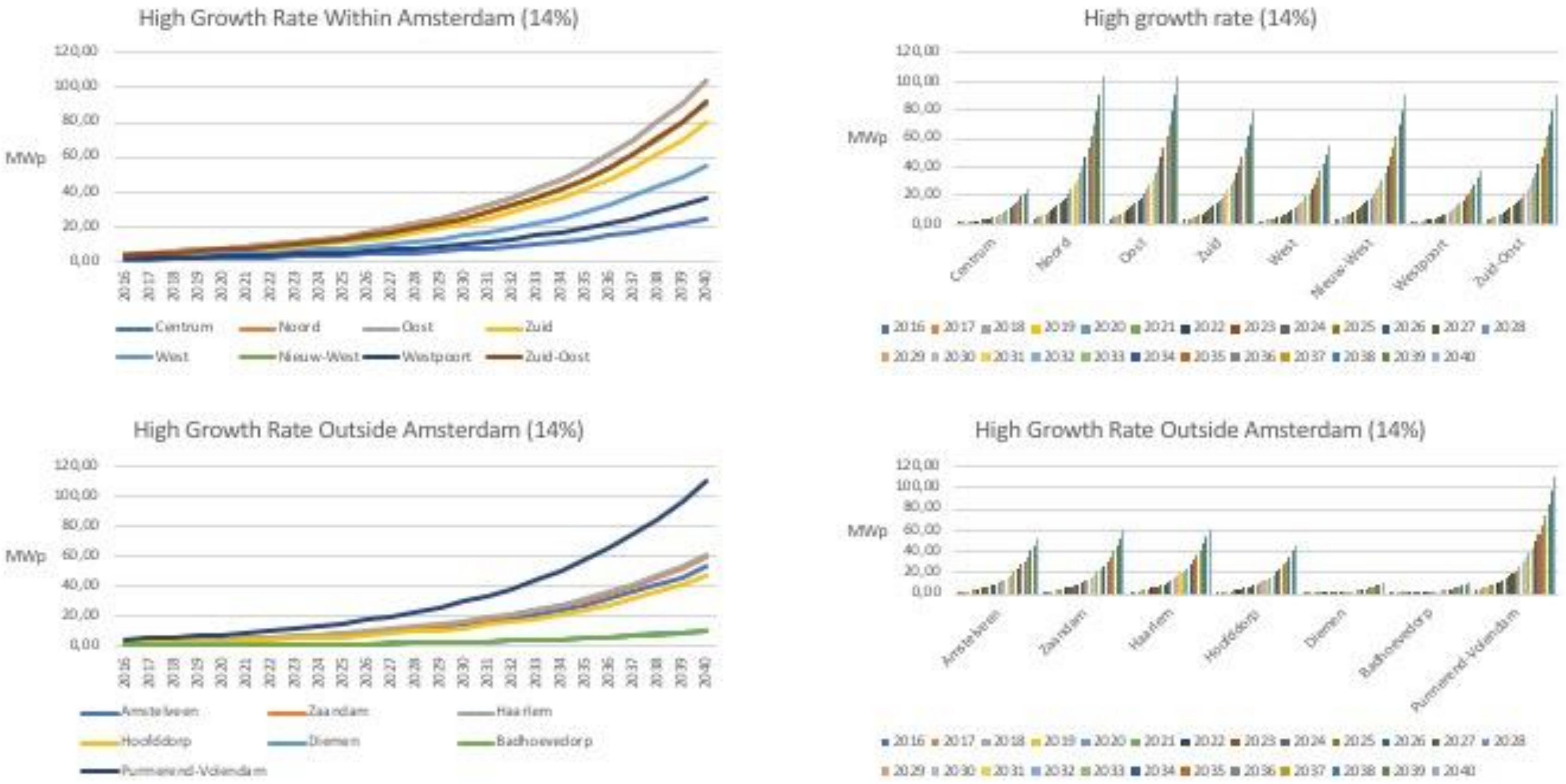


Figure 44, Complete sensitivity analysis of solar panels in high growth scenarios

A.3 SCENARIO ANALYSIS: ELECTRIC VEHICLES

In the Amsterdamse Thermometer voor de Bereikbaarheid, the municipaltiy of Amsterdam noted how many EVs and Hybrids were registered over all districts from 2010 until 2018. This data shows that the growth of EVs will surprise the number of hybrids soon (see figure 45 and table 32).

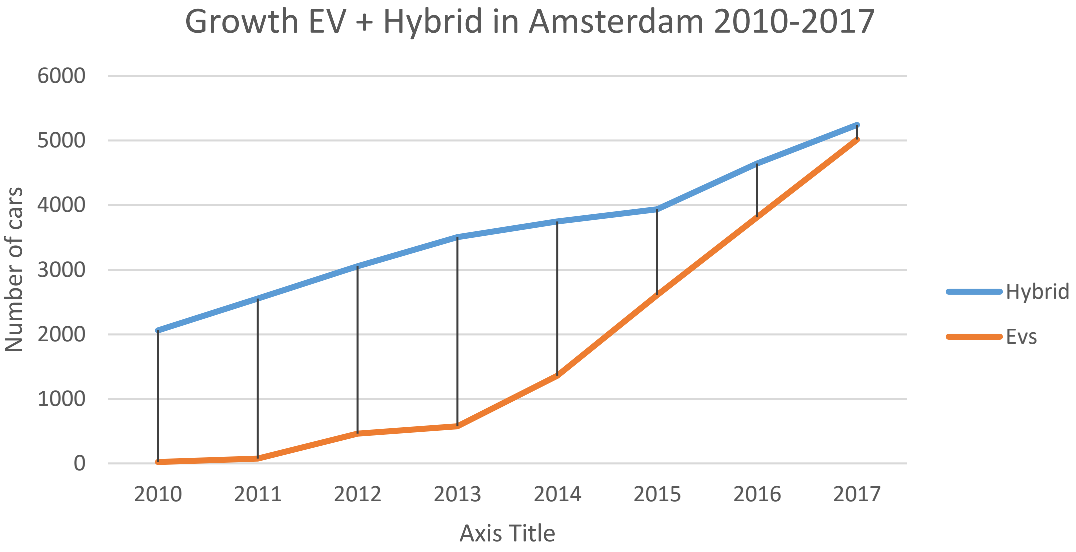
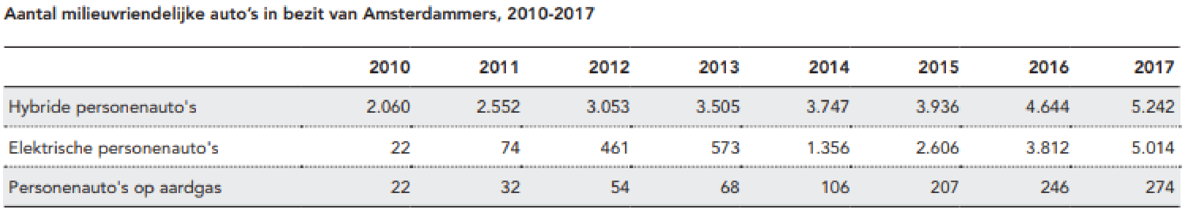


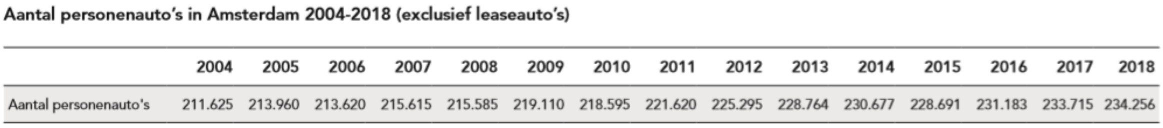
Figure 45, EV and Plug-in growth Amsterdam

Table 32, Growth table EVs and plug-in hybrids



Aantal milieuvriendelijke auto's in bezit van Amsterdammers, 2010-2017

	2010	2011	2012	2013	2014	2015	2016	2017
Hybride personenauto's	2.060	2.552	3.053	3.505	3.747	3.936	4.644	5.242
Elektrische personenauto's	22	74	461	573	1.356	2.606	3.812	5.014
Personenauto's op aardgas	22	32	54	68	106	207	246	274



Aantal personenauto's in Amsterdam 2004-2018 (exclusief leaseauto's)

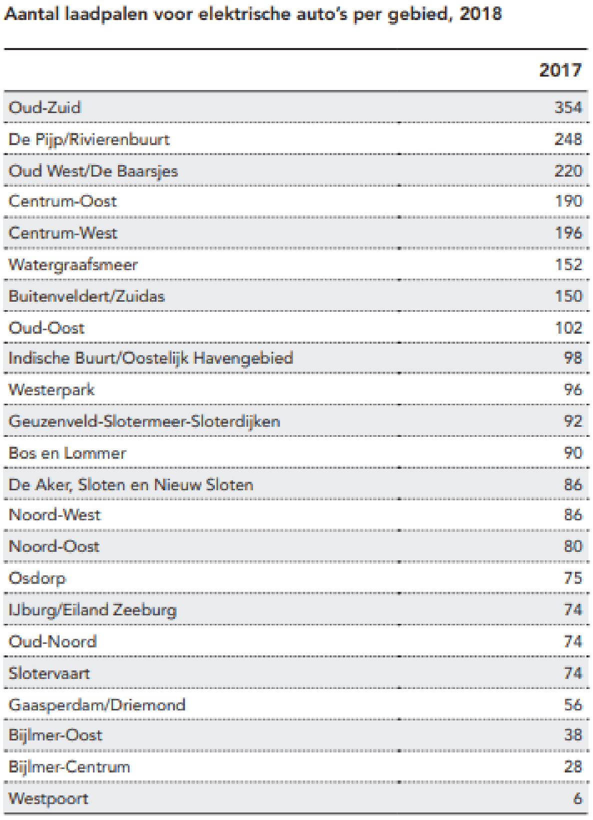
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Aantal personenauto's	211.625	213.960	213.620	215.615	215.585	219.110	218.595	221.620	225.295	228.764	230.677	228.691	231.183	233.715	234.256

Source: Amsterdamse Thermometer voor de Bereikbaarheid (Gemeente Amsterdam, 2019).

EVs distribution in Amsterdam

The number of EVs registered in Amsterdam are allocated over the Amsterdam districts with the help of public charging stations. A district with many public charging stations indicate that that district probably has many registered EVs, and vice versa. In the table 33 below, the number of public charging stations are noted.

Table 33, Number of PCS in Amsterdam



Aantal laadpalen voor elektrische auto's per gebied, 2018

	2017
Oud-Zuid	354
De Pijp/Rivierenbuurt	248
Oud West/De Baarsjes	220
Centrum-Oost	190
Centrum-West	196
Watergraafsmeer	152
Buitenveldert/Zuidas	150
Oud-Oost	102
Indische Buurt/Oostelijk Havengebied	98
Westerpark	96
Geuzenveld-Slotermeer-Sloterdijken	92
Bos en Lommer	90
De Aker, Sloten en Nieuw Sloten	86
Noord-West	86
Noord-Oost	80
Osdorp	75
IJburg/Eiland Zeeburg	74
Oud-Noord	74
Slotervaart	74
Gaasperdam/Driemond	56
Bijlmer-Oost	38
Bijlmer-Centrum	28
Westpoort	6

Source: Amsterdamse Thermometer voor de Bereikbaarheid (Gemeente Amsterdam, 2019).

EV distribution in surrounding districts

The same allocation method is used for surrounding districts. However, since no information is known on the combined number of EVs in these districts, this is estimated according to the national average. These national averages (table 34) then lead to the number of EVs in surrounding district (see table 35).

Table 34, EV distribution ratios

Description	Value
Total number of inhabitants NL*	17,2
Total number of cars NL*	8,4
Total number of EVs NL*	0,144
Percentage EVs**	18%
Average number of cars per inhabitants**	0,48

*Source: CBS Statline, 2018
**Source: Amsterdamse Thermometer voor de Bereikbaarheid (Gemeente Amsterdam, 2019)

Table 35, Number of PCS in surrounding districts

	Amstelveen	Zaandam	Haarlem	Hoofddorp	Diemen	Badhoevedorp	P-R
Public charging station	162	36	105	69	24	30	51
Inhabitants	88.600	155.000	159.700	75.000	10.000	12.600	102.200
EV per district	1715	381	1111	730	254	318	540
% of EVs of total EV fleet	0,34	0,08	0,22	0,14	0,05	0,06	0,11

Source: chargemap.com, accessed: 28-05-2019

A.4 COMMUTING TRENDS

This section will contain all the extra information concerning the commuting trends. This data is used to estimate the number of commuting traffic between districts. The number of aggregated commutes between districts (Vervoerregio, 2018) are as a basis to calculate the number of commutes by EV between all districts. To transform the aggregated data to detailed data the district characteristics in the tables below are used (see table **36-37**). The first table entails information concerning characteristics of the Amsterdam districts, where the second table entails information concerning the characteristics of surrounding districts.

Table 36, Amsterdam characteristics used for estimating the commuting trends

	Inhabitants	Number of jobs	Percentage of jobs of total	Number of working people	Working people take car
Centrum	86.400	102.598	0,194688	44707	7153
Noord	91.300	32.316	0,061322	47242	23621
West	142.800	48.402	0,091846	73891	9606
Nieuw-West	146.800	76.718	0,145578	75960	32663
Oost	128.700	62.622	0,11883	66595	16649
Westpoort	2.000	21.920	0,041595	1035	517
Zuid-Oost	84.600	76.770	0,145677	43776	14446
Zuid	141.400	105.642	0,200464	73166	18292
Diemen	10.000	22.100	0,040249	5174	1708

Sources: CBS Statline 2018

Table 37, Surrounding districts characteristics used for estimating the commuting trends

	Inhabitants	Number of jobs	Percentage of jobs of total	Modal Split** (%)	Number of working people	ModalSplit car
Amstelveen	88.600	43.300	0,26457	43	45845	19714
Haarlem	159.700	66.300	0,405104	43	82635	35533
Badhoeve-dorp*	12.600	7776	0,047513	43	6520	2804
Hoofd-dorp*	75.000	46285,71	0,282813	43	38808	16688
Total		163.662	1			
Zaanstad	155.000	52.800	0,655901	43	80203	34488
P-R	102.200	27.700	0,344099	43	52883	22740
Total		80.500	1			

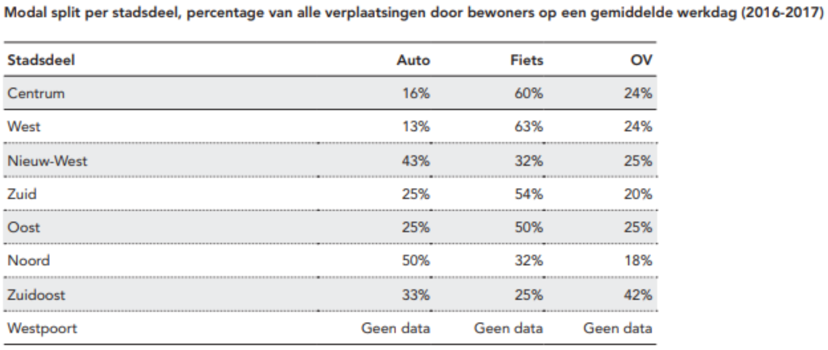
Sources: Statline 2018, Regionale Thermometer voor de Mobiliteit (Vervoerregio, 2018)

*Badhoevedorp and Hoofddorp are caculated with the help of Haarlemmermeer data. The number of jobs of schipol are substracted, leaving the number of jobs which can be divided over the districts.

Model split Amsterdam

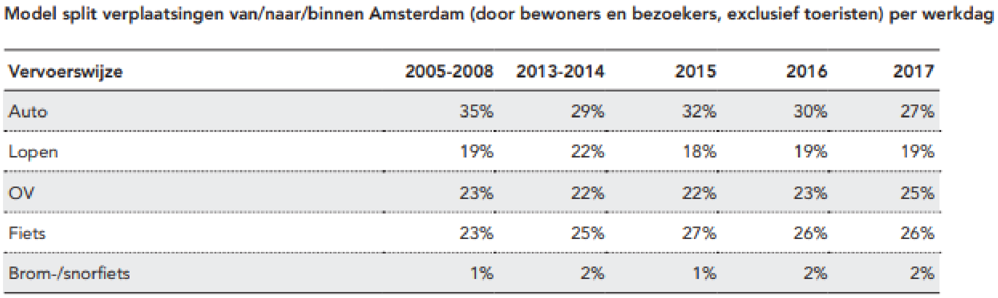
Modal split and extra information about the mode choices of Amsterdam inhabitants is derived from the a research into the mobility and accessibility of the city of Amsterdam (Gemeente Amsterdam, 2019). This research used these modal split ratios to calculate the commuting trends between districts (see table 38)

Table 38, Modal split data of Amsterdam districts



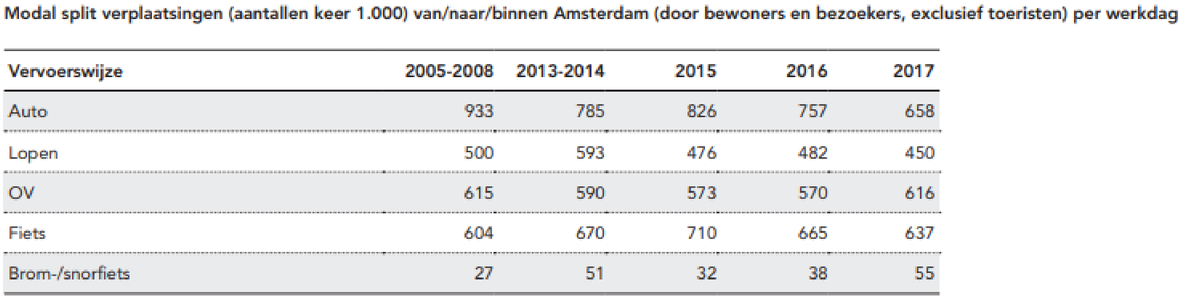
Modal split per stadsdeel, percentage van alle verplaatsingen door bewoners op een gemiddelde werkdag (2016-2017)

Stadsdeel	Auto	Fiets	OV
Centrum	16%	60%	24%
West	13%	63%	24%
Nieuw-West	43%	32%	25%
Zuid	25%	54%	20%
Oost	25%	50%	25%
Noord	50%	32%	18%
Zuidoost	33%	25%	42%
Westpoort	Geen data	Geen data	Geen data



Model split verplaatsingen van/naar/binnen Amsterdam (door bewoners en bezoekers, exclusief toeristen) per werkdag

Vervoerswijze	2005-2008	2013-2014	2015	2016	2017
Auto	35%	29%	32%	30%	27%
Lopen	19%	22%	18%	19%	19%
OV	23%	22%	22%	23%	25%
Fiets	23%	25%	27%	26%	26%
Brom-/snorfiets	1%	2%	1%	2%	2%



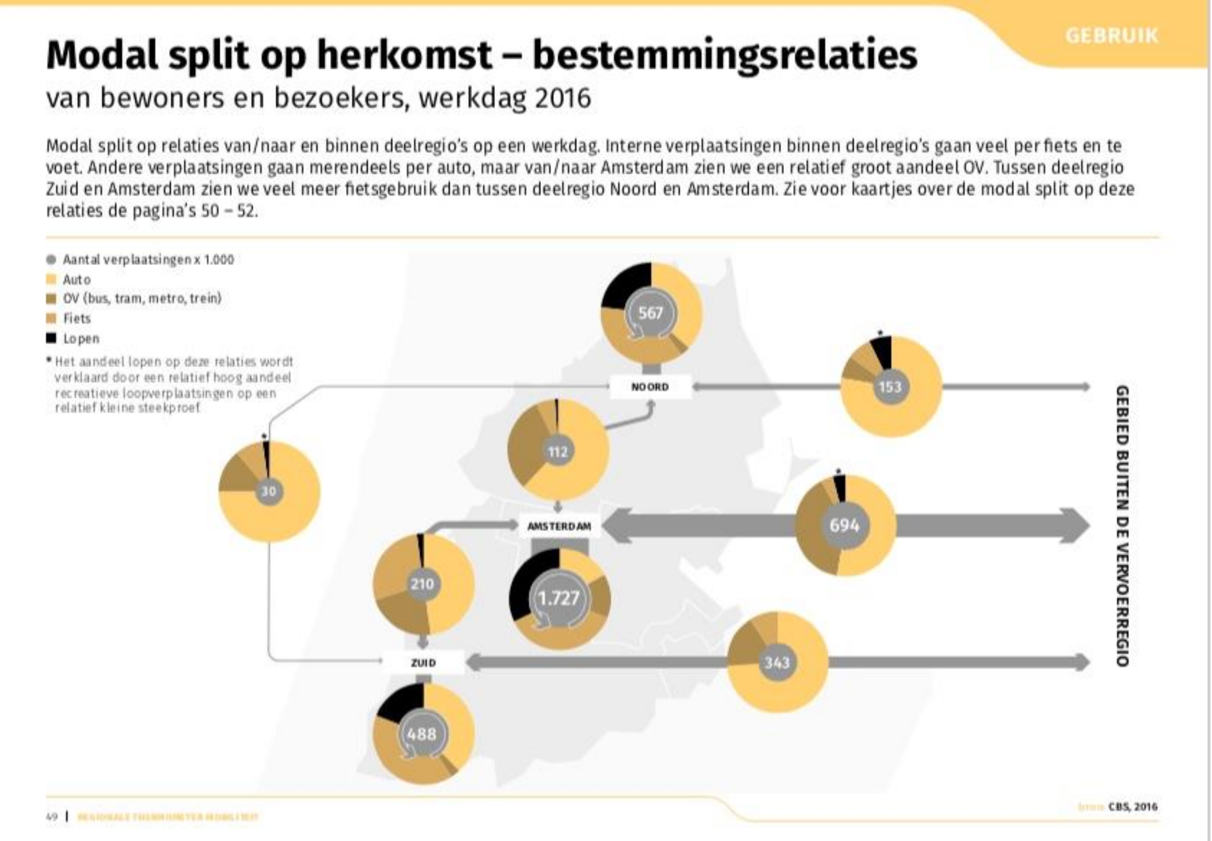
Modal split verplaatsingen (aantallen keer 1.000) van/naar/binnen Amsterdam (door bewoners en bezoekers, exclusief toeristen) per werkdag

Vervoerswijze	2005-2008	2013-2014	2015	2016	2017
Auto	933	785	826	757	658
Lopen	500	593	476	482	450
OV	615	590	573	570	616
Fiets	604	670	710	665	637
Brom-/snorfiets	27	51	32	38	55

Source: Amsterdam Thermometer voor de Bereikbaarheid (Gemeente Amsterdam, 2019).

Model split surrounding districts

The modal split of the surrounding districts is estimated using the Regionale Thermometer voor de Bereikbaarheid. This document has aggregated the districts north of Amsterdam, south of Amsterdam, and Amsterdam itself to three regions (see figure 46). The data from this report is converted to percentages (see table 39). These modal split data are transformed to district specific information using the number of inhabitants per district (see appendix A.1).



Modal split op herkomst – bestemmingsrelaties

van bewoners en bezoekers, werkdag 2016

Modal split op relaties van/naar en binnen deelregio's op een werkdag. Interne verplaatsingen binnen deelregio's gaan veel per fiets en te voet. Andere verplaatsingen gaan merendeels per auto, maar van/naar Amsterdam zien we een relatief groot aandeel OV. Tussen deelregio Zuid en Amsterdam zien we veel meer fietsgebruik dan tussen deelregio Noord en Amsterdam. Zie voor kaartjes over de modal split op deze relaties de pagina's 50 – 52.

* Het aandeel lopen op deze relaties wordt verklaard door een relatief hoog aandeel recreatieve loopverplaatsingen op een relatief kleine steekproef

Figure 46, Modal split data surrounding districts

Source: Regionale Thermometer voor de Bereikbaarheid (Vervoerregio, 2017)

Table 39, Modal split data of surrounding districts

Commutes	**Zuid**	**Noord**	**Amsterdam**
Zuid	488	30	210
Noord	30	567	112
Amsterdam	210	112	1727
Other	343	153	694
Total	1071	862	2743

%	**Zuid**	**Noord**	**Amsterdam**
Zuid	0,455649	0,034803	0,076558513
Noord	0,028011	0,657773	0,040831207
Amsterdam	0,196078	0,12993	0,629602625
Other	0,320261	0,177494	0,253007656
Total	1	1	1

Commuting traffic

The origin-destination data of the surrounding districts are estimated using the Regionale Thermometer voor de Bereikbaarheid. This document has aggregated the districts north of Amsterdam, south of Amsterdam, and Amsterdam itself to three regions (see figure 47). These origin-destination datas is transformed to district specific information using the number of inhabitants per district (see appendix A.1).

GEBRUIK

Aandeel auto per herkomst – bestemmingsrelatie

werkdag 2016

Aandeel auto op relaties van/naar en binnen deelregio's op een werkdag. Het grootste aandeel auto zien we tussen de deelregio's Noord en Zuid en het gebied dat buiten de Vervoerregio ligt, maar ook tussen de deelregio's Noord en Zuid onderling.

Figure 47, Original Origin-Destination data of surrounding districts

OD Matrix

The information above (see figure 39) have led to the OD below. This table contains the number of EV car commutes from district to district.

Table 40, Complete origin-destination matrix

	Centrum	**Noord**	**West**	**Nieuw-West**	**Oost**	**West-poort**	**Zuid-Oost**	**Zuid**	**Amstel-veen**	**Haarlem**	**Badhoeve-dorp**	**Hoofd-dorp**	**Zaanstad**	**P-R**	**Diemen**	Total To
Centrum	877	2897	1178	4006	2042	63	1772	2244	768	1384	109	650	873	576	206	19644
Noord	276	913	371	1262	643	20	558	707	242	436	34	205	275	181	65	6188
West	414	1367	556	1890	963	30	836	1058	362	653	51	307	412	272	97	9268
Nieuw-West	656	2166	881	2996	1527	47	1325	1678	574	1035	82	486	653	430	154	14689
Oost	536	1768	719	2445	1246	39	1081	1369	469	844	67	397	533	351	126	11990
Westpoort	187	619	252	856	436	14	379	479	164	296	23	139	186	123	44	4197
Zuid-Oost	656	2168	882	2998	1528	47	1326	1679	574	1035	82	486	653	431	154	14699
Zuid	903	2983	1213	4125	2103	65	1824	2310	790	1425	112	669	899	593	212	20227
Amstelveen	132	437	178	605	308	10	268	339	2347	4230	334	1987	274	180	32	11661
Haarlem	203	670	272	926	472	15	410	519	3594	6478	511	3042	419	276	48	17855
Badhoeve-dorp	24	79	32	109	55	2	48	61	421	760	60	357	49	32	6	2094
Hoofddorp	142	468	190	647	330	10	286	362	2509	4522	357	2124	293	193	34	12465
Zaanstad	188	620	252	857	437	14	379	480	388	699	55	328	14929	9844	45	29514
P-R	98	325	132	450	229	7	199	252	204	367	172	172	7832	5164	24	15627
Diemen	181	599	244	828	422	13	366	464	159	286	23	134	180	119	43	4061
Total From	5475	18079	7352	24999	12742	396	11056	14000	13564	24449	2072	11482	28460	18765	1289	

Table 41, Complete origin-destination table in percentages

	Centrum	**Noord**	**West**	**Nieuw-West**	**Oost**	**Westpoort**	**Zuid-Oost**	**Zuid**	**Amstelveen**	**Haarlem**	**Badhoevedorp**	**Hoofddorp**	**Zaanstad**	**P-R**	**Diemen**
Centrum	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,06	0,06	0,05	0,06	0,03	0,03	0,16
Noord	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,02	0,02	0,02	0,02	0,01	0,01	0,05
West	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,03	0,03	0,02	0,03	0,01	0,01	0,08
Nieuw-West	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,04	0,04	0,04	0,04	0,02	0,02	0,12
Oost	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,03	0,03	0,03	0,03	0,02	0,02	0,10
Westpoort	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,01	0,01	0,01	0,01	0,01	0,01	0,03
Zuid-Oost	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,04	0,04	0,04	0,04	0,02	0,02	0,12
Zuid	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,17	0,06	0,06	0,05	0,06	0,03	0,03	0,16
Amstelveen	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,17	0,17	0,16	0,17	0,01	0,01	0,02
Haarlem	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,26	0,26	0,25	0,26	0,01	0,01	0,04
Badhoevedorp	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,03	0,03	0,03	0,00	0,00	0,00
Hoofddorp	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,18	0,18	0,17	0,18	0,01	0,01	0,03
Zaanstad	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,52	0,52	0,03
P-R	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,08	0,02	0,28	0,28	0,02
Diemen	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,01	0,01	0,01	0,01	0,01	0,01	0,03
Total	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

APPENDIX B: CASE I

This appendix will contain all the information which is used to calculate the cost-effectiveness of the first case. The system components are transformers and cables.

B.1 ASSUMPTIONS

In the yearly quality and capacity document on Liander's electricity network the company documents its performance and identifies its (future) bottlenecks (Liander, 2018). This document is used to estimate component costs for upgrading the infrastructural (see section 2.5.). In this document, Liander noted the ratio of components which are likely to overload with the increasing supply of decentralized solar energy through the components in the foreseeable future. However, the document lacks a through scenario description of this foreseeable future.

IMPORTANT: This research assumes that Liander used an average growth rate of 10% with a time span of 22 years. The failure rates which are used for the high and low growth rates (see chapter 4) are derived from this assumption. This assumption is used in calculating the costs related to upgrading the transformers in all three cases.

B.2 LIANDER TRANSFORMERS COSTS

Extracted from a dataset received from Liander containing all transformers in the Amsterdam region (see table 42). These are then placed into the districts of their location.

Table 42, Number of Liander MV/LV and HV/MV transformers

	MV/LS transformer	HV/MV transformer
Centrum	274	10
Noord	193	4
Oost	209	3
Zuid	201	4
West	158	-
Nieuw-West	200	6
Westpoort	59	10
Zuid-Oost	112	-
Total	*1406*	*43*
Amstelveen	246	4
Zaandam	406	10
Haarlem	301	10
Hoofddorp	214	4
Diemen	64	-
Badhoevedorp	42	-
Purmerend-Volendam	342	-
Total	*1615*	*36*

Source: Liander dataset concerning all transformers in the Amsterdam region.

Upgrading cost per transformer

In order to calculate the extra capacity after which a transformer needs upgrading a roadmap is constructed. The costs are estimated with the help of Liander's base case scenario (Liander, 2018). This roadmap is listed below, further explanation can be found below the roadmap.

(1) Failure ratio (Base scenario, 10% increase in solar energy output)
(2) Calculate number of failed transformers with failure ratio
(3) Calculate difference in solar energy output between 2018 and 2040 (base case scenario)
(4) Divide (3) by (2) and you know the height of the increase in MWh which will result in the upgrading of a transformer

1: Failure rates

We calculate the MWh increase which result in upgrading a transformer. This is calculated by the fact that a 10% increase in solar energy output a X percent of transformers need to be updated (see table 43). Because the solar energy output almost doubles in the high growth scenario, relative to Liander base case scenario, the component fails ratio doubles to 20% and 80%. A reverse effect is seen in the low growth scenario. Here, the solar energy output is decreases by half, relative to the base case scenario. And therefore, also decreases the number fail ratio by half.

Table 43, Transformer failure rates

	Growth scenario10% (Base case)[5]
HS/MS transformatoren	10%
MS/LS transformer	40%

Source: Kwaliteit en capaciteitsdocument 2017, Liander (2018).

2: Number of failed transformers per district

The number of failed transformers is calculated with the number of transformers (see table 44) multiplied by the failure ratio (see table 43).

Table 44, Number of transformers which need upgrading identified by Liander

District	**Upgraded MS/LS Transformers**	**upgraded HS/MS Transformers**
Centrum	110	1
Noord	77	0,4
Oost	84	0,3
Zuid	80	0,4
West	63	0,1
Nieuw-West	80	0,6
Westpoort	24	1
Zuid-Oost	45	0,5
Amstelveen	98	0,4
Zaandam	162	1

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[5] Extracted from Kwaliteit en Capaciteiten document 2017. Assumes that they used a medium growth scenario of solar energy output (see section 6.2.)

Haarlem	120	1
Hoofddorp	86	0,4
Diemen	26	0,1
Badhoevedorp	18	0
Purmerend-Volendam	137	0,7

Source: Output of numerical model.

3: Growth difference of solar energy output

In the third step we subtract the output in the growth scenario, with the starting solar energy output in 2018. These numbers can be found in table 45, columns 1-3.

4: Failure rates of per increase of MWh

In the fourth and final step the increase in solar energy output, calculated in (3) is divided by the number of upgraded transformers per district (2). We now know what increase in MWh will lead to the upgrading of a transformer (see table 45). Upgrading transformers does not happen with a certain threshold level of increased MWh because it is not known what the current utilization of each transformer is. Also, because this thesis aggregates its data to a district level, a specific threshold per transformer is not necessary. For this reason, the districts have a different increase ratio of MWh per upgraded transformer.

Table 45, Ratio of transformers that need upgrading in Liander scenario

Base case scenario	2018 [MWh]	10% Scenario [MWh]	increase [MWh]	Total Upgrade MV/LV *	Total Upgrade HV/MV *	MWh / upgrade MV/LV	MWh / upgrade HV/MV
Centrum	1077	13159	12082	110	1,0	110	12082
Noord	4470	54617	50147	77	0,4	650	125368
Oost	4468	54593	50125	84	0,3	600	167083
Zuid	3435	41971	38536	80	0,4	479	96340
West	2372	28983	26611	63	0,1	421	266106
Nieuw-West	3920	47897	43977	80	0,6	550	73295
Westpoort	1588	19403	17815	24	1,0	755	17815
Zuid-Oost	3933	48056	44123	45	0,5	985	88246
Amstelveen	2283	27891	25609	98	0,4	260	64022
Zaandam	2575	31459	28884	162	1,0	178	28884
Haarlem	2653	32413	29760	120	1,0	247	29760
Hoofddorp	2003	24471	22468	86	0,4	262	56170
Diemen	465	5680	5215	26	0,1	204	52155
Badhoevedorp	437	5345	4907	17	0,0	292	0
Purmerend-Volendam	4751	58053	53302	137	0,7	390	76146

Source: Output of numerical model.
*Number of transformers (HV/MV and MV/LV) are derived from failure rate, see step 2 and 3.

B.3 LIANDER CABLE COSTS

Liander knows exactly how many kilometers of MS and LS cable it has operational in its area (Liander, 2018). It also kept track of how many of these cables are “old GPLK” cables (see table 46). The costs for upgrading the MV and LV cables is done by an estimation done by Verzijlbergh (2013). His research concluded that HV cables are unlikely to overload. MV and LV cables are expected to overload, however this thesis assumes that the electricity distribution on the LV grid does not cause problems. Therefore, only the MS-cables are taken into account. If the decentralized renewable energy production and the quantity of electricity put back into the grid increases, many of Alliander’s transformers are expected to overload. According to Verzijlbergh (2013) 13% percent of the MS-cables are likely to overload. Again, just as the failure rates of the transformers, this percentage is assumed to accompany a medium growth rate. Recalculated for the growth scenarios constructed in chapter 4, this leads to a growth rate of 6,5% in the low growth scenario and 26% in the high growth scenario.

Table 46, Liander cable data

Component	Price*	Failure ratio*	Quantity installed in the Amsterdam Region**
HV-cables	-	-	-
MV-cables	60 euro / meter	6,5% - 26% LOW - HIGH	5625 km
LV-cables	-	-	-

*Source: Verzijlbergh (2013)
** Source: Kwaliteit en capaciteitsdocument 2017, Liander (2017)

B.4 TOTAL COSTS

The high growth scenario and the low growth scenario are calculated my multiplying with the corresponding failure rate relative to the failure rate set by Liander's base case (Liander, 2018). These failure rates are:

Table 47, Transformer failure rates used in constructed scenarios

Component failure ratio	Growth scenario10% (Base case)	Growth scenario 5% (low)	Growth scenario 14% (high)
HS/MS transformers	10	9.5	20
MS/LS transformers	40	20	80

Source: Extracted from Kwaliteit en Capaciteiten document 2017. Assumes that they used a medium growth scenario of solar energy output (see section 6.2.)

The failure rates in the table above are used to determine the total costs associated by upgrading the transformers (see table 48). The total costs for upgrading the electricity infrastructure in the traditional way is by adding the investment costs of transformers and cables together.

Table 48, Total transformer IC in constructed scenarios

	5% growth scenario	14% growth scenario
Centrum	43069306	135213600
Noord	24383061	82706796
Oost	23799652	84079523
Zuid	25069425	85452250
West	15511814	58340893
Nieuw-West	28895901	93345429
Westpoort	24623288	61429529
Zuid-Oost	19389767	59027257
Amstelveen	28930219	100895427
Zaandam	54394303	180513588
Haarlem	45385783	144479507
Hoofddorp	26184765	89913612
Diemen	7447043	26081811
Badhoevedorp	3603408	14413632
Purmerend-Volendam	43034988	146195415
Total [million]	*413,72*	*1362,09*

Source: Output of numerical model.

APPENDIX C: CASE II

The cost calculation for V2H consists of multiple components. These components are: bidirectional chargers, transformers and cables.

C.1 V2H IMPACT

The potential impact of V2H in the Amsterdam districts can be assessed with 3 steps. The three steps are listed below.

Step 1: Surplus Solar Energy

Solar energy produced per district, minus the average electricity consumption per district (see table 49). The districts Noord, Oost, Westpoort, Zuid-Oost and Purmerend-Volendam produce more solar energy than they consume in the high growth scenario by 2040 (see figure 48). This surplus solar energy can then be stored in EVs.

Table 49, Electricity consumption per district

	Districts	kWh per year	MWh per year	Total MWh consumption
Amsterdam Districts*	Centrum	2620	2,62	58601
	Noord	2620	2,62	46705
	Oost	2620	2,62	74169
	Zuid	2620	2,62	86662
	Sest	2620	2,62	84456
	Nieuw-West	2620	2,62	84466
	Westpoort	2620	2,62	38
	Zuid-Oost	2620	2,62	44048
Surrounding Districts**	Amstelveen	2910	2,91	62369
	Zaanstad	2640	2,64	91906
	Haarlem	2470	2,47	95028
	Hoofddorp	2800	2,8	44394
	Diemen	3150	3,15	22261
	Badhoevedorp	2800	2,8	7819
	Edam-Volendam	3140	3,14	79180

*Source: Kerncijfers Amsterdam 2018
**Source: CBS Statline: Energieverbruik particuliere woningen, 2018

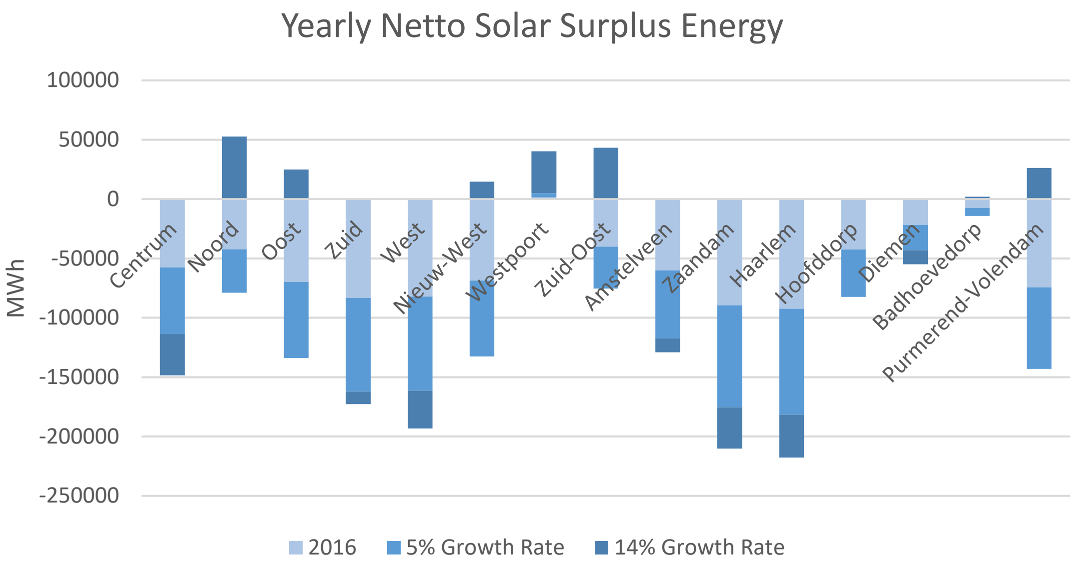

Figure 48, Yearly netto solar surplus energy per district

Step 2: Surplus Energy Stored

The number of MWh of surplus solar energy which can be stored is dependent on the consumption within this district. This thesis assumes that the surplus solar energy is able to transport freely over the LS infrastructure and thus can be distributed freely within the districts. The solar energy in districts which produce more than they consume can then be stored in EVs. The height of the storage is dependent on the storage capacity of each district. This is calculated with the formulas below. Figure 49 shows how many MWh are stored in EVs per district. The stored surplus solar energy is low compared to the total solar energy output in each district. This is due to the fact that large portions of the produced energy is consumed within the district. This low number of surplus solar energy which can be stored in EVs is also found in a Tokyo case study (Yamagata & Seya, 2015).

$$if\ SC_{i,EV} < \ Surplus_{i,solar}\ then \quad SS_i = \ SC_{i,EV}$$

$$if\ SC_{i,EV} > \ Surpus_{i,solar}\ then \quad SS_i = \ Surpus_{i,solar}$$

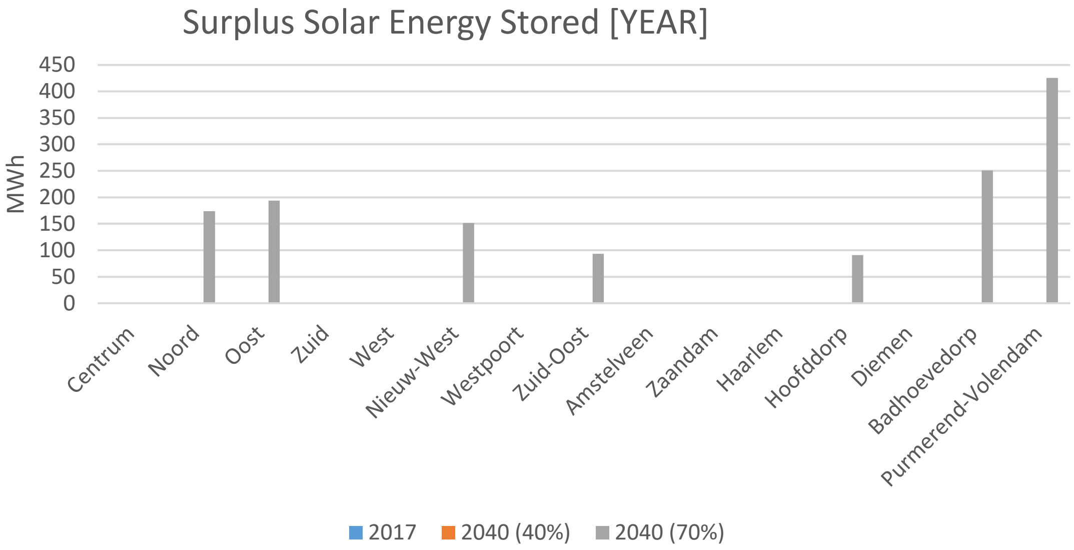

Figure 49, Yearly surplus solar electricity per district

Step 3: Energy Supply of EVs
Potentially the energy which can be supplied by EVs is dependent on the State-Of-Charge (SOC) of the EV as well as the minimum amount of EV charge (20%). This thesis assumes an average SOC of 0,7. Figure 50 shows how much electricity can potentially be transferred back to the districts using V2H.

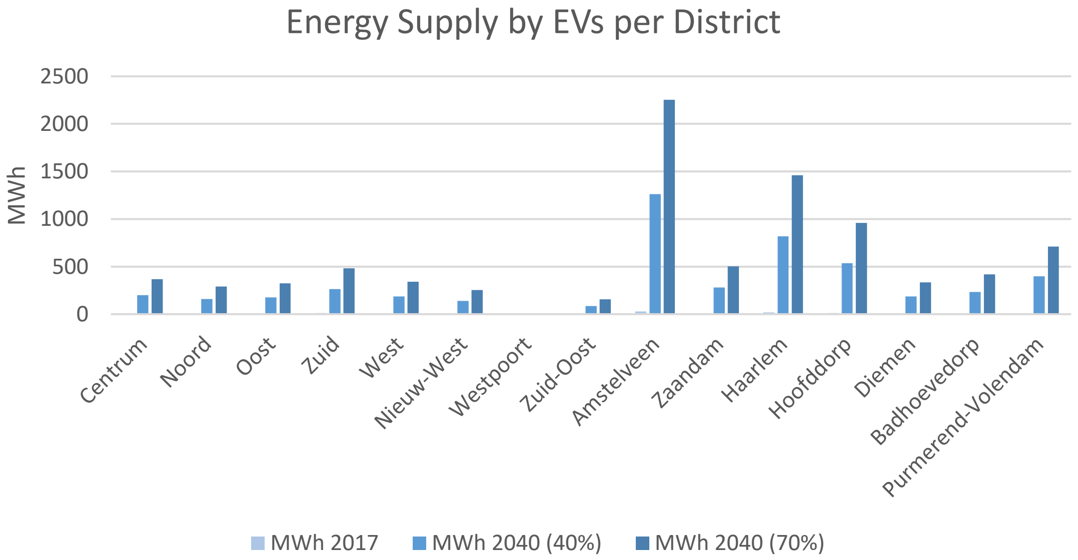

Figure 50, EV discharge capacity per district

C.2 BENEFITS

Table 50, shows how much of the surplus solar energy is stored. These MWh do not need to be transported over the infrastructure. Therefore, less transformers need to be upgraded. This output is then used as inputs in order to calculate the prevented investments costs in transformers.

Table 50, Surplus solar energy per district

District	2018	2040 (40%)	2040 (70%)
Centrum	0	0	0
Noord	0	0	63362,1
Oost	0	0	25048,1
Zuid	0	0	0
West	0	0	0
Nieuw-West	0	0	14544,5
Westpoort	9,8	3495,7	313,2
Zuid-Oost	0	0	43312,8
Amstelveen	0	0	0
Zaandam	0	0	0
Haarlem	0	0	0
Hoofddorp	0	0	90,9
Diemen	0	0	0
Badhoevedorp	0	0	1897,2
Purmerend-Volendam	0	0	26355,1

Source: Output of numerical model

By multiplying the quantities of MWh with the increase of MWh per upgraded transformer (see appendix B.2), the potential cost savings per district can be calculated (see table 51).

Table 51, Number of prevented transformers per district per scenario

	Less MS/LS Transformers			Less HS/MS Transformers			Potential cost savings		
	2018	*2040 low*	*2040 high*	*2018*	*2040 low*	*2040 high*	*2018*	*2040 low*	*2040 high*
Centrum	0	0	0	0	0	0	0	0	0
Noord	0	0	574,8	0	0	5,2	0	0	20661859
Oost	0	0	227,2	0	0	2,1	0	0	8167991
Zuid	0	0	0	0	0	0	0	0	0
West	0	0	0	0	0	0	0	0	0
Nieuw-West	0	0	131,9	0	0	1,2	0	0	4742825
Westpoort	0,08	31,70	2,8	0,0008	0,3	0,03	3212	1139905	102137
Zuid-Oost	0	0	392,9	0	0	3,6	0	0	14123949
Amstelveen	0	0	0	0	0	0	0	0	0
Zaandam	0	0	0	0	0	0	0	0	0

Haarlem	0	0	0	0	0	0	0	0	0
Hoofddorp	0	0	0,8	0	0	0,008	0	0	29653
Diemen	0	0	0	0	0	0	0	0	0
Badhoevedorp	0	0	17,2	0	0	0,2	0	0	618664
Purmerend-Volendam	0	0	239,1	0	0	2,2	0	0	8594183

Source: Output of numerical model

The transformers which need to be upgraded (see table above) are used to calculate the total costs savings. The component costs can be found in section 6.3. The total costs prevented in investing in infrastructural components accumulates to between 1,14 and 57,04 million euro (see table 52).

Table 52, Total prevented costs per scenario

	2040 low	**2040 high**
Total [euro]	1139905	57041265
Total [million euro]	1,14	57,04

Source: Output of numerical model

C.3 COSTS

The costs of bidirectional chargers are calculated with the help of data in table 53.

Table 53, PBC assumptions

Type	Number	Description
Private bi-directional chargers*	0,333333	Households with home charger
Public bi-directional chargers**	10	EV per public charging station

*Source: Authors assumption
**Source: Roll-out of public EV charging infrastructure in the EU (Mathieu, 2018)

The total investment costs related to bi-directional chargers are calculated with the component costs. These costs can be found in section 6.3. The number of components is derived from the number of EVs (see section 4.3). The total costs of bi-directional chargers can be found in the table below (see table 54).

Table 54, Total BDC IC per district

$\mathbf{IC}_{\mathbf{chargers}}$	**description**	**2018**	**2040 low**	**2040 High**
BDC	Number of public chargers	3142,00	17908,21	32182,94
	Number of private chargers	2912,68	59694,03	107276,47
households costs	[million]	29,13	596,94	1072,76
Public costs	[million]	31,42	179,08	321,83

Source: Output of numerical model

APPENDIX D: CASE III

This case's cost calculation uses transformers and cables to calculate its total case cost. This case also uses the V2H technology. The costs for this case can be found in appendix C. In this case these costs would have to be made. The costs presented below will be on top of the V2H cost, but they will improve the effectiveness of the case.

D.1 TOTAL COSTS

The cost calculation for this case can be divided into three steps. The steps are explained in more detail below. The steps are:

(1) Calculate the difference between the night time surplus difference of the districts in the proposed network links
(2) Calculate the MWh flow between these districts
(3) Calculate the number of components which need to be upgraded
(4) Calculate the total costs of these upgraded components

Step 1: Difference

This first step calculates the difference between the night time consumption and the night time storage capacity of the districts subjected in the proposed network links (see table 55). This is called the surplus discharge. A district with a positive surplus discharge value means that this district has more EV storage capacity than the district consumes in the evening. A negative value means that the district consumes more electricity than it stores in EVs in the night.

Table 55, Difference between surplus solar energy and EV discharge capacity

Surplus discharge in MWh	**Amstelveen**	**Zuid**	**Zuid-Oost**	**Bahoevedorp**	**Nieuw-West**	**Hoofddorp**
2018	-59364	-85249	-43594	0	0	0
2040 LOW	75814	-57717	-34751	17770	-57429	14462
2040 HIGH	184463	-33681	-27030	37891	-44891	60738

Source: Output of numerical model

Step 2: Calculate flow of electricity

The discharge surplus of Amstelveen is divided over Zuid and Zuid-Oost (see table 56). The flow between Badhoevedorp - Nieuw-West and Hoofddorp - Nieuw-West does not need to be divided since it entails only one connection. The maximum amount of electricity flow is used in this calculation.

Table 56, Flow of electricity per district

Flow of electricity [MWh]	**Link 1: Zuid**	**Link 1: Zuid-Oost**	**Link 2: Nieuw-West**	**Link 2: Wieuw-West**
2018	0	0	0	0
2040 LOW	57717,39	18096,93	39658,44	14461,68
2040 HIGH	33681,32	27030,12	37890,58	44890,99

Source: Output of numerical model

Step 3: Calculate number of components

The number of components which need to be upgraded are calculated with the same failure ratios as in case I. The same procedure was followed as in case I. See appendix B.2 to find these procedures and ratios. Table 57, contains the number of transformers which need to be upgraded.

Table 57, Number of transformers which need upgrading in new case

	Link 1			**link 2**		**link 3**	
	Amstel-veen	Zuid	Zuid-Oost	Badhoeve-dorp	Nieuw-West	Hoofd-dorp	Nieuw-West
2018	0	0	0	0	0	0	0
2040 LOW	291,3	120,4	18,4	60,8	72,1	55,1	26,3
2040 HIGH	708,8	70,3	103,9	129,7	68,9	231,4	81,7

Source: Output of numerical model

Furthermore, the MV-cables must be updated in this case. This thesis assumes that the electricity connection between districts is facilitated by 1 MV-cable connection. The distances between the district's centres are used to calculate the investment costs (see table 58).

Table 58, Distance of network links

From	To	Distance [km]
Amstelveen	Zuid	5
Amstelveen	Zuid-Oost	10
Badhoevedorp	Nieuw-West	5
Hoofddorp	Nieuw-West	15

Source: Output of numerical model

Step 4: Calculate the costs of the components

The formulas used to calculate the total costs of transformers are the same as used in the previous component costs calculations. For formulas, see section 2.4. Transformers costs are costs for upgrading the transformers in both districts (origin and destination). Furthermore, the OMC calculations for the cables and transformers, and the calculations regarding the transportation costs are the same as used in the calculation of the previous cases (see table 59).

Table 59, Cable investment costs per network link

	Cables [km]	**Cables** [m]	**Costs cables** [million]	**OMC total (High / low scenario)** [million]
Amstelveen - Zuid	5 km	5000	5,148	5,69
amstelveen - Zuid-Oost	10km	10000	10,296	11,52
Badhoedorp – Nieuw-West	5 km	5000	5,148	1,35
				2,71

Hoofddorp – Nieuw-West	15 km	15000	15,444	1,51
				4,49

Source: output of numerical model

The table below state the total costs for each network link in both scenarios (see table 54). The maintenance and operation costs for cables and transformers can be found in the table above (see table 60).

Table 60, Total IC in network links

IC	Amstel-veen	Zuid	Zuid-Oost	Badhoeve-dorp	Nieuw-west	Hoofd-dorp	Nieuw-west
2018	0	0	0	0	0	0	0
2040 LOW	124,97	51,66	7,88	26,10	13,87	23,64	11,29
2040 HIGH	304,07	30,15	44,56	55,65	29,57	99,27	35,03

Source: output of numerical model

D.2 ASSUMPTIONS

The assumptions made with within the calculations are:

- SOC= 70%
- Minimum SOC= 20%
- Night time is half energy demand of total energy consumption

APPENDIX E: SENSITIVITY ANALYSIS

This appendix will entail details about the sensitivity analysis performed on the costs of all the three cases. The sensitivity analysis on the total costs of each case is performed with a 5% increase and decrease (see table 61).

Table 61, Complete sensitivity analysis on total cost of all cases

	Case I		**Case II**		**Case III**	
	High Growth Scenario	Low Growth Scenario	High Growth Scenario	Low Growth Scenario	High Growth Scenario	Low Growth Scenario
-5%	1430,2	434,4	732,2	407,4	1360,4	700,2
-4%	1416,6	430,3	725,2	403,5	1347,4	693,5
-3%	1403,0	426,1	718,2	399,7	1334,5	686,8
-2%	1389,3	422,0	711,2	395,8	1321,5	680,2
-1%	1375,7	417,9	704,3	391,9	1308,5	673,5
1%	1348,5	393,0	690,3	384,1	1282,6	660,1
2%	1334,8	397,2	683,4	380,3	1269,7	653,5
3%	1321,2	401,3	676,4	376,4	1256,7	646,8
4%	1307,6	405,4	669,4	372,5	1243,8	640,1
5%	1294,0	409,6	662,4	368,6	1230,8	633,5