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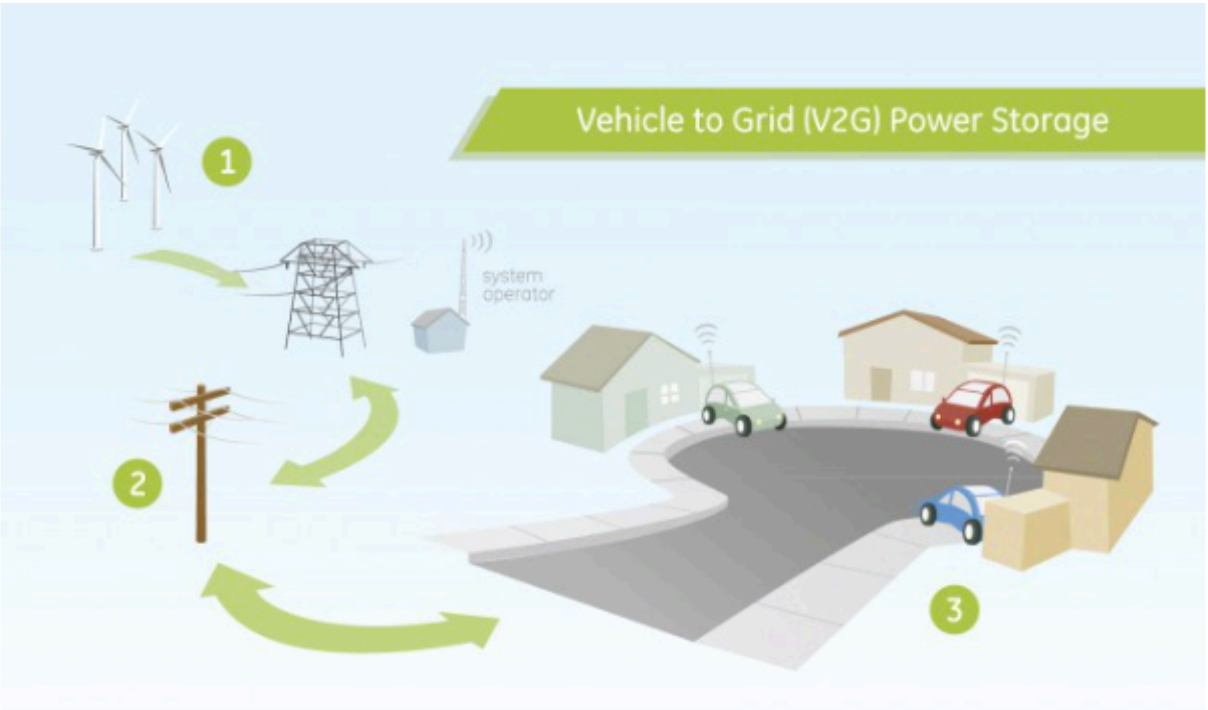
Analysis of the impact of controlled charging and vehicle to grid on growth of electric vehicle and photovoltaic systems: a case study in Amsterdam



Energy Science Master Thesis (30 ECTS)

Date	31-08-2016
Author	S.J. de Haan (Sander)
Student number	5537401
Contact details	S.J.dehaan@students.uu.nl
UU supervisors	dr. W.G.J.H.M. van Sark
	W.L. Schram MSc
UU second reader	B. Elsinga
Resourcefully	H. Niesing

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Abstract
In this research the impact of increasing share of photovoltaics (PV) and electric vehicles (EV) growth on the existing low voltage (LV) grid in Amsterdam is assessed. A model has been created that simulates the impact of the changing electricity supply and demand in a typical neighbourhood in the centre of Amsterdam based on governmental target until 2040. In order to make statements on impact in different kind of areas, an uncertainty analysis has been performed as well.

Besides grid performance with existing technology, two new charging technologies are assessed to determine their impact. These are controlled charging (CC), where the charging speed of EVs can be altered, and vehicle to grid (V2G), which has the potential to return electricity from an EV back to the grid. Furthermore, also battery degradation due to CC and V2G services is looked into.

The simulations have shown that overdemand will firstly occur in January 2018. From 2021, overdemand also occurs during evening demand peak on weekdays in July. From then overdemand grows every year until EV growth stagnates. Oversupply due to exceeding PV power generation only occurs in periods with high solar intensity, starting in 2031 when installed PV capacity equals 57,5% of fixed electricity demand in the neighbourhood. From then the amount of overcapacity grows with increasing PV capacity.

Controlled charging avoids overdemand by slowing down charge speed during peak electricity demand and by charging EVs with PV surplus during midday. Although charge speed is reduced during peak demand, all EVs were able to perform their required trip. CC reduces PV oversupply with two years and increases PV self-consumption in one neighbourhood in 2040 from 42,1% to 50,9%.

Vehicle to grid has shown the same results as CC. The main reason is that CC already avoids overdemand, so from the point of view of the electricity grid V2G is not required with CC technology in place.

CC reduces the average state of charge of an EV battery, which improves battery performance. Since V2G services are not simulated, the impact on battery degradation could not be found. A short literature study on battery degradation due to V2G services however indicated that despite the lack of consistency on this topic, intensive V2G use could have a notable impact on battery degradation. However, flexible pricing mechanisms and new business cases for EV batteries could turn this into profit for EV owners.

Table of Contents

List of figures

List of tables

List of abbreviations

Abbreviation	Explanation
BAU	Business As Usual
BEV	Battery Electric Vehicle
CC	Controlled Charging
Com	Commercial
DOD	Depth Of Discharge
DSO	Distribution System Operator
EV	Electric Vehicle
ICE	Internal Combustion Engine
LV	Low Voltage
MV	Medium Voltage
PHEV	Plugin Hybrid Electric Vehicle
PV	Photovoltaics
Res	Residential
SC	Self-Consumption
SOC	State Of Charge
TSO	Transmission System Operator
UU	Utrecht University
V2G	Vehicle to Grid

Description of terms used

Concept	Description
Vehicle to grid	Ability to provide emergency support to the grid (Peterson et al, 2009) and utilize electricity surplus when supply exceeds demand (Roy et al, 2011).
Prosumer	Owner of PV panels that uses the PV generated power to charge an EV for personal transportation
Controlled charging	EV charging that is able to control charging power to satisfy both EV demand and grid functionality
Electric vehicle	Vehicles that are both able to directly connect to the LV grid and able to perform bidirectional power exchange; PHEV and BEV
Oversupply	Oversupply is when there is more electricity returned to the grid than the grid can process
PV surplus	When PV yield exceeds electricity demand in the neighbourhood
Overdemand	When the electricity demand in a neighbourhood exceeds the MV/LV transformer capacity
Business as usual technology	EV and charging infrastructure that use technology that is currently in place. EVs start charging when connected and stop when disconnected or fully charged
Energy transition	Increasing shares of PV and EVs in one neighbourhood
Smart charging	Use of new charge technologies: CC and V2G

1. Introduction

The Netherlands is facing a transition within its existing electricity network (Duurzaam Amsterdam, 2015). This transition, from a fossil-fuel based energy system to a more renewable energy-based energy system, is mainly noticeable in the rapidly growing share of photovoltaic capacity and electric vehicles in urban areas (Eising et al, 2014). The following statistics grant some insight in this transition. The installed PV capacity in The Netherlands has increased with over 45% in 2015: from 1048 MW to 1525 MW (Rijkswaterstaat, 2016) and the amount of registered EVs has more than doubled in 2015: from 36.937 to 78.163 (RVO, 2016). In this report, EV includes plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). The government of Amsterdam has ambitious targets to further integrate PV and EVs in the city (Duurzaam Amsterdam, 2015). However, a concurrent increase of EVs and PV systems does not necessarily complement each other.

There is a peak in residential electricity demand in the morning and in the evening, especially on weekdays. EV charging, which usually occurs directly after a trip, leads to an increase of these demand peaks (IEA, 2015). PV availability, on the other hand, is uncontrollable due to its intermittent character: it is available when the sun shines (Elsinga & v. Sark, 2015). Therefore, the resulting discrepancy between the electricity demand and PV supply is expected to increase when both EV and PV shares increase (v.d. Kam & v. Sark, 2015). Load shifting seems required to reduce this imbalance and simultaneously increase self-consumption rate of PV power. As a result, the existing low voltage grid seems incapable of handling a rapid diffusion of EVs and PV on a short term (IEA, 2011). The LV grid also has a maximum capacity for processing returned PV surplus, exceeding this capacity would damage the grid (Westering et al, 2016). The question rises what the impact a rapid diffusion of PV and EVs is on the existing electricity grid and how this can be handled.

Controlled charging of EVs enables the charging of EVs while satisfying grid demands by controlling the charging power (IEA, 2012). This is one way to reduce the peak charging impact of EVs. Furthermore, to allow increasing shares of PV in the electricity mix, the grid should be more flexible. One of the potential solutions to facilitate this is to enable load shifting by using EVs as mobile storage for PV power and allowing them to return energy to the grid during peak demand (Mwasilu et al, 2014). This concept is known as vehicle to grid, where 'EVs are integrated into the electricity supply through an advanced smart grid network with two-way communication technologies' - (IEA, 2011).

These technologies also have potential drawbacks. Besides the question whether the technology is in place on sufficient scale to facilitate CC and V2G, these technologies could impact battery performance, and reducing charging rates could result in insufficiently charged EVs. V2G increases charge/discharge cycles of the battery which could impact battery degradation (Han et al, 2012); (Peterson et al, 2012) and reduces the average state of charge (SOC). This directly impacts the battery performance and therefore also the EV owner.

1.1 Problem statement and knowledge gap

The first research on impact of increasing amounts of EVs on the electricity grid was done in the mid 1990's. At that time, EVs were found to have a positive influence on electricity grid (Fort, 1994). Several other studies concluded that either the EV share would not increase sufficiently to impose a threat to the grid (Rachman, 1993), or that grid development and charging behaviour would outpace EV growth (Webster, 1999). The general concern in more recent studies however is that the current growth of EVs and PV capacity is diffusing more rapidly than the required grid technology (Mwasilu et al, 2014); (Clement-Nyns et al, 2010). Although it is unclear in what exact situations problems will occur, it seems inevitable to pursue solutions to enable increasing shares of EVs in the market.

One of the key statements made at a recent conference on EVs and the smart storage solutions they could provide was that if all existing personal transport cars would be replaced by EVs, there would still be sufficient grid capacity to charge all of them. However, a better utilization of the existing assets is required (McGrath, 2016). One of the key energy policy goals of the European commission is to continue the development of smart city's. The European Commission Directorate-General for energy states that in order to continue this development, higher levels of electricity storage are required to keep the LV grid stable and more flexible in the future (European commission, 2015).

Although the existing Dutch grid is currently functioning quite well (ECN, 2012), many parties agree that technical barriers will arise in the coming decades (IEA, 2010); (ECN, 2012); (Lopes et al, 2009). Eising et al (2014) concluded that grid functionality in Amsterdam would be at risk as early as 2015. However, potential barriers depend on many different aspects (Mwasilu et al, 2014) and it is therefore difficult to draw a single conclusion on the impact of the energy transition, especially in a dynamic area like Amsterdam (Eising et al, 2014). For example, Westering et al (2016) concluded in their research to 7000 LV transformer stations that grid overdemand will occur at 6% of transformers in 2030.

The scientific relevance of this research is that it will identify the critical EV and PV integration where this will damage the LV grid in the centre of Amsterdam. Then, it simulates the impact of controlled charging and V2G to determine their potential value to alleviate the LV grid. Potential drawbacks of these technologies are increased battery degradation (IEA, 2010) and potential EV failure due to charge speed reduction. This research also provides background on impact on battery degradation due to CC and V2G implementation.

1.2 Research question

This research looks at the impact of increasing shares of EVs and PV in the electricity grid and analyses the impact controlled charging and vehicle to grid can have. The research question for this research is formulated as follows:

What is the impact of increasing shares of EVs and PV on the low voltage grid in Amsterdam and what is the impact of controlled charging and vehicle to grid?

In order to answer this research question, two sub-questions have been formulated, that together will provide an answer to the research question.
The first sub-question addresses the impact of changes in the energy system on the LV grid:

1. *What is the impact of the energy transition in Amsterdam on the LV grid and what influence can controlled charging and the vehicle to grid effectuate on grid impact?*

To provide an answer to this question, insight is required in the changing energy system. This has been researched with a stepwise approach, where each new situation presents an addition to the previous situation. This distinguishes three situations, formulated as sub-questions:

1.1 What is the impact of the energy transition on the LV grid using current technology?
1.2 What is the impact of controlled charging on the LV grid?
1.3 What is the impact of vehicle to grid on the LV grid?

Implementation of CC and V2G can impact EV owners by influencing battery performance. Therefore, the second sub-question regards the impact of smart charging technologies on battery performance:

2. *What factors have impact on battery degradation and how do controlled charging and vehicle to grid impact these factors?*

Two topics are considered in this sub-question:

2.1 What does existing literature state on battery impact due to controlled charging and vehicle to grid services?
2.2 How are battery degradation factors influenced by controlled charging and vehicle to grid in this research?

1.3 Scope

The Netherlands is one of the most progressive countries in terms of urban PV and EV integration (IEA, 2012). Amsterdam has been identified as high risk regarding overdemand of LV transformers (Eising et al, 2014). Therefore, neighbourhoods in the centre of Amsterdam form the geographical scope of this research.

This research focuses on the ancillary service of EVs to interact with the electricity grid by charging and providing additional power to the grid when required (discharging). This is done in situations where overdemand occurs due to high fixed demand and EV charging demand. Other possible services, like voltage and frequency regulations, are not considered to be key factors in determining the impact of V2G implementation and are therefore not taken into account (Clement-Nyns et al, 2010); (Kempton & Letendre, 2005).

This research looks into impact on the LV grid, therefore impact on medium/high voltage grid or power plants has not been taken into account. Furthermore, only PV and EV growth are considered in the energy transition. The impact from other changes in the energy mix or new technologies are not considered.

It is assumed that aggregators responsible for EV interaction with the grid are in place, i.e. that the aggregator controls charging or discharging of the vehicles, given some specific owner requirements. Furthermore, the technology required to perform CC and V2G services is assumed to be in place in all EVs and charging stations. EVs in this research are passenger cars and include vehicles that are able to connect to the electricity grid; PHEVs and BEVs.

PV and EV growth is assumed to be technically and practically able to take place. Therefore, this research does not look at the available area for PV panel installation, nor the availability of sufficient charging stations in the centre of Amsterdam.

This research looks at the development of LV grid impact in the period 2015-2040. In order to do so, the average impact in July and January has been looked at, since these are expected to be extremes in terms of LV grid impact. This is mainly based on solar intensity and fixed electricity demand in these months.

1.4 Societal relevance

This research adds to the understanding of the impact of energy transition on the existing electricity grid. More specifically, it looks into the impact of increasing shares of PV and EVs and the potential barriers and solutions that accompany this transition. As Lyon et al (2012) describe, it is essential to understand impact on the grid to ensure smooth deployment of increasing shares of EVs.

This research focusses on the centre of Amsterdam, which can be expected to be among the first to encounter LV grid overdemand due to increasing EV shares (Eising et al, 2014). Data on EV charging behaviour, LV grid capacity, governmental targets on PV and EV growth and impact of EVs will be combined in this research. A multidisciplinary perspective takes the position of the government, distribution system operator (DSO) and prosumers to provide independent insight on the impact of the energy transition. This research provides an incentive to look into different areas, or could be extended to increase applicability into a wider area.

1.5 Structure of this document

The theoretical background required to fully understand this research and its outcomes is discussed in chapter two. It includes a discussion of the Dutch electricity grid, the EV and PV situation in Amsterdam, an explanation of the concepts controlled charging and vehicle to grid and an explanation of battery performance indicators. Chapter three presents the methodology used for this research, which is mainly the development of a model to simulate LV grid impact and battery degradation. This chapter also describes the performance indicators, future visions and the uncertainty analysis. The fourth chapter presents the used data as input in the model. After that, in chapter five the results are presented and shortly elucidated. Chapter six discusses simulation results, compares different studies, presents the limitations of this research and provides some recommendations. This is followed by the conclusion in chapter seven, which will answer the research question.

2. Theoretical background

2.1 Dutch transmission and distribution system

The Dutch electricity grid is one of the most reliable electricity grids in the world (ECN, 2012), with an electricity certainty of 99,996%. Of this 0.004% power outage, 4% is due to overload of the grid. TenneT is the transmission system operator (TSO), managing the high voltage (HV) transmission grid (380 and 220 kV). Their domain stops at the transformer stations where the electricity is transformed from medium voltage (MV) to LV. That is where the distribution system operator (DSO) takes over responsibility of the grid, with eight active DSO's in The Netherlands.

2.1.1 Potential problems for the LV grid

Liander is one of the largest DSO's in The Netherlands and manages the grid in large parts of the country, including Amsterdam, as presented in Figure 1 (Liander, 2015).
To keep the grid stable, it must be maintained on a frequency of 50 Hz. With changing demand, supply must be balanced in order to keep the frequency between 49,99-50,01 Hz (UTCE, 2009).
A sudden increase in electricity demand could cause problems to the grid in two ways (Liander, 2015). First, there could be an imbalance in the grid which would require reserve capacity to restore the balance. According to Kempton (2005), EVs are designed to handle large and frequent power fluctuations. Therefore, using them in a V2G situation could provide this reserve capacity. Second, the demand could increase with such quantity that the transformer station does not have sufficient capacity to facilitate this demand (Liander, 2015), most likely during peak demand.

Figure 1. Overview of operation area of Liander. Source: Liander, (2015)

The city of Amsterdam is divided in multiple local grids, each with its own MV/LV transformer substation managed by Liander. Previous research has indicated certain areas in The Netherlands with high chance of grid overdemand due to increasing EV demand during peak hours (Eising et al, 2014). This research looks at areas in the centre of Amsterdam with a maximum transformer capacity of 400 kW (Liander, 2016). However, there is an efficiency loss in transformer stations, which differs in The Netherlands between 3% and 10% (V. Oirsouw, 2012). The average loss of 8% (V. Oirsouw, 2012) will be used to represent transformer loss in Amsterdam in this research. Therefore, the maximum usable capacity is reduced to **368 kW**. The amount of power that can be returned to the grid, either by the EVs or by PV surplus, is also limited by this capacity. Therefore, a maximum of 400 kW can be returned to the grid without causing a threat to the transformer station.
Westering (2016), a Liander employee, explained in a personal meeting that an MV/LV transformer station can withstand an overdemand/supply for a couple of minutes before the hardware gets damaged.

2.2 EVs in The Netherlands

2.2.1 Dutch EV fleet

According to the IEA (2015) The Netherlands has the second largest EV growth of all participating countries in the Global EV outlook 2015 (IEA, 2015). Commissioned by the Dutch ministry of economic affairs, the 'Rijksdienst voor ondernemend Nederland' (RVO) registers the development of the EVs for personal transportation in The Netherlands. Table 1 presents the amount of relevant EVs in The Netherlands on three dates, clearly indicating a rapid increase. Appendix A presents more details on the amount of PHEVs and BEVs.

Type	31-12-2014	31-12-2015	31-03-2016
BEV	6.825	9.368	10.393
PHEV/E-REV	36.937	78.163	79.626
Total	43.762	87.531	90.019

Table 1. Amount of registered EVs in The Netherlands. Source: **(RVO, 2016)**

2.2.2 EV battery characteristics

The characteristics of EV batteries is important for this research because these determine the potential storage capacity. There are many characteristics related to batteries and battery performance in EVs, of which some have a direct impact on EV performance (v.d. Kam & v. Sark, 2015); (Eising et al, 2014); (Clement-Nyns et al, 2010) and the grid:

- Battery capacity (C_{bat}, kWh) is a measure of the amount of energy that can be stored in the battery.
- Energy consumption (E_{cons}, kWh/km) is the amount of energy required from the battery to transport an EV over a certain distance. Although many aspects have influence on the total consumption, average values per EV have been used.
- Charge efficiency (η_{charge}, %) is the efficiency for charging/discharging of an EV. V2G technology will lead to an increase in electricity loss due to the doubling of efficiency loss, since electricity must be charged and discharged again.
- Charging power (P_{charge}, kW) is a measure for the charging speed. A higher charging power leads to faster charging.
- Range (km) is a measure for the distance an EV can drive using its electromotor.
- State of charge (SOC, %) is the relative amount of energy remaining in an EV. To maintain battery performance, a minimum state of charge (SOC_{min}) of 20% is used.

Appendix B and Part 4.1.1 present these characteristics for the top-5 EVs in The Netherlands.

2.3 Controlled charging and Vehicle-to-Grid

Controlled charging, also referred to as smart charging or intelligent charging, enables the charging stations to control charge power. Lopes et al (2009) define smart charging as a strategy that uses an active management system that continuously monitors all grid elements and its states. This management deals with available energy resources and grid restrictions at each moment in order to minimize grid impact.

Valentine et al (2011) define intelligent charging as the ability of charging stations to start charging at any time the EV is connected rather than when an EV is plugged in, in order to minimize total system costs. They performed a research on price minimization in three different neighbourhood types in New York City. They found that EV charging was done in 80% of the time during off-peak hours. Although for this research the definition by Lopes et al (2009) is more suitable, the results from Valentine et al (2011) show promising possibilities

for controlled charging. Here, controlled charging has been used to describe the ability of charge stations to determine charge speed based on grid impact and EV requirement.
The IEA describes vehicle to grid as 'EVs that are integrated into the electricity supply through advanced smart grid network with two-way communication technologies' (IEA, 2010). A research by the IEA to the feasibility of V2G to enable load shifting concluded: "*The 'vehicle-to-grid' (V2G) concept could help cut electricity demand during peak periods and prove especially helpful in smoothing variations in power generation introduced to the grid by variable renewable resources such as wind and solar power*" - (IEA, 2010)

EVs have the potential to store renewable energy sources, like PV power, in their battery as an energy buffer. EVs in this research have 30% of the battery capacity available for PV surplus storage. This energy can be used to provide energy support to the power grid and help avoid surplus in case of oversupply (Bishop et al, 2013). By collaborating with the grid, this can lead to a reduction of peak demand and an increase of PV implementation in the electricity mix (Niesing, 2015). Figure 2 explains the potential impact of V2G on the LV electricity grid. The left figure presents a typical electricity grid with increased amounts of EVs, resulting in a strong increase of the evening peak due to EV charging. The right figure presents the potential impact V2G can have on the grid. There is a reduction of electricity peaks and a more continuous distribution of electricity during the day.

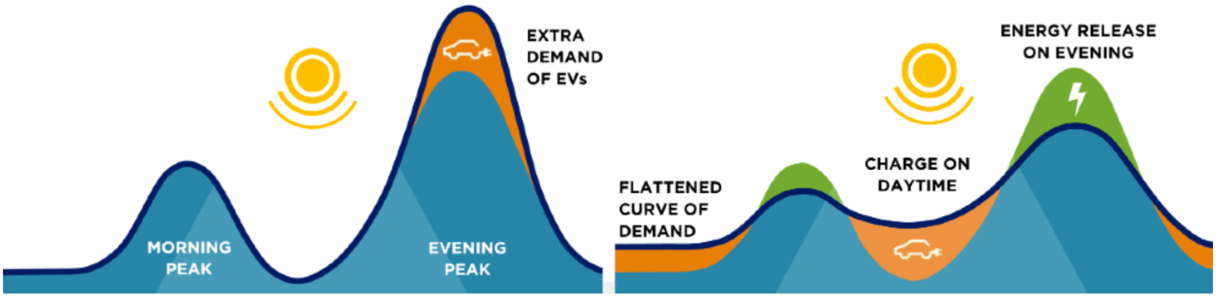

Figure 2. Graphical display of (left) the risk of increased shared of EVs on the LV grid, and (right) the potential impact that V2G can have on this problem. Source: Resourcefully (2015)

2.4 Battery degradation

2.4.1 Li-ion performance

The battery of an EV presents a large share of the total EV purchase cost. Anxiety for decrease of battery performance is a common reason to avoid EV purchase (Saxena et al, 2015). Although there is no clear consistency in statements of battery degradation rate or the lifetime of batteries, Li-ion batteries in EVs have proven to have a lifetime of over 3000 cycles with a depth of discharge (DOD) of 80% (Geth et al, 2011). Saxena et al (2015) even concluded that after a capacity diminishment of 70%, EVs can meet performance requirements.

Car manufacturers usually express the state of a battery in years or, more specifically, in the amount of cycles that the battery can be used, from fully charged to fully discharged. However, in practice an EV battery is not always fully discharged and also not always fully charged. The state of charge (SOC) of a battery is a measure for the relative amount of electricity available in the battery, with a SOC of 100% when fully charged. The SOC could also be expressed as the depth of discharge (DOD), which is the counterpart of SOC, so the DOD is 0% when fully charged. In order to maintain battery capacity and to avoid rapid degradation, in this research the minimum SOC has been held at 20% (Kempton & Letendre, 2005), (v.d. Kam & v. Sark, 2015).

2.4.2 Previous research on EV battery degradation

Research on battery degradation in EVs and the factors that influence this degradation has recently gained in interest. This part discusses some recent researches and specialist's views on battery degradation due to CC and V2G services as well as the main factors that influence degradation.

Czechowski (2015), Hoke et al (2014), Fernandez et al (2013) and Zhou et al (2011) have all conducted research on the financial impact of battery degradation due to V2G services. They all used DOD (or SOC) and the operating temperature to determine battery degradation. Czechowski concludes: "*An important result from the studies which consider V2G potential and battery degradation costs, is that the battery ageing is too expensive for V2G arbitrage to be performed to any larger extent*" - (Czechowski, 2015). She further states that there is opportunity to make V2G work by providing the prosumer with additional economic incentive to overcome battery degradation costs. Where Hoke et al and Fernandez et al do not conclude the financial interest of V2G applications, Zhou et al (2011) concluded that Li-ion batteries are cost effective for use in V2G appliances. These researchers agree that there is a rapid increase in degradation rate with very high rates of DOD and temperatures above 50°C. However, very high rates of DOD for V2G do not occur in this research and temperature impact is outside the scope so these factors are not accounted for in this research.

Peterson et al (2012) ascribed the amount of cycles, DOD per cycle and total energy throughput to have influence on battery degradation, however, the total energy throughput is by far the most influential factor. They quantify battery capacity loss as the amount of energy processed by the cells and found that the capacity loss was -6.0×10^{-3}% and -2.70×10^{-3}% per normalized Wh processed for EV driving and V2G support respectively. This indicated that battery degradation due to V2G services reduced battery capacity about half as fast as EV driving. Their main argument is that the continuous, galvanostatic cycles of V2G services are less harmful to the battery than the rapid vehicle motive cycles.

Both Bishop et al (2013) and Morano et al (2009) consider that total energy throughput is the single most important indicator to approximate battery degradation, given that temperature and DOD are not extremes. Bishop et al (2013) researched battery degradation due to V2G services under various situations, concluding that "*Best case minimum impacts of providing V2G services are severe such as to require multiple battery pack replacements over the vehicle lifetime*" - (Bishop et al, 2013). Morano et al (2009) concluded that EVs with Li-ion batteries can drive about 250.000 km, but they did not differentiate between EV driving cycles and V2G cycles.

The research by v.d. Kam and v. Sark (2015) concluded that V2G services have dramatic impact on battery performance and significantly reduce battery lifetime. They found that V2G services fiercely increase total energy throughput, concluding that in extreme situations energy throughput of the battery triples compared to normal driving patterns. The average SOC however was almost cut in half, which on its turn improved battery performance. Overall they found strong indicators for increased battery degradation for V2G use in a Dutch urban area.

Data on battery degradation from a pilot project of V2G in Amsterdam that has been running for over two years shows a battery performance reduction of about 7% in two years (Recurcefully, 2016). This battery has increased the self-consumption rate of a single household with a PV capacity of about 106% of total yearly electricity demand from 34% to

65%. However, in that same period, this battery was also used for personal transportation and could therefore not provide sufficient insight in battery degradation solely due to V2G services. This transportation is limited to a handful of trips per year, but no clear data is available to quantify its impact on battery degradation. It does however indicate that the 7% capacity reduction in two years is mainly caused by V2G services.

M. Fendt (2016), one of the panel speakers on a recent conference on EVs and the smart storage potential they could provide, stated that the business model of EV batteries is expected to change in the near future. There are currently already options for second life use of EV batteries that can no longer provide sufficient capacity for the vehicle and that are financially profitable. Therefore, the battery business model could change to a lease model and this would make battery degradation a much less important factor for EV owners. One of the other panel speakers on the conference and initiator of a V2G test installation in an area in Utrecht, R. Berg (2016), agrees with Fendt (2016) and states that the combination of battery technology improvement and changing pricing mechanisms will make V2G financially interesting for prosumers. He further states that smart charging technology has the ability to take battery degradation factors into account, like to stop charging when the battery is almost fully charged. This will reduce battery degradation on its turn.

3. Methodology

This chapter explains the methodology used for this research. First, a typical neighbourhood in Amsterdam is shortly discussed (3.1). Then, the model created for this research is presented (3.2). After that the performance indicators are discussed (3.3), followed by battery degradation (3.4). Subsequently, the future visions are presented (3.5) and finally the sensitivity analysis is elucidated (3.6).

3.1 Neighbourhoods in Amsterdam

The focus area of this research is a typical neighbourhood in the centre of Amsterdam, bordered by the range of a single MV-LV transformer. As previously discussed, this concerns a transformer with a capacity of 400 kW. This area is chosen because it has the highest amount of charge sessions per public EV charging point and a relative large share of unique EV users (Gemeente Amsterdam, 2015). There is not a lot of PV installed currently, but with an average potential of about 50 kWh/m^2 (City of Amsterdam, 2016) there is potential for PV capacity growth. This will have to be installed mainly on rooftops, since there is not much space available for PV installations in the neighbourhood elsewhere. Furthermore, this area is relatively old and densely populated, which makes replacement of the existing electricity grid a difficult and expensive task.

Two prosumer types have been distinguished in this research, residential and commercial consumers. These two consumer types each have specific driving and charging behaviour, which determines when a vehicle is connected to the grid and what trips it makes. These two consumer types both have a specific PHEV/BEV ratio and both have their own battery specifications. Figure 3 presents a schematic overview of the representation of the neighbourhood, showing two consumer types and per type 2 EV options, summing up to 4 different EV requirement types. A 400 kW transformer station facilitates on average 330 connections. Part 4.4.1 presents more details on the battery characteristics of the EVs in this research.

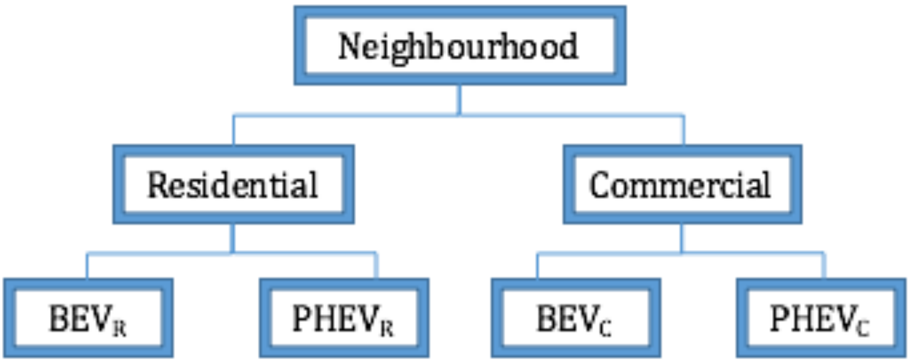

Figure 3. Schematic overview of neighbourhood representation

3.2 Model setup

In this section the design of the model is presented. First, the general setup of the model is discussed (3.2.1), followed by extensions to simulate energy transition (3.2.2), extensions to enable controlled charging (3.2.3) and finally with extensions to enable V2G technology (3.2.4). These different situations provide insight on grid impact by evaluating the performance indicators and performing an uncertainty analysis.

3.2.1 Model components

The first part presents the current situation. Four main components are included: the first two components regard the supply side, components three and four the demand side. Figure 4 presents a graphical overview of these components.

The first component of the model is the MV/LV transformer, which determines the maximum capacity of the grid, 'T4' in Figure 4. In the model this is included by adding a continuous threshold value that presents the maximum demand. The second component is the PV capacity, 'Solar farm' in Figure 4. The PV capacity installed in the simulation is gradually increased over time (see part 4.2.3).

The demand side is divided into two parts: fixed electricity demand and EV electricity demand. The third component is the electricity demand for the fixed load, referred to as 'Residential house(s)' in Figure 4. This is the electricity consumption of normal households and commercial connections. The fourth and last component is the electricity requirement of the EVs, 'Charging station' in Figure 4. In the baseline scenario, this demand will act similar to the fixed load: it starts charging at full power when connected and stops charging when it is fully charged and only a unidirectional power flow is possible.

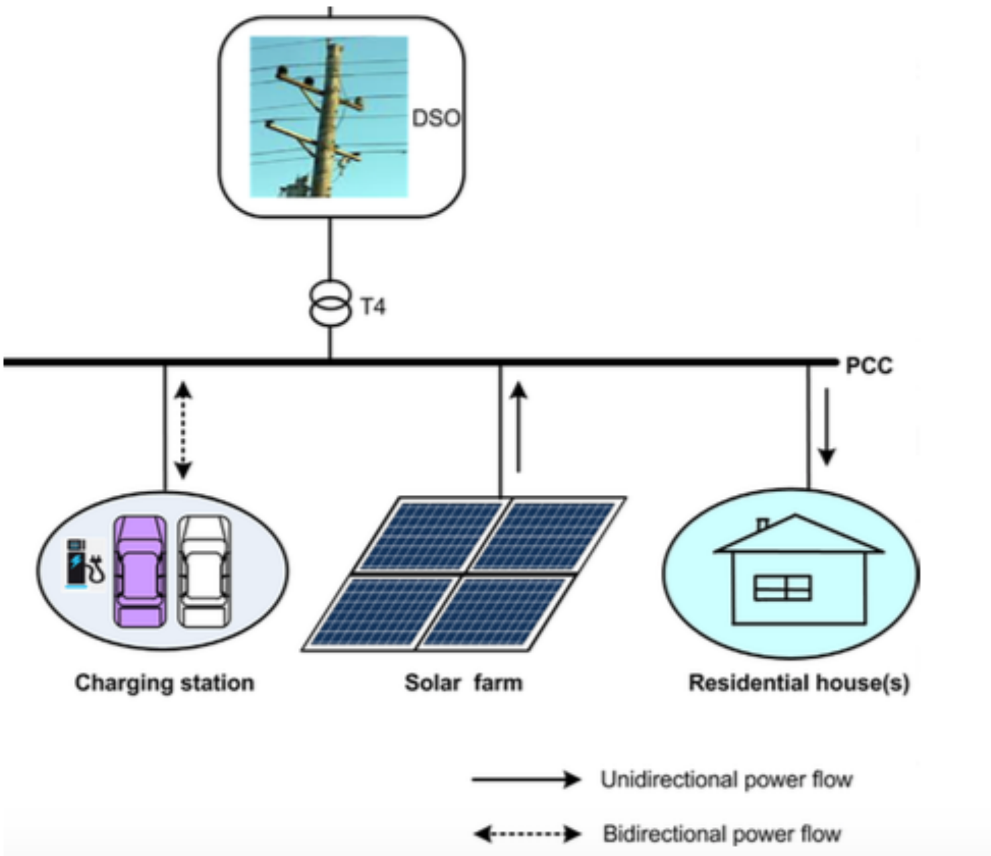

Figure 4. Schematic presentation of the four components of the model. Source: Mwasilu et al. (2014)

The amount of EV and PV has been increased gradually to determine their impact on the LV grid. The time step size in this model is per minute, similar to comparable research (v.d. Kam & v. Sark, 2015); (Eising et al, 2014). Modellers at Liander use a step size of fifteen minutes, since transform stations are designed to withstand a slight overdemand for some minutes (Westering et al, 2016). Table 2 presents an overview of all components in the operating functions.

Component	Description	Unit
P_{grid}	Demand from LV grid	kW
P_{fix}	Fixed electricity demand	kW
P_{EVmax}	Maximum charge rate within one timestep	kW
P_{EV}	Power taken by the EV	kW
P_{PV}	Power generated from PV	kW
P_{tres}	Maximum LV grid capacity (386)	kW
P_{dem}	Power demand from the LV grid	kW
P_{ret}	Power returned from the EV to the grid	kW
P_{loss}	Power loss due to storage in EV and return to grid	kW
$P_{available}$	Power available from the grid without causing overdemand	kW
η_{charge}	Charging efficiency	%
$\eta_{discharge}$	Discharge efficiency	%
SOC_{needed}	SOC required at t, share of total battery capacity	%
SOC_{max}	Maximum SOC, total battery capacity	%
SOC_{req}	Total SOC that an EV needs	%
SOC_{bat}	Current SOC of the battery	%
$SOC_{(t-1)}$	SOC in the previous timestep	%
ΔSOC_{charge}	SOC recharge at the given timestep	%
ΔSOC_{trip}	SOC reduction due to EV driving in one timestep	%
SOC_{min}	Minimum SOC required to limit battery degradation	%
C_{bat}	Total battery capacity	kWh
T	Time factor (=1/60)	-

Table 2. Factors in operating functions with description and unit

Key operating functions in this model

$P_{grid}= (P_{EV}+P_{fix})-P_{PV}$ (1)

$SOC_{needed}= SOC_{max}-SOC_{bat}$ (2)

Formula 1 states that power required from the grid is the fixed load and EV demand min the PV yield. Formula 2 states that the battery charges until fully charged. When the battery capacity is known, the SOC could also be expressed in energy available in the EV.

3.2.2 Business as usual

In order to simulate the electricity grid assuming all governmental targets are being met, the baseline model has been updated to include increasing shares of PV and EVs. This directly increases the input parameters for components 2 (PV power capacity) and 4 (EV demand). Future situations with this technology in place is referred to as business as usual (BAU).

Key operating functions business as usual

If $SOC_{bat}<SOC_{max}$ **And** EV=Connected $P_{EV}=\eta_{charge}P_{EVmax}$ (3)

Else $P_{EV}=0$

$SOC_{bat}=SOC(t-1)+ \Delta SOC_{charge}(t) - \Delta SOC_{trip}(t)$ (4)

Formula 3 states that the EV charges with full power when required and connected, until fully charged. Formula 4 presents the energy in a battery at one timestep. Obviously an EV will never be charging and on a trip (hence: unplugged) in the same time step.

3.2.3 Controlled charging

This situation extends the previous model by including controlled charging of EVs in order to reduce electricity demand peaks. Future situations with this technology in place is referred to as controlled charging (CC). This has three important influences on the charging pattern:

1. The charging power can be regulated, including being switched off (i.e. P_{EV}=0 kW).
2. The battery will be charged until the required SOC for a planned trip is met. This is set at 70% of the battery capacity, in order to provide extra battery capacity for PV power storage during midday.
3. If there is PV surplus ($P_{PV}>P_{dem}$) the battery will be fully charged to store PV power

Key operating functions controlled charging

If	$P_{dem}<(P_{tres}-P_{EVmax})$	**And**	EV=Connected	$P_{EV}=\eta_{charge}*P_{EVmax}$	(5)
Elif	$P_{dem}>(P_{tres}-P_{EVmax})$	**And**	$P_{dem}<P_{tres}$	$P_{EV}=P_{tres}-P_{dem(t-1)}$	
Else				$P_{EV}=0$	

If	$P_{PV}(t)>P_{dem}(t)$	$SOC_{req}=100\%$	(6)
Else		$SOC_{req}=70\%$	

Formula 5 updates (3) by avoiding EV charging during peak demand. Formula 6 is an update on (2) by allowing a battery to charge extra in case of PV surplus. Figure 5 presents the flow chart of this model for EV charging.

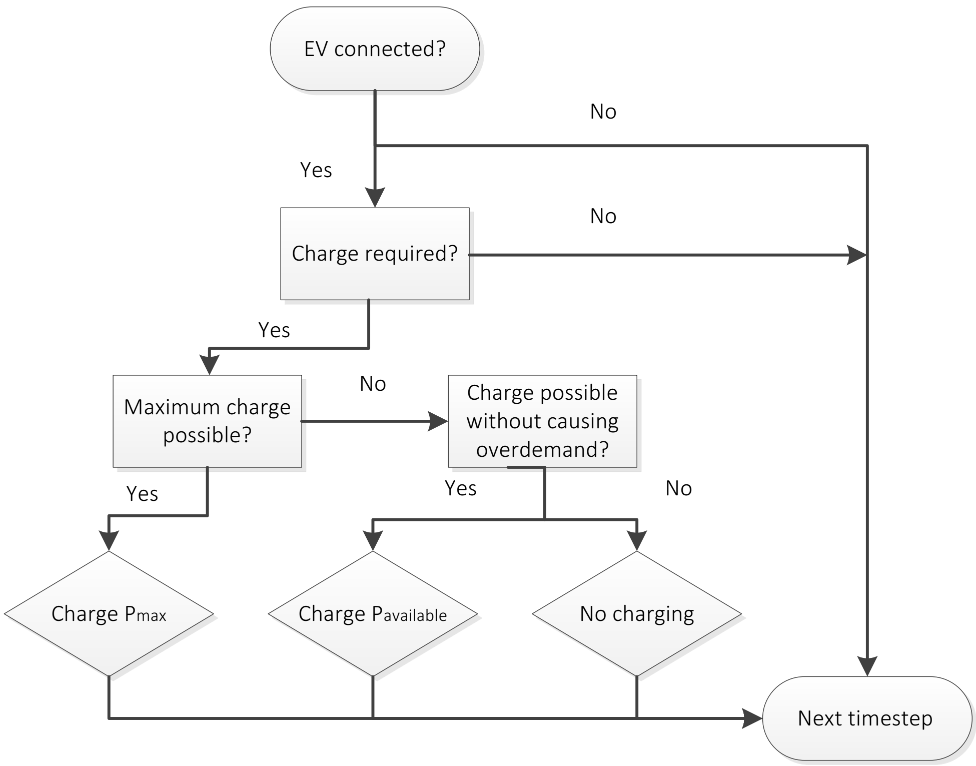

Figure 5. Flow chart of the model with controlled charging

3.2.4 Vehicle to grid

This situation is modelled by allowing bidirectional flow of electricity in component 4, 'Charging station'. Now this component is both the supply as well as the demand side. Here, the electricity grid tries to find optimal solutions on the (dis)charging of EVs. Fixed demand is primarily being met from PV. When not available, it will take electricity either form the EVs (when required) or from the LV grid. The maximum discharge speed is the same as charging speed. Future situations with this technology in place is referred to as vehicle to grid (V2G).

Key operating functions V2G

If $P_{grid} \geq P_{tres}$ **And** EV=Connected P_{ret}=$(SOC_{bat}-SOC_{min}+SOC_{need}*C_{bat}*\eta_{charge}*T$ (7)

Else $P_{ret}=0$

$$P_{grid}= P_{EV}+P_{fix}-P_{PV}-P_{ret} \quad (8)$$

$$P_{loss}=P_{ret}*\eta_{charge}+ P_{ret}*\eta_{discharge} \quad (9)$$

Formula 7 allows EVs to return electricity back to the grid when there is a surplus of electricity in the battery ($SOC_{bat}>SOC_{req}$) and the grid needs it. Formula 8 is an update on (1), by adding the power returned to the grid. Formula 9 gives the amount of electricity loss by storing energy in an EV and later return this to the grid. Figure 6 presents the flow chart of the model with V2G technology for EV (dis)charging.

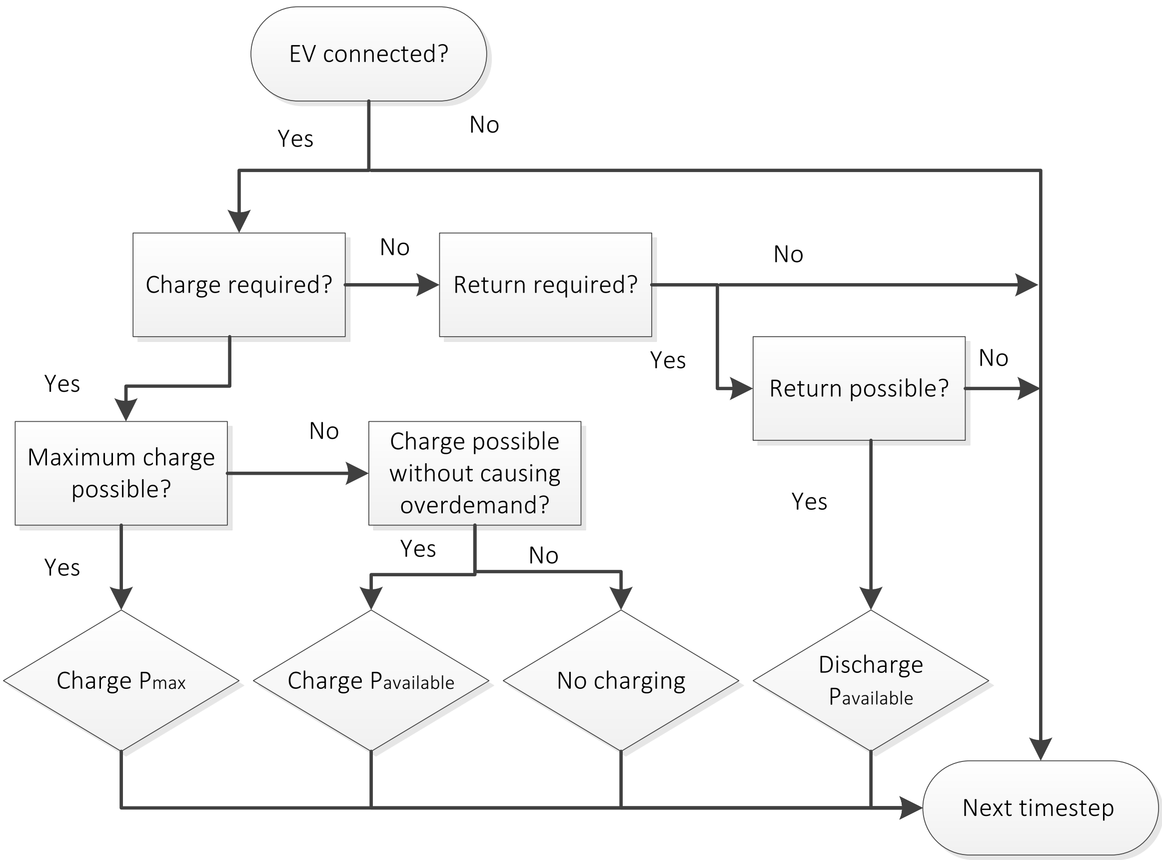

Figure 6. Flow chart of the model with vehicle to grid

3.3 Performance indicators

In order to quantify the impact on the LV grid, several performance indicators have been distinguished. The focus of this research is the impact on the LV grid, of which two indicators are overdemand by consumers and oversupply from PV. Furthermore, two technologies have been proposed to prevent damage to the grid, which however might result in failure to charge all available EVs sufficiently. Therefore, another performance indicator is the potential occurrence of EVs that are charged insufficiently, referred to as EV failure. Besides alleviating the LV grid, these proposed technologies are expected to increase self-consumption of PV power, which is therefore also a performance indicator. Note that this regards consumption of PV power on neighbourhood level, not on household level.

1. Overdemand

The effective capacity of a transformer station is 368 kW. If demand exceeds this capacity this will harm the transformer station. This is the case when P_{grid}>368 kW, this happens when:

$$Pev(t) + Pfix\,(t) - Ppv(t) - Pret(t) > 368kW \quad (10)$$

A transformer station can withstand a slight overdemand for a short period of time, due to a delay in the hardware of about 5-10 minutes (Westering, 2016). An overdemand of at least 5 consecutive minutes would pose a direct threat to the grid.

2. Oversupply PV

A transformer station has a maximum capacity to take in returned PV power. This capacity is 400 kW (Westering, 2016) and occurs when:

$$Ppv\,(t) > Pfixed\,(t) + Pev(t) - Pret(t)\ + 400kW \quad (11)$$

A transformer station can withstand a slight oversupply of PV power returned for a short period of time, due to a delay in the hardware of about 5-10 minutes (Westering, 2016). Therefore, only oversupply of at least 5 minutes is considered a threat to the grid.

3. EV failure

A drawback from alleviating the grid by controlled charging and vehicle to grid is that there could be a reduction of available electricity in the EV. In the worst case, the SOC of an EV becomes below SOC_{min}. This is the case when SOC is lower than 20 percent of its maximum, which is determined as the lower SOC boundary due to quality and safety aspects.

$$EV\,failure \quad \boldsymbol{IF} \quad SOC\,(t) < SOCmin \quad (12)$$

4. PV self-consumption

An important aspect of the two technologies of interest in this research is increased self-consumption of PV generated electricity within the neighbourhood. It is expressed as a relative share, which presents the amount of PV power that is not returned to the grid.

$$SC = \frac{Ppv\,(t) - Ppv,ret\,(t)}{Ppv(t)} * 100\% \quad (13)$$

3.4 Battery degradation

There is no clear agreement to quantify battery degradation in practice, especially not in a simplified model as has been constructed for this research. Since this research focusses on the load on the LV grid, indicators like temperature, voltages used and specific vehicle characteristics are outside the scope. Including these would require many assumptions that would greatly impact the rectitude of this research. Therefore, battery degradation due to controlled charging and V2G has been regarded based on three performance indicators that can be subtracted from the model that has been created for this research. These are energy throughput, depth of discharge for V2G services and average state of charge.

First of all, energy throughput (ET, %) has been simulated. Energy throughput is the amount of energy that is discharged and charged from the battery. For example, if a battery with a capacity of 10 kWh is discharged 50% and then recharged again, the energy throughput is 5 kWh. Increased energy throughput considers the relative increased amount of energy that is discharged from the battery, compared to the situation that regards the use of current technology. Furthermore, the depth of discharge (DOD) used to return electricity to the grid in the V2G scenario has been looked into. This is the DOD that the EV battery makes extra, so what increases battery degradation. A 10 kWh battery discharging 5 kWh has a DOD of 50% for that cycle. Third, average SOC will be regarded. Since controlled charging does not lead to increasing discharge cycles, the average SOC still gives an indication on the impact of the battery.

Although it cannot be stated quantitatively what total battery impact occurs from possible increased energy throughput and the related DOD, some quantitative findings can be stated on the related impact, similar to v.d. Kam and v. Sark (2015). Furthermore, a short literature review on battery degradation for V2G services has been performed.

Energy throughput

The increased amount of energy throughput has been measured by comparing total energy throughput in the baseline situation (ET_{base}) with the energy throughput (ET) with controlled charging and V2G technology.

$$ET(T) = \sum_{t=t0}^{T} ET\ (t) - \sum_{t=t0}^{T} ETbase\ \ (t)*(\sum_{t=t0}^{T} ETbase\ (t))^{-1}*100\% \quad (14)$$

Average DOD for discharging

The DOD for return to the grid with V2G technology in place has been determined by adding all electricity that is returned per day, divided by the battery capacity. Depending aspects like energy required by the grid, energy available in the EV, the amount of EVs connected and PV power, the DOD for discharging varies day to day. Therefore, the average DOD is used in this research, which is determined by adding to total amount energy returned to the grid (in % of total capacity), divided by the amount of discharge cycles.

$$DOD_{avg}=\frac{Total\ energy\ returned\ to\ grid}{amount\ of\ discharge\ cycles} \quad (15)$$

Average SOC

The average SOC gives an indication of the amount of energy that is present in an EV on monthly average. This has been determined with the average energy in an EV, divided by the total capacity of the EV. This is specific for all four EVs simulated in the model.

$$SOC_{avg}=\frac{average\ electricity\ in\ EV}{total\ electricity\ capacity} \quad (16)$$

3.5 Future visions

To determine the impact of energy transition in Amsterdam, different visions have been distinguished which are based on PV capacity and EV targets set by the government (Duurzaam Amsterdam, 2015). Though the increase of EV and PV shares in the city are only targets that the local government has set for itself, these are assumed to be realistic and will provide a grip on the energy transition.

Four visions have been distinguished in this research. First, the current situation, with data from 2015, is examined. Then, the first target for PV growth is regarded, with the expected amount of EVs at that time. The last PV target is planned in 2040, which has been included as well. Another vision has been assessed in between the last two visions, since these are planned far apart (20 years). The growth rates have been interpolated between the other two visions. Table 3 provides an overview of the PV targets, with the share of EV that is expected to be in place at that time and an estimation of the year in which this is reached in a central neighbourhood with 330 grid connections. See part 4.1-4.2 for more information on EV and PV data input.

Estimated year[1]	PV installed (kWp)	EV target (#)
2015	52,5	16
2020	161	102
2030	584	168
2040	1007	168

Table 3. Four PV installed targets, expected EV share and estimated year. [1] (Duurzaam Amsterdam, 2015)

3.6 Uncertainty analysis

Although data input for this research has been gathered as realistic and up to date as possible, a number of assumptions and simplifications have been made. Therefore, an uncertainty analysis has been performed to determine the impact of changes in data input. This uncertainty analysis is performed by changing relevant input data and then running the model multiple times to determine its impact. Subject to uncertainty analysis are crucial factors, that also might change in the near future and therefore could have a significant impact on grid demand.

1. EV growth

In this research the centre of Amsterdam is used as a case study. To be able to make more general statements about the impact of different EV growth rates and for neighbourhoods with a larger EV potential, EV growth has been altered in the uncertainty analysis. With this growth, the maximum amount of EVs in one area is neglected because there could be neighbourhoods with a larger share of EVs per household.

2. PV growth

Like the EV growth described above, PV growth has been altered to determine its impact on the results and to be able to make more general statements of PV growth impact on existing electricity grids.

3. EV availability

Assumptions have been made on the availability of different EVs during the day. However, an increase of EV availability could lead to improved performances since it would increase the options for the LV grid, e.g. at what time to charge certain EVs or provide increased storage capacity during midday.

4. Commercial: residential ratio

A commercial/residential ratio of 3:7 has been assumed in the neighbourhoods in the centre of Amsterdam. However, this ratio varies from between different areas and this is therefore an interesting factor to perform an uncertainty analysis on.

5. Maximum charging speed

The maximum charging speed differs among EVs and could also be restricted by the capacity of the charging stations. Also, some EVs have the potential to charge with direct current (DC), which is the case when multiple parallel connected chargers simultaneously charge an EV. This could influence the grid impact and therefore this factor has been regarded in the uncertainty analysis as well.

6. Grid capacity

One way to improve the electricity grid is by increasing its capacity. Therefore, also grid capacity has been looked at in this uncertainty analysis. This provides insight in potential solutions of replacing the existing grid.

7. Fixed demand

Development of technology and electrification could increase fixed electricity demand in the near future. Therefore, also changing fixed demand has been looked at.

The variation in these seven factors is based on five scenarios. First, there is the ‘Normal’ (0) scenario where input values are simulated as in the main simulation. Then, there is the ‘Lower’ (-1) scenario, where input values are either reduced by 25% or the share of residential houses and EV availability is reduced. On the other hand, there is the ‘High’ (1) scenario where input values are increased by 25% or the share of residential houses and EV availability are increases. In the ‘Highest’ (2) scenario the values are increased double the amount as in the ‘High’ scenario. The ‘Extra’ (3) scenario is added to see impact of more changes, mainly to enable a very strong growth of charging speed, which is set at +300% in that scenario. Table 4 presents the used values in the different scenarios.

There are more scenario’s used for increasing values (1, 2 and 3) that for reduced values (-1). This is based upon the consensus that technology usually improves over time, which would cause an increase in most of these values.

Parameter	Lower -1	Normal 0	High 1	Highest 2	Extra 3
EV growth	-25%	Figure 8	+25%	+50%	+100%
PV growth	-25%	Figure 8	+25%	+50%	+100%
EV availability	-	Table 6	+	++	+++
Commercial: residential ratio	1:9	3:7	5:5	7:3	9:1
Charging speed	-25%	3,7	+25%	+50%	+300%
Grid capacity	-25%	400 kW	+25%	+50%	+100%
Fixed demand	-25%	2970 kWh/wk	+25%	+50%	+100%

Table 4. Five uncertainty scenarios

4. Data input

4.1 EVs

4.1.1 EVs in Amsterdam

To represent EVs in Amsterdam, the weighted average specifications of the top 5 used PHEVs and BEVs have been used. Table 5 presents these weighted averages; Appendix B presents more details on their characteristics. The ratio PHEV/BEV is based on data from the RVO (2016) and set at 7/1.

Weighted average	SOC_{min} (%)	C_{bat} (kWh)	E_{cons} (kWh/km)	Range (km)	P_{charge} (kW)
PHEV	20	11,57	0,190	51,69	3,7
BEV	20	57,09	0,181	252,7	3,7

Table 5. Characteristics of the average PHEV and BEV

The total amount of EVs in a neighbourhood with the capacity of 330 households in 2016 is about 16. This is supported by the the following data: for about 440.000 households in Amsterdam, there are about 225.000 passenger cars, which is on average 168 cars per neighbourhood with 330 households. The estimation that 10% of all passenger cars in Amsterdam are currently EVs gives 16,8 EVs in the neighbourhood. The battery capacity of EVs is expected to improve in the near future. The IEA (2015) expects energy density for EV batteries to increase with 250% in the next ten years, which seems very ambitious. Tesla, one of the main producers of BEVs, strongly invests in EV battery technology and expects energy density of EV batteries to double in ten years (Straubel, 2015). In this research the also ambitious vision of Tesla has been used, increasing average battery capacity in EVs with 10% per year.

4.1.2 EV trips

Beside EV battery characteristics, EV availability and trips are important for this research. As mentioned before, the government of Amsterdam has been gathering data from charging stations for the past years. However, this data was not readily available to base specific charging profiles from in Amsterdam. Another research has been performed by Spoelstra et al (2014) to identify patterns in Dutch EV charging behaviour, based on a database from Oplaadpalen.nl of over 900.000 EV charging transactions between January 2013 and April 2014. Based on that research, findings from the government of Amsterdam and further available literature EV charging and driving behaviour is shortly explained in the following section. This results in a simplification of EV driving and charging behaviour to represent EVs in this research.

Connection time

Spoelstra et al (2014) identified two main trends: there is a clear difference between residential and commercial EV drivers and there is a difference between weekdays and weekends.

Commercial EVs are usually connected to the grid during office hours. There is a peak in start of charges around 08:20 and a peak in stop of charging in the evening, around 18:20. It is assumed that the charging of these EVs always occurs in the neighbourhood of interest. During weekends, also half of the commercial driving EVs are connected to the grid (Gemeente Amsterdam, 2015).

Residential EVs have two start and two stop peaks, both one around 08:30 and around 17:50. This indicates that they are mostly connected during evening/night time and disconnect during and between two trips. Therefore, this charging behaviour is referred to as ‘pillow chargers’ by the local government (Gemeente Amsterdam, 2015).

The weekend shows a much more dispersed pattern for EV charging. This indicates that EVs are connected more randomly throughout the day. In this research, the majority of the weekend EVs has been connected to the grid, except 2-3 hours around their trips. Appendix C presents data on the connection times of Dutch EVs (Spoelstra et al, 2014).

Trips
Based on connection time, there are differences expected in the trips made between residential and commercial driving EVs, as well as between trips during weekdays and the weekend. First of all, during weekdays, a large share of the trips in Amsterdam is for home-to-work trips. These are trips that are made typically in the morning and in the afternoon of the same day and same distance. Residential drivers also mostly make home-to-work trips, but are assumed to make more personal trips in the neighbourhood as well.

Second, weekend days show a much smaller amount of trips and are difficult to simulate due to the lack of clear charging patterns (Spoelstra et al, 2014). Therefore, assumptions have been made to represent EV trips during weekend days. First of all, commercial EVs are at home during weekend days. Second, residential drivers make one trip per day during weekend days, which takes place around noon.

Distance
Driving behaviour of EVs is important since this requires a certain capacity from the battery. The CBS is a Dutch organization that does statistical research on, amongst others, the Dutch transport sector. According to their latest reports, Dutch home-to-work trips are on average 36 km for a man and 21 km for a woman per day (CBS, 2016) for higher educated people. In this research a 50:50 share of man and woman is assumed in Amsterdam, so an average daily trip of 28,5 km is assumed for home-to-work travel for commercial drivers.

Residential users live in the neighbourhood and therefore make more trips besides home-to-work trips. Based on data from the CBS (2016), a passenger car in The Netherlands drives on average 13.000 km per year. Assuming that about two trips are made in the weekend and 10 during the week, this gives an average of 27,7 km per trip. Furthermore, it is estimated that PHEVs drive half of the distance of their trips electric powered and the other half using their internal combustion engine (ICE). BEVs drive the full distance electric driven. A summary of the data as used in the model is presented in Table 6.

Vehicle	**Trips**		**Connection time**	**Distance/trip** (km)	
	Week	**Weekend**		**Week**	**Weekend**
PHEV residential	10	2	18:30-08:30	13,85	13,85
PHEV commercial	10	0	08:30-18:30	7,12	0
BEV residential	10	2	17:00-07:30	27,70	27,7
BEV commercial	10	0	07:00-17:30	14,25	0

Table 6. EV charge and driving behaviour of four EV types

4.1.3 EV growth

There are multiple visions for the growth of EVs in Amsterdam. A personal meeting with V. Giessen (2016), who works for the government of Amsterdam and is burdened with the planning of public charge installations and enabling increase of EV in the city, proposed to let the EV share double every year. This is mainly based on the doubling of EVs over the last two years in the city. Although this statement partially included increase in battery capacity and potential increase in BEV share, this assumption would lead to very rapid EV growth, especially on the longer term. Therefore, the absolute growth of EVs in Amsterdam over the last two years has been used to estimate EV shares in the next years. Since there is an average amount of maximum 168 cars in one neighbourhood (see 4.1.1), this is also the maximum amount of EVs that can be located in one neighbourhood. Once this amount is reached, this amount will remain constant, which is expected to be the case in 2025 (see figure 8). This estimation is consistent with the target of the local government to have all vehicles in the centre of Amsterdam emission-free by 2025 (Giessen, 2016).

4.2 PV

4.2.1 PV yield in Amsterdam

Photovoltaics is a method to convert solar irradiance to a flow of electrons between two differently doped layers of semiconductor material. This flow of electrons produces direct current (DC) electricity that can be used directly to charge batteries.

Due to increasing insights and improving technologies, the average solar yield changes regularly. Commissioned by the RVO, Utrecht University (UU) has performed a research for the latest update on average PV yield in The Netherlands (van Sark, 2014). The average factor for The Netherlands was determined at 875 kWh/kWp installed capacity. However, there is some variation in different areas, with larger PV yield near the coast (van Sark, 2014). Amsterdam has been found to be located near the coast and therefore above national average. Discussion with the researcher (van Sark) has led to the decision to use **900 kWh/kWp** as more realistic yield in Amsterdam.

More recent measurement from within Amsterdam has shown an average yield of 3780 kWh from a PV capacity of 4 kWp, giving 945 kWh/kWp (Niesing, 2015). This results from a single system and could therefore not be used as an average for the whole city. It does however enforce the statement that the yield in Amsterdam is above Dutch average.

4.2.2 PV yield used

The months January and July are simulated to determine grid impact in two extreme months, solar intensity wise. Actual data on solar intensity is used instead of average intensity, since the occasional peaks in solar intensity occur for all PV systems at the same time, causing a sudden peak in PV yield which poses a potential threat to the electricity grid.

PV yield from the V2G pilot project in Amsterdam has been used to represent realistic PV yield in January and July. Figure 7 present this data for a week in January and a week in July (2015). However, more generally accepted data from van Sark (2014) is used to determine total yield, in combination with total installed capacity.

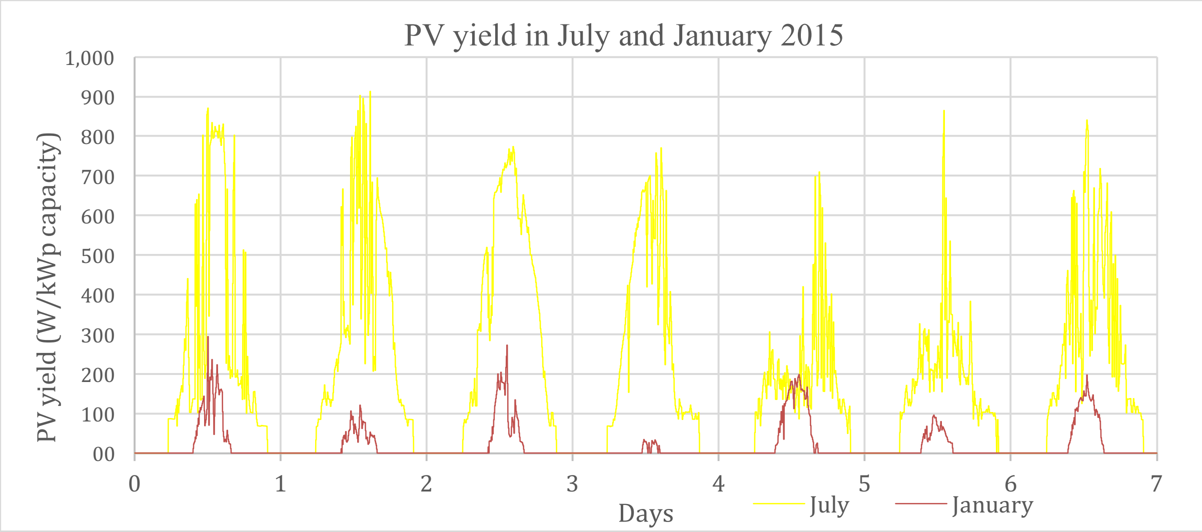

Figure 7. PV yield for one week in July and January, 2015

4.2.3 PV growth

As previously stated, the government of Amsterdam has ambitious goals to increase PV capacity within the city. Growth rate of PV is based on these targets (Duurzaam Amsterdam, 2015). Targets are set for different years; a linear growth is assumed to determine goals for years in between. The growth is aimed for the entire city, in this research is assumed that installed PV capacity in the different neighbourhoods will increase with the same rate. The current average PV capacity installed for 330 households has been determined at 52,5 kWp. Figure 8 presents the EV and PV rates over the years. In 2040, total PV capacity installed will be equal to 92,45% of total yearly fixed electricity demand in the neighbourhood.

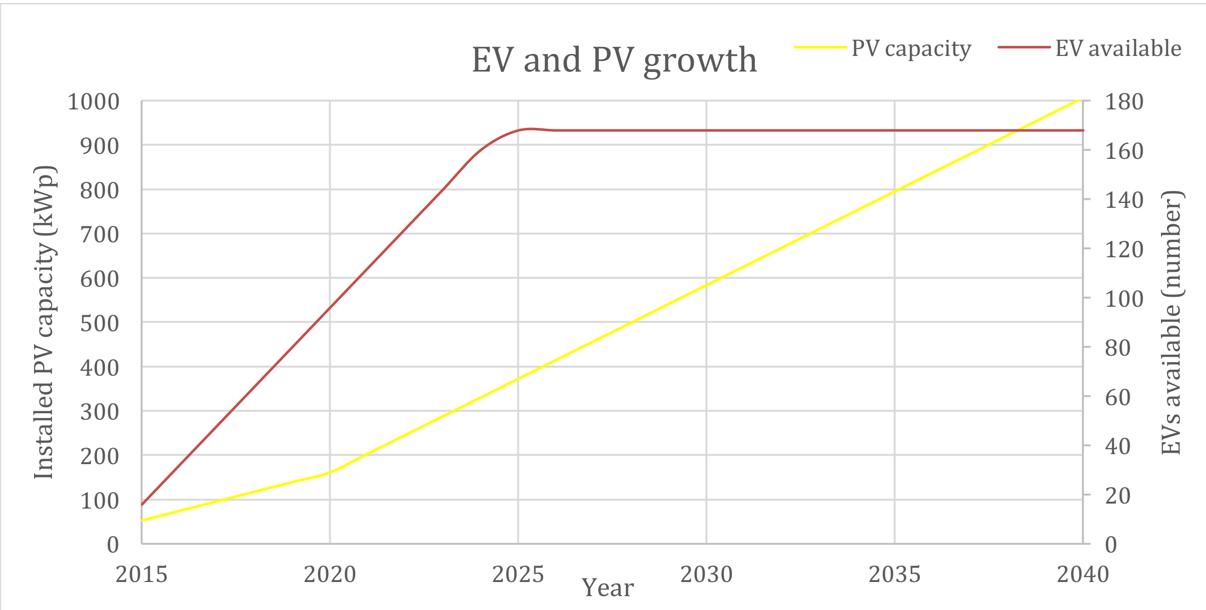

Figure 8. EV and PV growth in Amsterdam

4.3 Fixed load

Contrary to PV yield, fixed load has been represented by using average demand. This will reduce the impact of very short and extreme demand peaks, but since the demand on the grid is based on 330 connections the total demand levels out possible extreme peaks. Because every connection will have such peaks at different moments, these do not enforce each other like PV yield does. Average electricity use for a residential household in Amsterdam is 2970 kWh/year, based on an average household consisting of just below two persons (NIBUD, 2016). Fixed load patterns to represent energy consumption has been taken from the NEDU (Vereniging Nederlandse Energie Data Uitwisseling) (NEDU, 2015) and presented in figure 9. Total average electricity demand for fixed load for the neighbourhood is 16.043 kWh/week in July and 22.155 kWh/week in January.

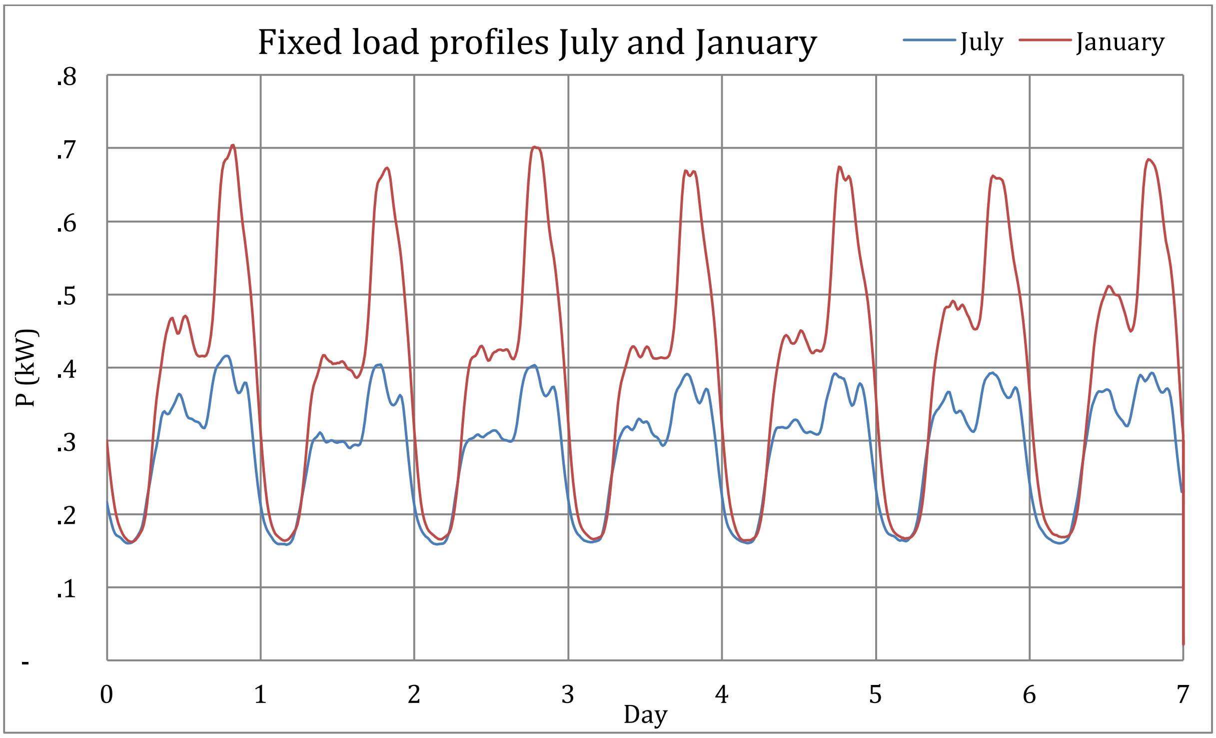

Figure 9. Fixed load first week in July and January, 2015

4.4 Neighbourhood dimension

The DSO in Amsterdam, Liander, uses the Strand-Axelsson model to determine the amount of buildings enclosed by one MV/LV transformer (Phase to Phase BV, 2006). This model takes the peak demand of one building and assumes that the larger the amount of connections and variety of buildings, the lower the *relative* peak becomes. In other words, it uses the lack of synchronicity of peak demand, since the amount of connections is large enough to have a variance in peak demand. Therefore, the amount of buildings in a neighbourhood depends on the types of similar buildings. At Liander, Amsterdam residences are dimensioned at 1.1kW peak (Westering, 2016). Typical urban transformer stations have an effective capacity of 368 kW. In Amsterdam, there are some 400 kW transformers with over 600 connections. However, this does not always imply that these are all single households. On average, about 330 residential buildings could be located within one neighbourhood has been used in this research, based on data from Liander.

5. Results

The model as described in chapter 3 has been run using the data input as described in chapter 4. This chapter presents the results of these simulations and is structured as follows. First, demand and supply on the grid in the four different visions is presented by showing impact of the three different technologies possible in July and January. The reason for this is that it visualizes the impact on the grid and it clearly shows what factors cause what impact. Therefore, part 5.1 could be seen as background information to understand the development of the performance indicators in 2015, 2020, 2030 and 2040 which are presented in part 5.2. The uncertainty analysis is presented in the same way as the performance indicators in part 5.2, but then regarding the five different scenarios (5.3). Finally, in part 5.4 the results on the performance indicators of battery degradation are presented.

5.1 Grid impact

Grid impact is presented in six different graphs: three possible solutions are presented next to each other; the upper graphs present a weekday in the first week of July and the lower graphs a weekday in the first week of January. After the presentation of the grid demand some notable results (key points) are elucidated. The impact is visualised for four visions, as described in part 3.5: first the current vision (2015), then 2020, 2030 and 2040. The explanations follow the same structure: first results from July are looked into, BAU and then CC and V2G. After July, the results for January are presented with either BAU, CC and V2G technology in place.

The graphs present one weekday, so from 00:00-23:59. The horizontal lines, at P=368 kW and P=-400 kW, present the maximum grid capacity for demand and supply, respectively. This means that when the demand line crosses one these borders there is either overdemand or PV oversupply. The graphs present 4 other lines: Fixed load, EV charging, PV and Demand. This fourth line, Demand, is build up from the other three factors: Demand is Fixed load plus EV charging min PV.

Every graph presents one weekday, where the five weekdays have a similar pattern. Weekend days are very different, lack a clear pattern and also have less impact on the performance indicators compared to weekdays. Therefore, only weekdays are presented and explained in this chapter.

5.1.1 2015

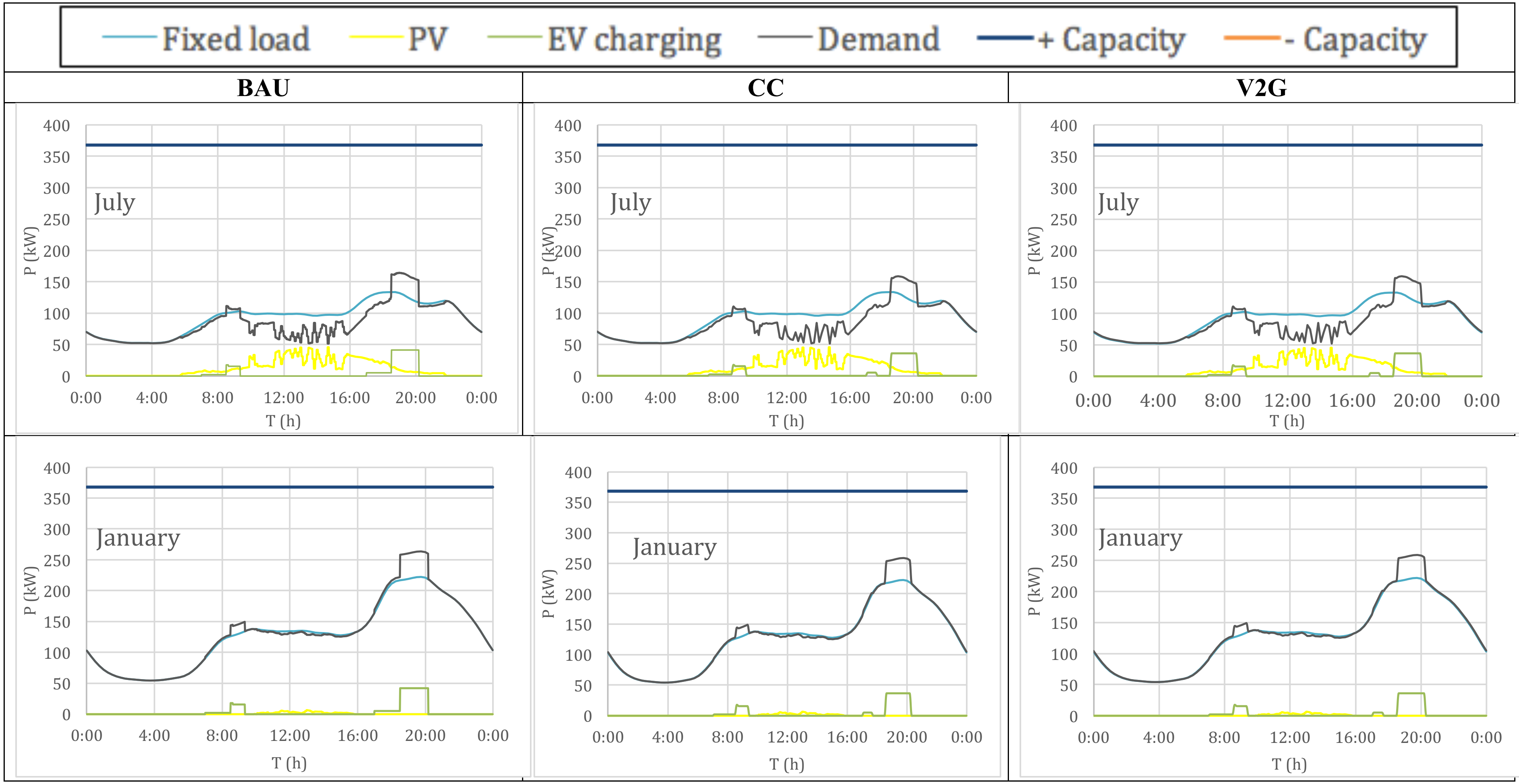

Figure 10. Grid impact 2015

Key points July 2015
The current vision (2015) shows a clear pattern in July, presented in figure 10. The different technologies in place (the three top graphs) show very similar results, indicating that CC and V2G technology do not have much impact in this situation. Furthermore, there is an EV charging peak in the evening that coincides with the electricity demand peak in the evening. PV is generated during midday and reduces total demand on the LV grid during midday. Demand is always above zero so no PV surplus is found, therefore also no oversupply.

Key points January 2015
In January, electricity demand peaks of 260 kW are clearly higher than evening electricity peaks in July with about 160 kW, as presented in Figure 10. This results from higher fixed electricity demand in January compared to July. EV charging peaks occur in the morning and even stronger in the afternoon and collides with electricity demand peaks of the fixed load. This increases existing peaks even further, although total demand does not come close to maximum grid capacity. Just like in July, the graphs with the three different technologies in place are very similar.

5.1.2 2020

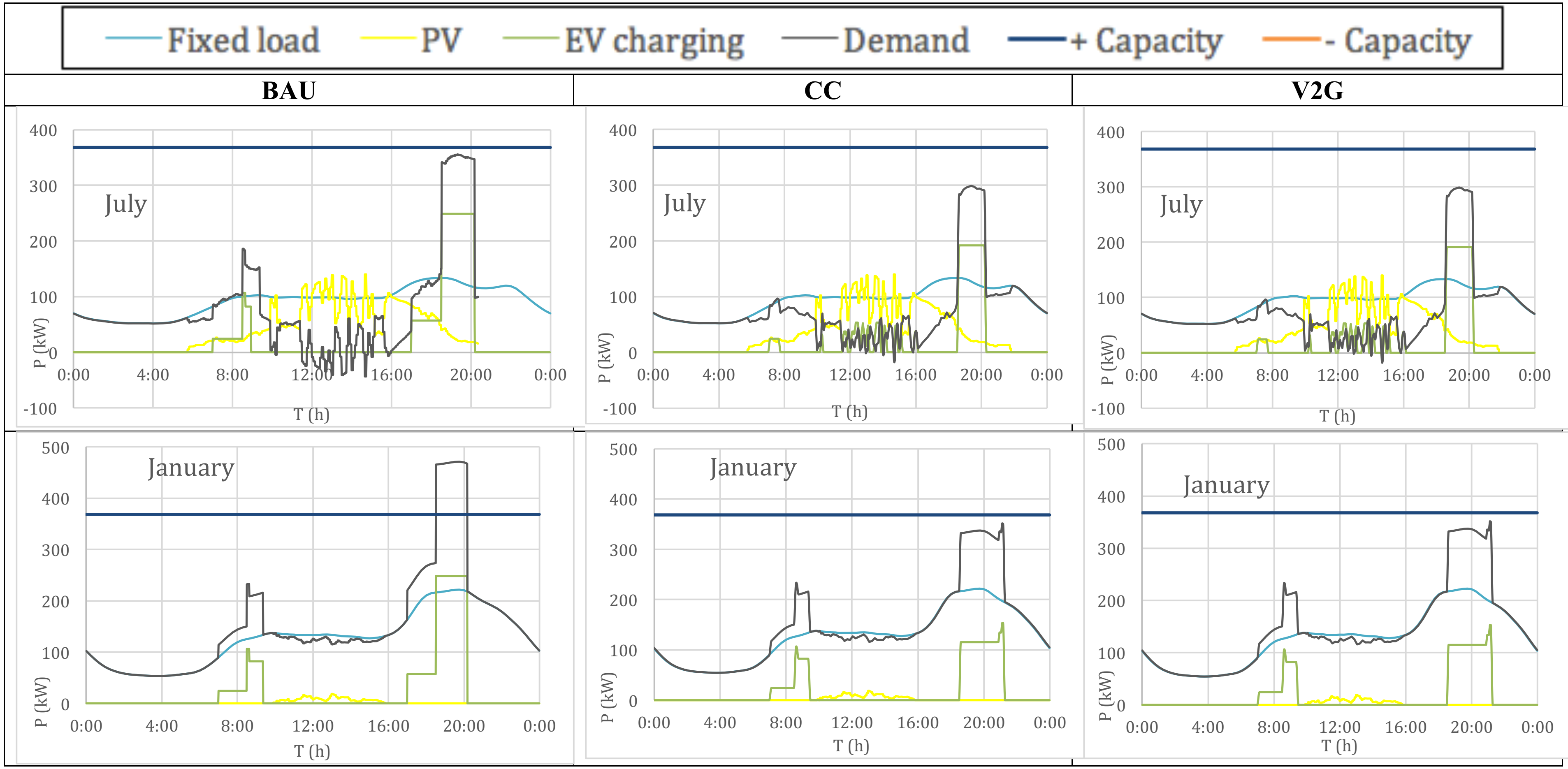

Figure 11. Grid impact 2020 vision

Key points July 2020
As indicated in Figure 11, in July 2020 there is a large increase expected in EV charging and therefore in total electricity demand, especially around the evening demand peak. EV charging starts around 17:00 and the peak starts around 19:00. This makes total demand to approach the maximum capacity with BAU technology in July. Besides, there are PV power peaks that occasionally exceeds fixed demand for about seven hours between 09:45 and 16:45, which results in negative demand. CC and V2G technology start charging EVs with PV surplus during midday, avoiding negative demand and at the same time partially charge EVs. The evening demand peak is increased compared to 2015 but does not come near the maximal capacity.

Key points January 2020
In January there is already overdemand in the BAU situation from 18:30 till 20:15. The simultaneous peak of fixed demand and EV charging causes demand to exceed the maximum grid capacity with about 23%. CC and V2G avoid this overdemand by spreading the EV charging over a longer time period. These are the green lines in the right graphs, they are for CC and V2G lower and broader, avoiding crossing the grid capacity. The charging peak is extended with about one hour, till 21:15. With CC and V2G technology there is a small increase in EV charging at the end of the evening charging peak. This occurs due to a decrease in fixed demand at that time, which provides more grid capacity to increase charging speed for a large amount of EVs. After about 15 minutes this will charge EVs sufficiently after which charging stops. Therefore, this is represented as a small peak in grid demand.

5.1.3 2030

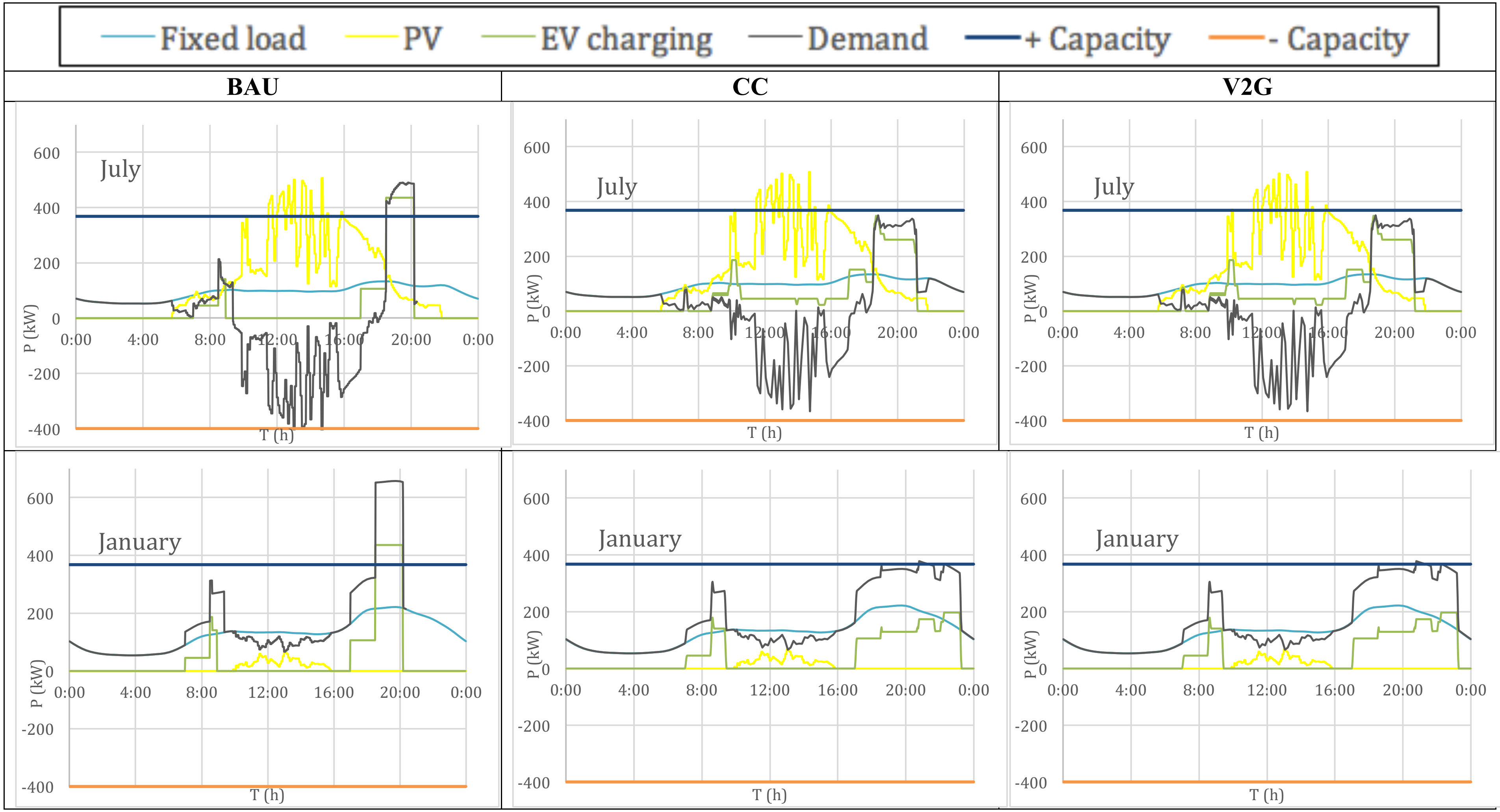

Figure 12. Grid impact 2030 vision

Key points July 2030

In July 2030, huge PV peaks are visible during midday, as presented in figure 12. This leads to negative demand, which occasionally has peaks that exceed the capacity of the transformers and cause oversupply. This happens with BAU technology in place, where also the EV charging peak in the evening causes grid overdemand. Compared to 2020, EV charging has increased and only EV charging itself exceeds capacity with a demand of over 460 kW. High PV yield does however result in a small reduction of the total peak demand, because PV power is available in July until after 21:00. With CC and V2G technology, EVs charge throughout the day, which is indicated with the green line (EV charging) in figure 12. Also, oversupply from PV peaks does not occur in both situations although it occasionally comes close to grid capacity. Again, these technologies do not cause overdemand in the evening and also the evening charging peak is reduced to about 45 minutes only, starting at 18:30.

Key points January 2030

In January EV charging causes overdemand in the evening, with only EV charging exceeding grid capacity with 24% between 18:30 and 20:15. Since this EV charging peak coincides with fixed demand peak this increases overdemand. PV power is still quite low and only has some short PV peaks that exceed fixed demand during midday. With CC and V2G technology demand does not exceed grid capacity, but total demand approximates the maximum capacity in the evening hours between 18:30 and 21:03. There is no extra EV charging during midday and PV yield is the same as with BAU technology. The V2G situation shows the exact same results as the CC situation. This indicates that there is no electricity returned to the grid.

5.1.4 2040

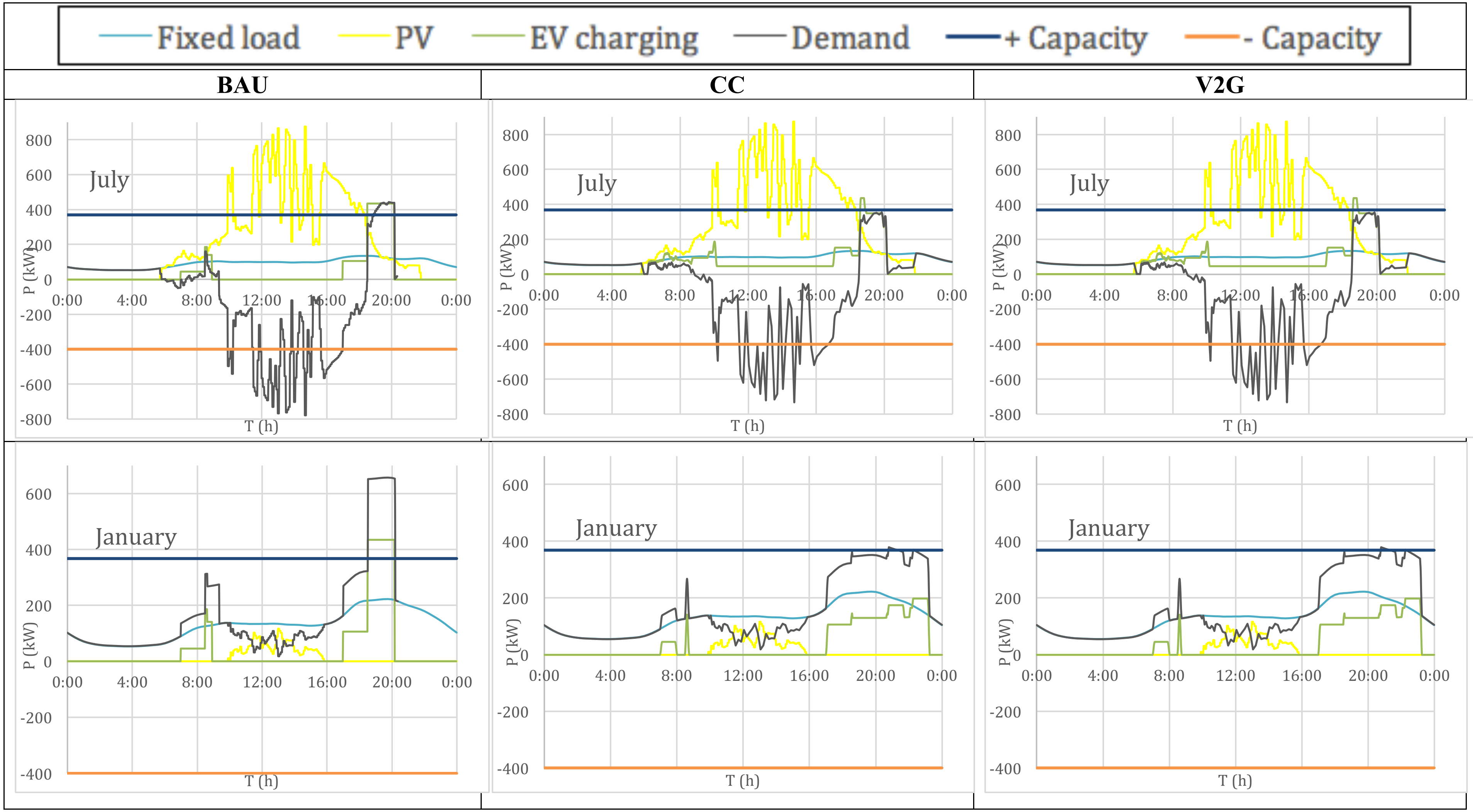

Figure 13. Grid impact 2040 vision

Key points July 2040

In July 2040 PV yield is much higher than in 2030, causing large oversupply both with occasional peaks as well as for longer periods of time during midday, as presented in figure 13. For BAU, EV charging has the same trend as in 2030, because the amount of EVs in the neighbourhood remained constant. CC and V2G also see large amount of PV that causes oversupply in July, although this is less than with BAU technology in place. EV charging is similar to EV charging in 2030, with constant charging of EVs during daytime and relatively small peaks in the morning and evening. Extra EV charging during midday causes reduction of oversupply, however this is only a small share of total oversupply. Morning charging peaks are reduced with CC and V2G technology because there EVs usually charge extra the previous day, therefore less charging is required.

Key points January 2040

In January there is still a large peak in EV charging, similar to 2030. A share of PV surplus is returned to the grid, although it does not come near oversupply. With CC and V2G in 2040 there is also in January occasionally extra EV charging during midday. The evening charging peak does not cause overdemand but is extended until 23:36.

5.2 Performance indicators

This part of the results presents the development of the four performance indicators until 2040. They are presented per indicator, of which the changes are displayed over the years. In each graph six lines are plotted, representing either BAU or CC technology in place, in January and July. V2G is not displayed since it presents the exact same results as CC, as found in the previous part (5.1). After each graph, a short description of the results is presented, highlighting the most notable findings. The performance indicators are presented over the increase of EV and PV till 2040. Therefore, on the secondary Y-axis the relative amount of EV and PV is presented with dotted lines (lines five and six). This regards the amount of EVs per household and the PV capacity installed as share of the total annual fixed electricity consumption of the neighbourhood, which includes all electricity demand except for EV charging. This means that a share of 100% signifies that every household uses one EV and that the total installed PV capacity is equal to the yearly fixed electricity demand of the neighbourhood.

5.2.1 Overdemand

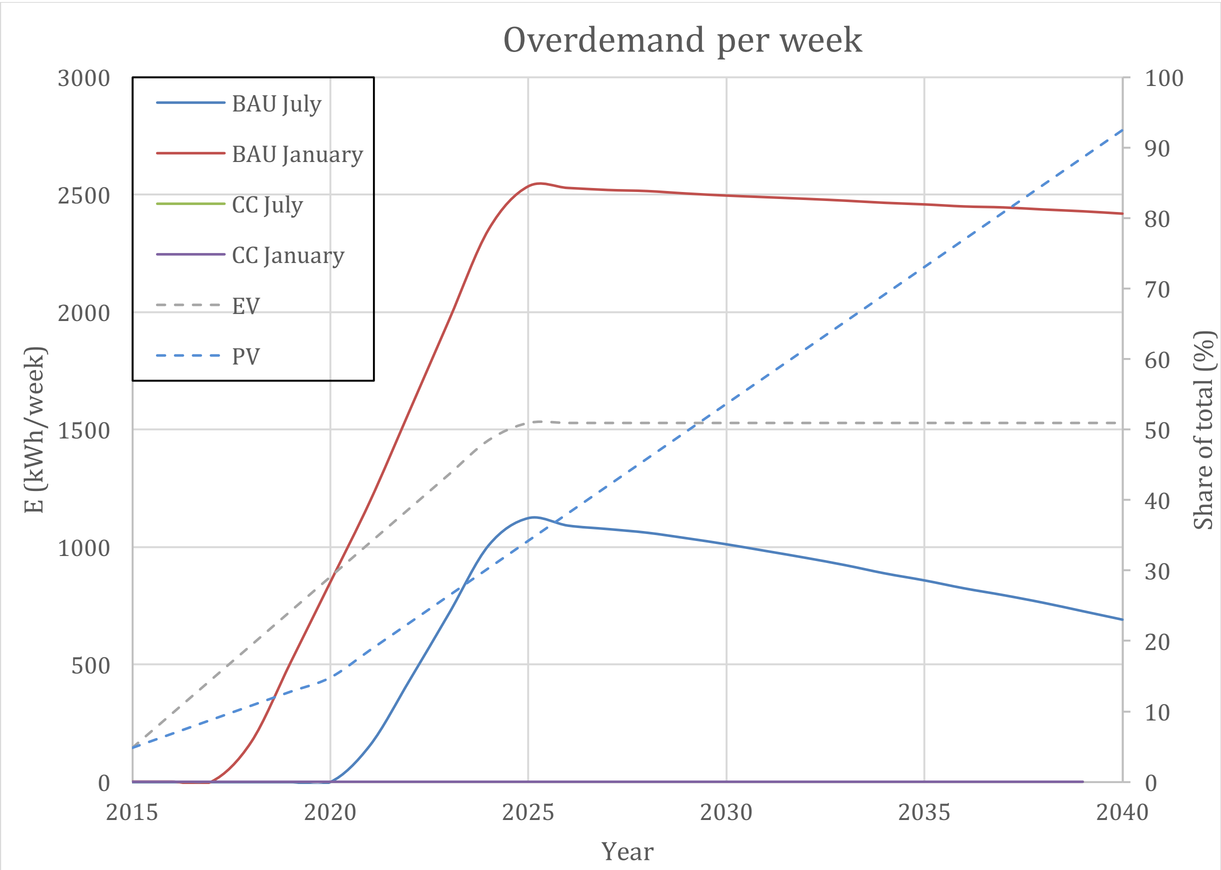

Figure 14. Overdemand per week

Key points overdemand
Figure 14 indicates that overdemand first occurs in January 2018 with BAU technology in place. After 2018 overdemand keeps growing in January, reaching its peak in 2025. In that year, the overdemand is 2536 kWh per week, while total fixed demand is about 22.000 kWh/week. This means that 11,4% of total demand in that week could not be delivered in the neighbourhood and harms the transformer. The demand peak coincides with the maximum amount of EVs in the neighbourhood, with on average 0,5 EV per household. Installed PV capacity is about 34,2% of total fixed demand in that year. After this peak, EV share remains constant and total overdemand reduces every year but remains around 10% of all demand until 2040. This is because a part of the PV yield can be used to charge EVs in the evening peak, thus reducing overdemand. The morning peak for EV charging collides with fixed demand peak in the morning, but in all scenarios the grid has shown to be capable of dealing with this demand without facing overdemand.

Overdemand in July occurs later, starting in 2021. From then, the curve follows the same trend as in January, although the overdemand peak with BAU technology in July is in 2025 at 1123 kWh. This is 7,0% of total fixed electricity demand in one week in July. After 2025 the amount of overdemand reduces per year, faster than in January. Same as in January, the reason of this reduction is that PV capacity keeps growing while EV charging demand increases at a much smaller rate, leading to reduction of overdemand. Because in July PV yield is significant until about 21:00 (see figure 13), this has direct impact on the reduction of overdemand. Increasing shares of PV further reduce this overdemand, although there is significant overdemand in 2040.

CC and V2G technology avoid overdemand mainly by reducing charging power in order to spread EV charging over an extended period of time. Figure 12 clearly shows that in January 2030 peak EV charging in the evening takes about twice as long as with BAU technology in place and that all EVs can be charged sufficiently before 00:00 without causing overdemand. Because no overdemand occurs with these technologies in place these graphs are not presented. Results for controlled charging and vehicle to grid are exactly the same, therefore vehicle to grid does not seem required for the LV grid to avoid overdemand or oversupply. The LV grid can be maintained by optimal performance of controlled charging and technically seen V2G has not been required in this research.

Oversupply

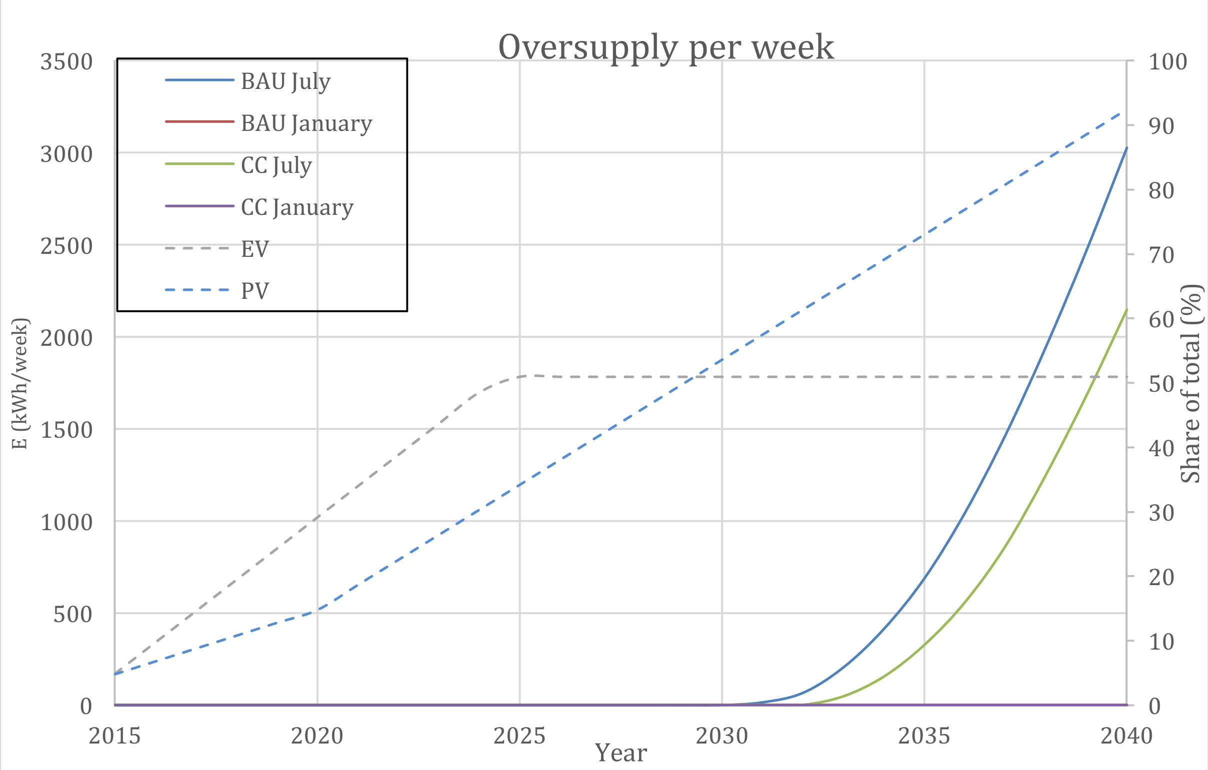

Figure 15. Oversupply per week

Key points oversupply
As figure 15 presents, oversupply occurs with high PV capacity installed in July. With BAU technology, oversupply first occurs in 2031 when PV capacity is 75,5% of fixed electricity demand. From then on there is a strong increase which continuous until the latest point in this research in 2040 with 3025 kWh/week. This oversupply is 18,9% of all fixed electricity consumption per week in July. With CC technology in place, oversupply occurs two years later for the first time when installed PV capacity is over 65% of total fixed electricity demand. There is a similar trend visible as with BAU technology, however it increases at a lower rate and the maximum oversupply in July 2040 is 2148 kWh/week, which is 13,4% of total fixed electricity demand per week in that month. The main reason for this reduction in oversupply compared to BAU technology is that EVs start charging during daytime, something that starts occurring in July 2020 when PV surplus charges available EVs. As visible in figures 12 and 13, CC and V2G enable all connected EVs to charge with PV surplus to provide storage for PV yield. With high PV capacity this flexible storage capacity from EVs provides only 45 kW storage, because of the small amount of EVs connected to the grid during midday. In July 2040, for an extended period of time during the day there is over 350 kW PV power available, then the 45kW can store less than 13% of PV surplus. Therefore, these technologies can only reduce a certain part of total oversupply.

The low PV yield in January is insufficient to cause oversupply to the grid, therefore these values are constantly 0 kWh/week.

5.2.3 Self-consumption and EV failure

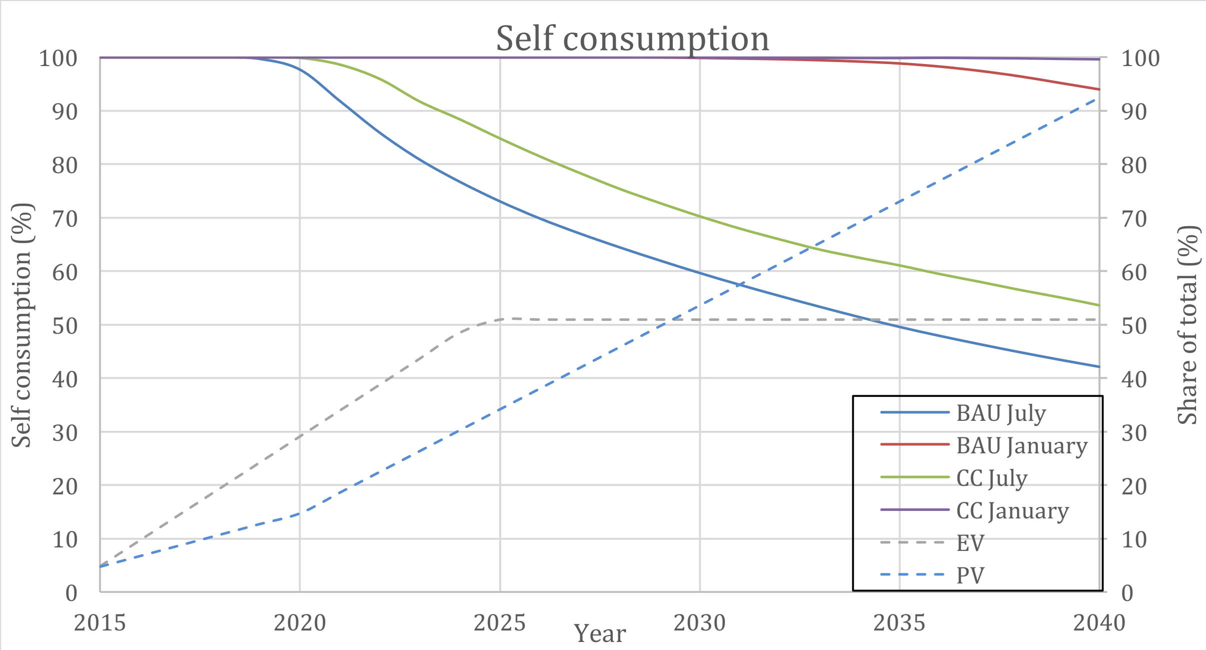

Figure 16. Self-consumption per week

Key points self-consumption and EV failure

Self-consumption is 100% in 2015, indicating that currently all PV power generated can be used locally, presented in figure 16. In the BAU situation in July PV self-consumption begins to drop in 2020 because PV yield is higher than fixed demand, so PV surplus will be returned to the grid. This starts when about 14,7% of total fixed demand installed as PV. The self-consumption keeps dropping down to 42% in 2040, although the steepness of the line decreases over time. With CC and V2G technology in place, self-consumption reduces one year later and decreases at a lower rate. In 2040, 50,9% of PV yield will be consumed within the neighbourhood itself. Note that in that case, 92,5% of yearly consumption installed as PV capacity in July 2040. As mentioned multiple times before, self-consumption is measured on neighbourhood level, so this regards the amount of energy from PV panels that is used within that neighbourhood. The main reason that these technologies allow for increased self-consumption is the availability of EV batteries to serve as mobile storage devices for PV power surplus. During midday these EVs use part of their capacity to store PV power, clearly visible in figures 11, 12 and 13 in July. In 2040 (figure 13), even in January PV surplus is used to charge EVs extra during midday.

In January self-consumption remains 100%, until 2035 for BAU situation where a small share of the PV power will be returned to the electricity grid. With CC technology in place the neighbourhood is able to consume 100% PV in January until 2040.

EV failure is not found in these simulations, therefore no graph is presented for this performance indicator. This indicates that EVs are connected sufficiently to the LV grid to ensure required capacity to make all planned trips.

5.3 Uncertainty analysis

This part presents results from the uncertainty analysis, based on changes on seven data input variables that are either focussed on the specific neighbourhood or are expected to change in the near future. Furthermore, it provides insight in values for the performance indicators in areas with different development than this research assumes in the centre of Amsterdam. Since the values for the performance indicators change over the years, different years will give different results. Because the main focus in this analysis is on the relative change compared to the actual data used, the absolute change is less important. For this analysis, data from 2035 is used. The values are varied using five scenarios, as described in section 3.6. First, impact on overdemand is looked into (5.3.1), then oversupply is considered (5.3.2) and finally self-consumption and EV failure is researched (5.3.3). The graphs in this section present these different scenarios on the X-axis, counting minus one to three, with 0 for the scenario used in this research. See table 7, which is a copy of table 4.

Parameter	Lower -1	Normal 0	High 1	Highest 2	Extra 3
EV growth	-25%	Figure 8	+25%	+50%	+100%
PV growth	-25%	Figure 8	+25%	+50%	+100%
EV availability	-	Table 6	+	++	+++
Commercial: residential ratio	1:9	3:7	5:5	7:3	9:1
Charging speed	-25%	3,7	+25%	+50%	+300%
Grid capacity	-25%	400 kW	+25%	+50%	+100%
Fixed demand	-25%	2970 kWh/wk	+25%	+50%	+100%

Table 7. Five uncertainty scenarios

5.3.1 Overdemand

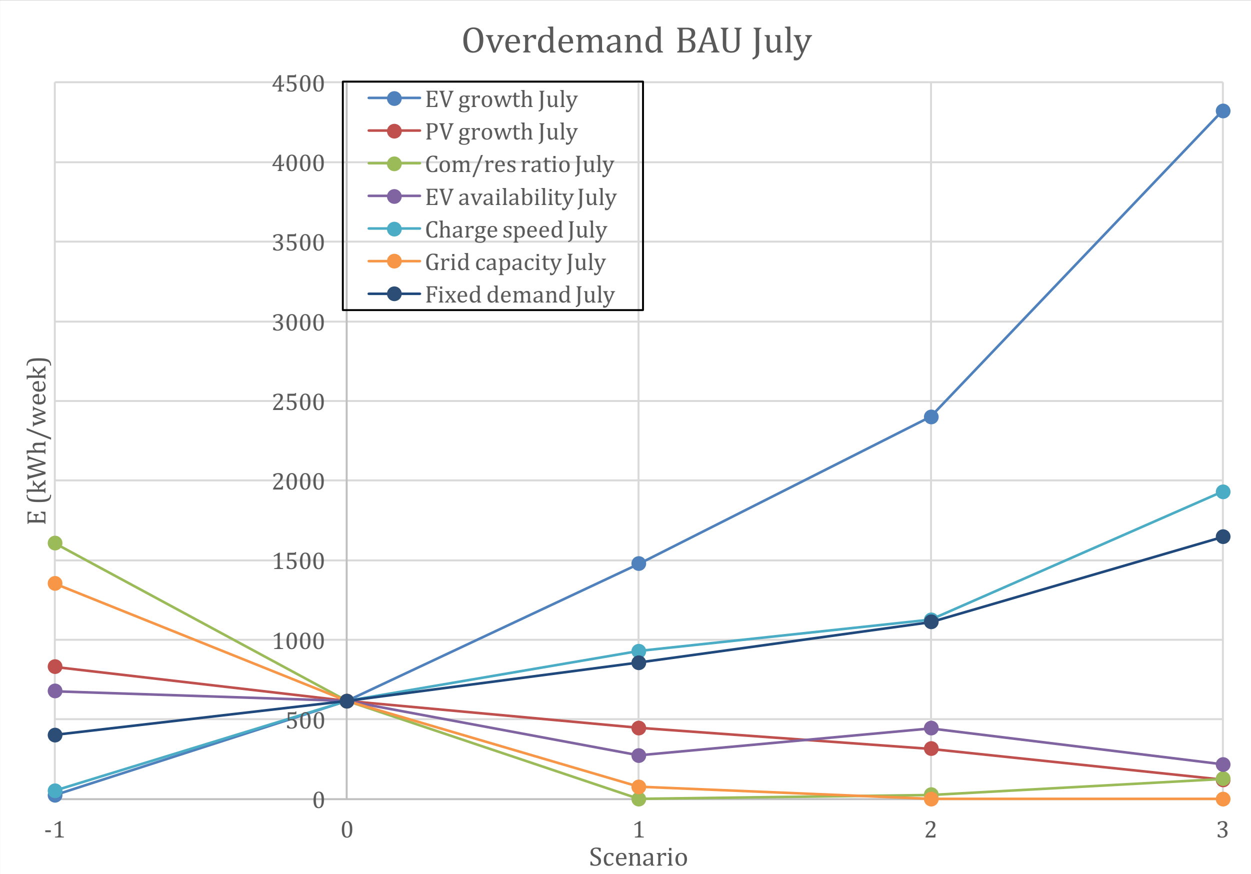

Figure 17. Uncertainty analysis: overdemand per week with BAU July

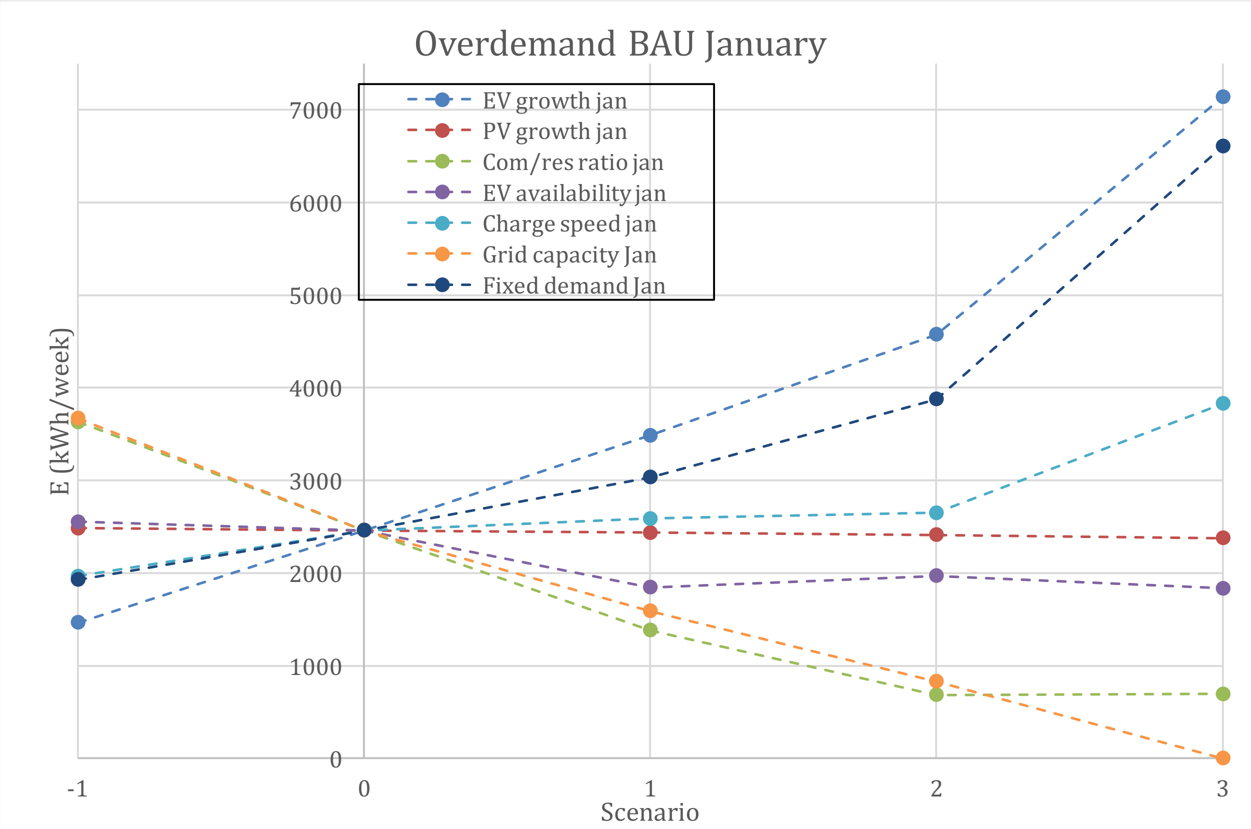

Figure 18. Uncertainty analysis: overdemand per week with BAU January

Key points overdemand

First of all, overdemand is always zero with controlled charging or vehicle to grid technology in place. This is because the main characteristic of these technologies is that if overdemand occurs the EV charging speed is reduced. With BAU technology in place overdemand does occur, therefore only these graphs are presented in figures 17 and 18 and will be explained.

EV growth has strong impact on the amount of overdemand, as could be expected. This occurs both in January as well as in July and there seems to be a direct relation between the growth rate of EVs and the amount of overdemand on the grid. 100% increased EV growth would also in the morning result in overdemand during weekdays. Since there is already overdemand with the EV growth used, higher growth rates would increase the existing peaks even further. Therefore, +50% EV growth increases overdemand with more that 50%.

Increasing PV growth leads to a reduction of overdemand in July. A 25% increased PV growth leads to a reduction of about 20% overdemand. Furthermore, a reduction in PV growth leads to an increase in overdemand. In January there is less influence from PV growth, since PV yield is low in January. However, with very high growth rates there is a small reduction in overdemand.

An interesting trend is found with changing commercial/residential ratio. In July this has very strong influence on the total overdemand, leading to more than doubling of overdemand with a higher residential ratio (1:9 in scenario -1). This also works the other way around, with a higher commercial share overdemand drops to 0 kWh/week, mainly because a higher commercial share means more electricity demand during daytime and reduces EV charging peak in the evening. A neighbourhood with 80% or more commercial buildings would again lead to overdemand due high EV charging peaks in the morning.

With very high commercial rate (9:1 in scenario 3) overdemand starts again, although at a much lower rate. In January a similar trend is visible but overdemand is always higher and a large share of commercial does not totally reduce overdemand, but in the ideal situation overdemand is at the same level as normal in July (about 680 kWh per week).

Increased EV availability leads to a reduction of overdemand with same rates in January as in July. With BAU technology overdemand reduces about 22% when more EVs are available to the grid, both in January and in July. This is because EVs can now charge at more different times during the day. However, most EVs still charge during the evening peak since that is the time many EVs return from a trip. Because EVs still start charging as soon as they are connected to the grid this is uncontrollable for the grid itself.

Increasing charging speed increases overdemand, as could be expected. With faster charging the impact of EVs on the grid becomes more intense for a shorter period of time. Since the problems with the grid mainly occur due to insufficient distribution of electricity supply and demand, this faster charging does not contribute to a stable LV grid.

A reduction of 25% grid capacity (scenario 1) will more than double overdemand because overdemand starts at lower demand. Increase of grid capacity, which would occur if DSO's would replace/improve the existing grid, leads to a reduction of overdemand. An MV/LV transformer with 150% capacity (scenario 2), which would be 600kW, would be a solution to avoid overdemand in July. In January there is more overdemand than in July, but a same trend is visible. Increasing grid capacity reduces overdemand and avoids overdemand when grid capacity is doubled, so in January a stronger grid is required because fixed demand is higher.

If fixed demand would increase due to electrification this has direct impact on overdemand, because this would add to the evening demand peak. In January this impact is strongest because fixed demand is higher in this month. This means that more efficient electricity use or a shift of electricity consumption mainly in residential buildings could help reduce or even avoid overdemand of the grid.

5.3.2 Oversupply

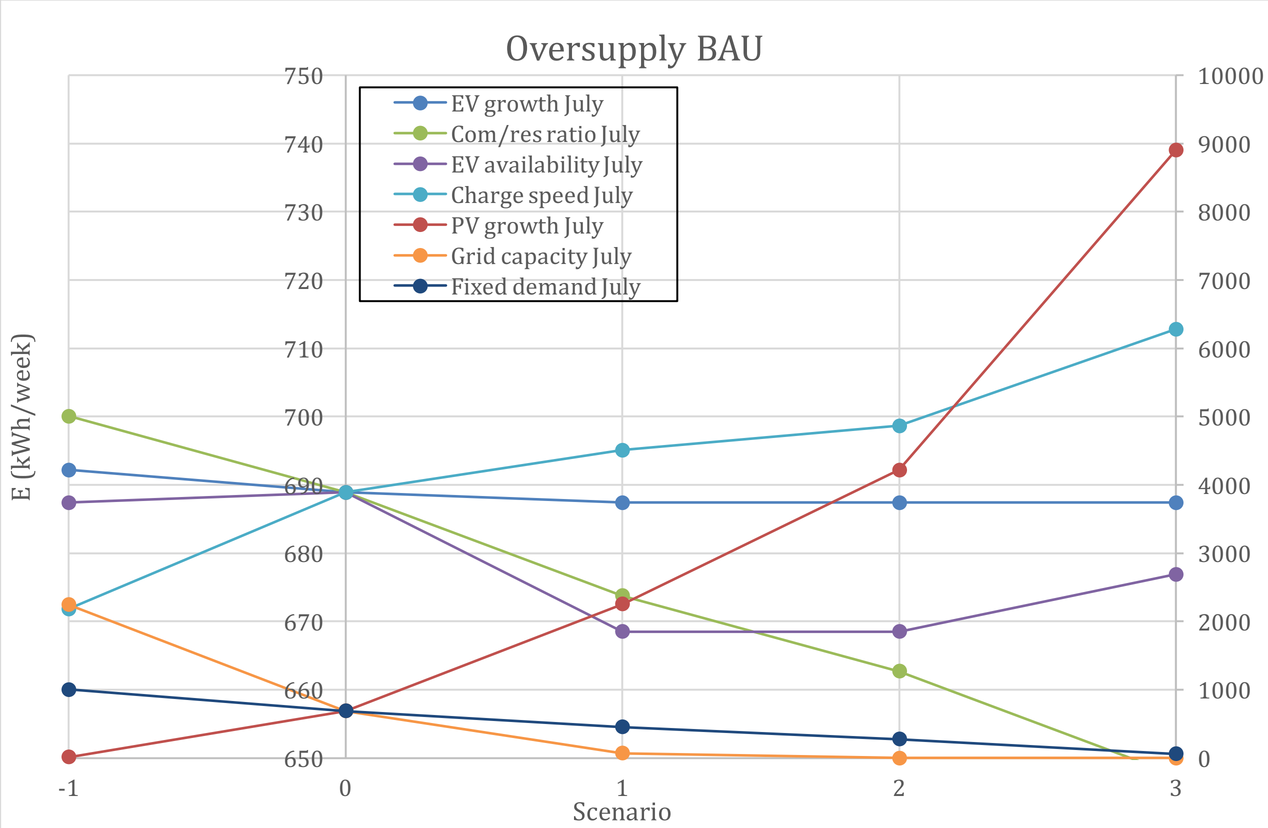

Figure 19. Uncertainty analysis: oversupply with BAU per week

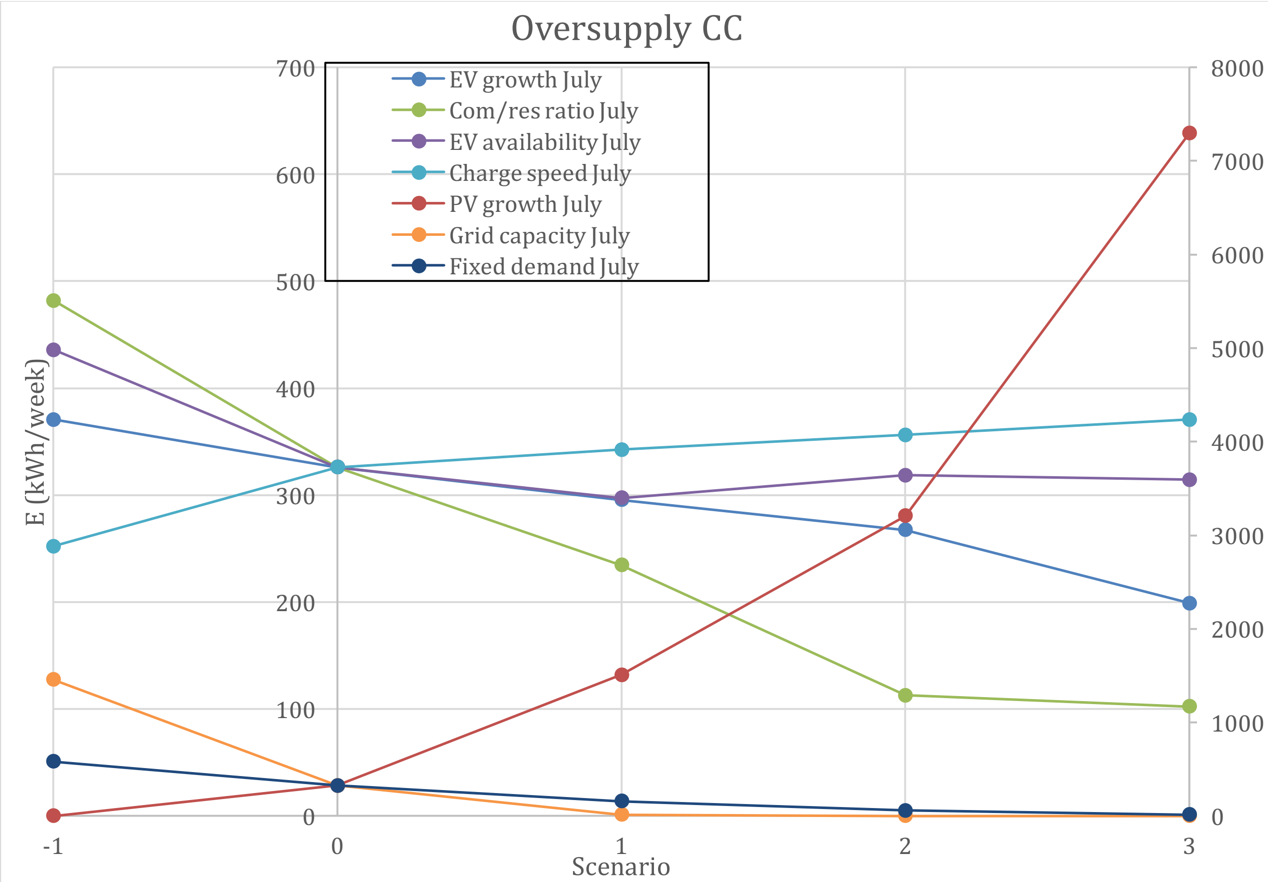

Figure 20. Uncertainty analysis: oversupply with CC per week

Key points oversupply

First of all, there is no oversupply in January because solar intensity is very low, the technology in place does not change this. Therefore, in figure 19 (BAU) and 20 (CC and V2G) only results in July are visible, all others run along the 0 line. Furthermore, the figures have a secondary axis, on which the overdemand values are plotted for **PV growth, grid capacity** and **fixed demand.** This is done because the variation is so large that it does not fit on one axis without making the impact from other factors invisible.

With BAU technology in place in figure 19, EV growth does not seem to have any influence on oversupply. With smart technology in place however, oversupply clearly reduces with larger EV growth. The reason is that increased amounts of EVs lead to more capacity available during daytime, which also enables EVs to store more PV power. In scenario 4, with 100% higher EV growth there is about one EV per household on average. Then, the oversupply is reduced by 38%.

Increasing share of commercial connections leads to a strong reduction in oversupply, since this building type has more electricity demand during daytime and increased amount of commercial EVs are connected during midday. This occurs both with BAU and CC technology, although with smart technology in place this reduction is stronger.

With EV availability there is again a reduction of oversupply with more EVs available in both situations. The impact is limited however, because many EVs make a trip in the afternoon and can thus charge at night. Also commercial EVs, that usually charge during daytime, can charge at night after their trip back home when they are more available to the grid. For only commercial EVs this means that they charge less during daytime, which reduces PV power consumption. All residential EVs that are now able to charge at daytime do increase total PV yield and therefore also increase self-consumption, but the total impact is limited. CC technology is designed to reduce overdemand and therefore tries to charge EVs either during midday or at night. Since more EVs are also available at night there will be increased EV charging here. Different assumptions on EV availability would therefore impact the amount of oversupply.

Similar as found with overdemand, there is an increase in oversupply with increasing charging speed, both with BAU as CC technology in place. The main reason for increase in oversupply is that an EV battery is filled faster and therefore the capacity available for PV power storage is filled faster as well. Because with CC and V2G technology EVs charge extra when there is PV surplus, this usually occurs before there is so much surplus that oversupply could be avoided.

Increasing PV growth has very decisive impact on oversupply. With 25% lower growth there is no oversupply and doubling the PV growth gives about twelve times more oversupply. With CC technology in place the oversupply is about 8% lower than with BAU, however has the same trend.

Changing grid capacity is also plotted on the secondary axis and presents similar results as on overdemand. With CC technology there is less oversupply from PV power, but increasing grid capacity would reduce oversupply of PV power with about the same rate for BAU and V2G technology in place. A growth of 50% grid capacity (from 400 to 600 kW) would avoid oversupply in 2035 in both cases.

An increase in fixed electricity demand has opposite effect on oversupply than on overdemand; increasing demand reduces oversupply because more PV power can be used within the neighbourhood. A 100% fixed demand growth would almost reduce oversupply to almost zero.

5.3.2 Self consumption and EV failure

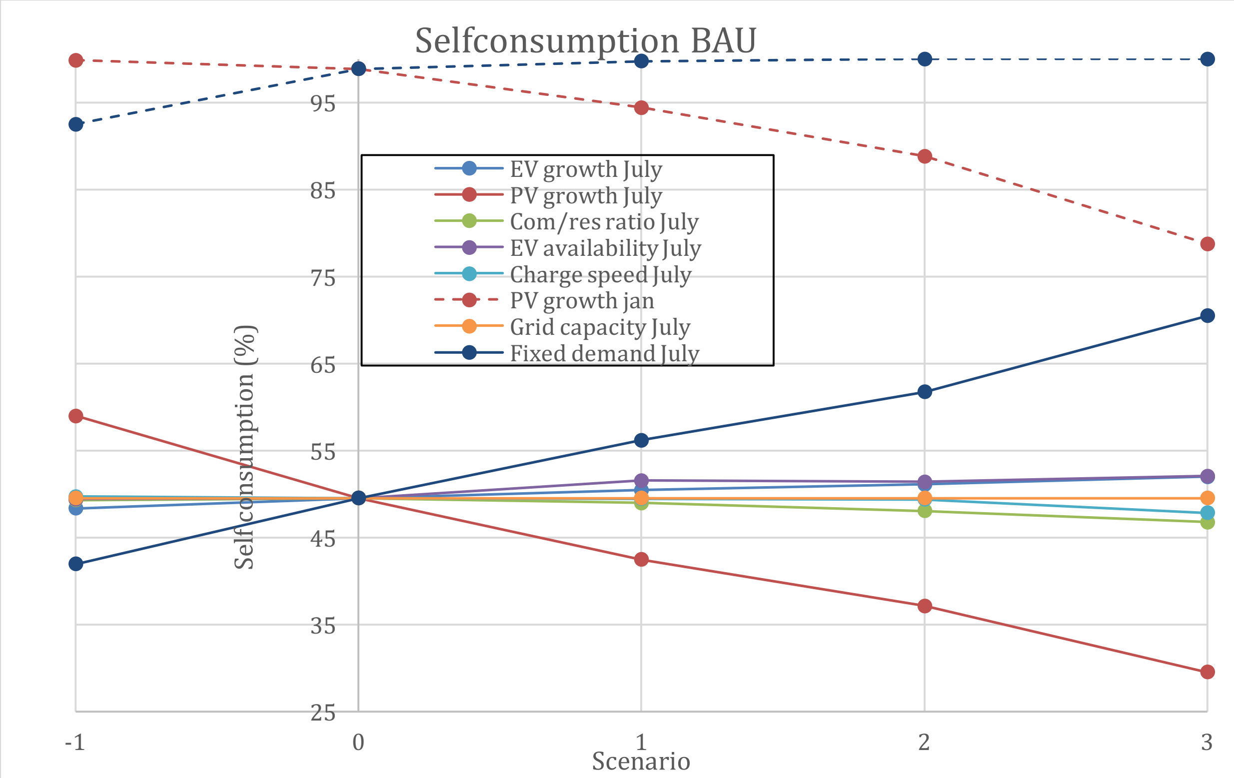

Figure 21. Self-consumption per week

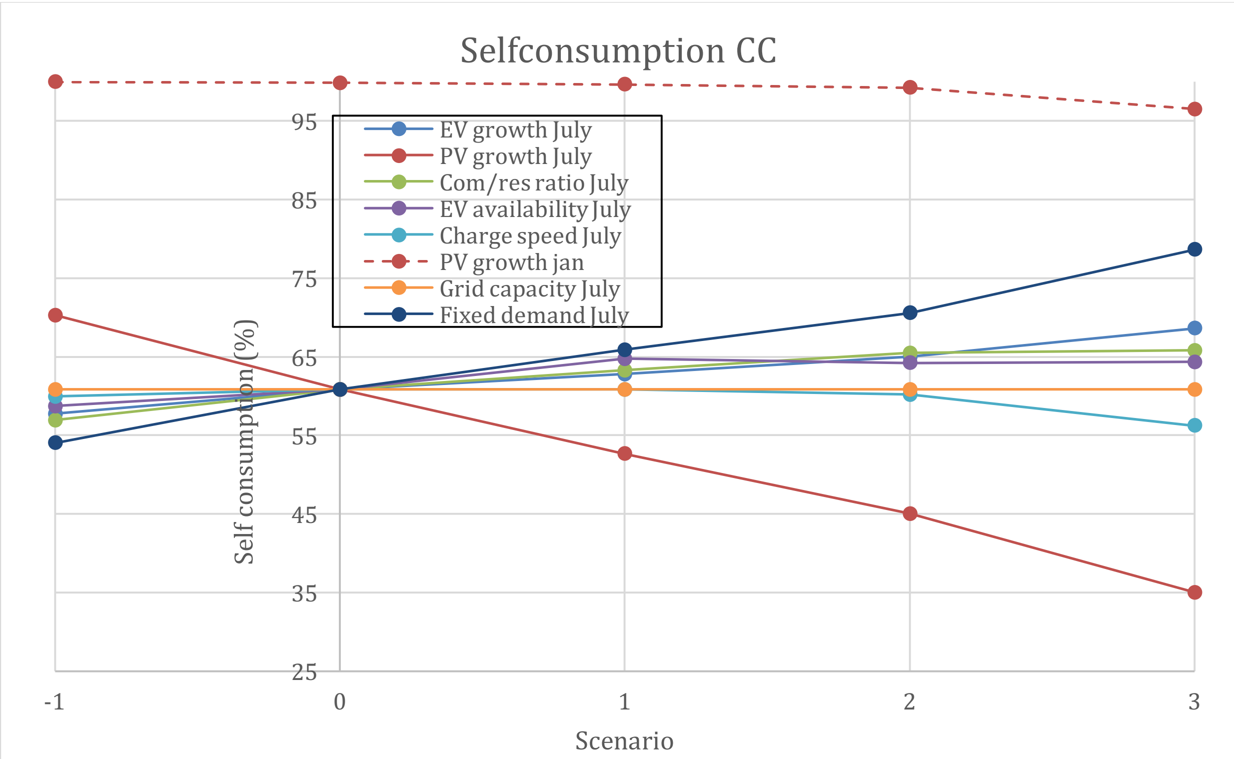

Figure 22. Self-consumption per week

Key points self-consumption and EV failure
First of all, no changes in input values of data considered in this uncertainty analysis has led to EV failure, therefore there are no graphs presented for EV failure. This means that smart technologies that can reduce charging speed do not cause EVs to run out of energy and can provide sufficient energy to the EV to make unexpected trips.

Second, what stand out in figures 21 and 22 is the high self-consumption rates in January, which is almost always 100%. Only a strong increase in PV growth reduces self-consumption in January, especially with BAU technology in place. In scenario 3, with 100% extra PV growth, self-consumption reduces to 80% in January. Note however that this would indicate the the total PV capacity installed is then 140% of total yearly energy consumption, which seems unrealistic high.

Third, the overall impact on self-consumption is relatively small, since there is very large PV capacity installed, about 70% of total fixed electricity consumption of the neighbourhood. This means that changes in a single factor has a relatively small impact on self-consumption.
Increasing EV growth gives a slight increase in self-consumption with BAU technology, where CC technology could increase self-consumption with 12,5% in scenario 3. As could be expected, a larger PV capacity growth leads to a strong reduction of self-consumption of PV power. This is clearly visible in both graphs, where self-consumption decreases with about 40% in scenario 3.

Changing composition of the neighbourhood only has a little impact, where again a larger share of commercial buildings leads to higher self-consumption and vice versa. The total share is not very high, since the high PV capacity installed leads to strong peaks that still cause a large share of PV power to be returned to the grid, as explained before.
Increasing EV availability also increases self-consumption in both situations. The increase from scenario 0 to 3 is 4,8% and 8,3% for BAU and CC technology in place respectively.
Maximum charging speed does not have much impact on self-consumption, however in scenario 3, with 300% increase, there is a slight reduction of self-consumption. Same as described previously on charge speed impact on oversupply, this is caused by the more rapid saturation of EV batteries. The capacity of the grid does not have impact on PV self-consumption on neighbourhood level.

Increasing fixed demand leads to reduction of oversupply. The main reason is that more PV power will be required within the neighbourhood and therefore the self-consumption rate of PV power will increase as well, as can be seen in figures 21 and 22. A reduction of fixed demand would at the same time reduce self-consumption with BAU technology in January as well, which can be seen in the left top corner in figure 21.

5.4 Battery degradation

Following from the simulation runs of the model that has been constructed for this research, the results in this part consider battery degradation performance indicators. As found in the previous parts of this chapter, there has been no discharge of EVs to the grid, indicating that also for battery degradation results for CC and V2G are the same.

Energy throughput

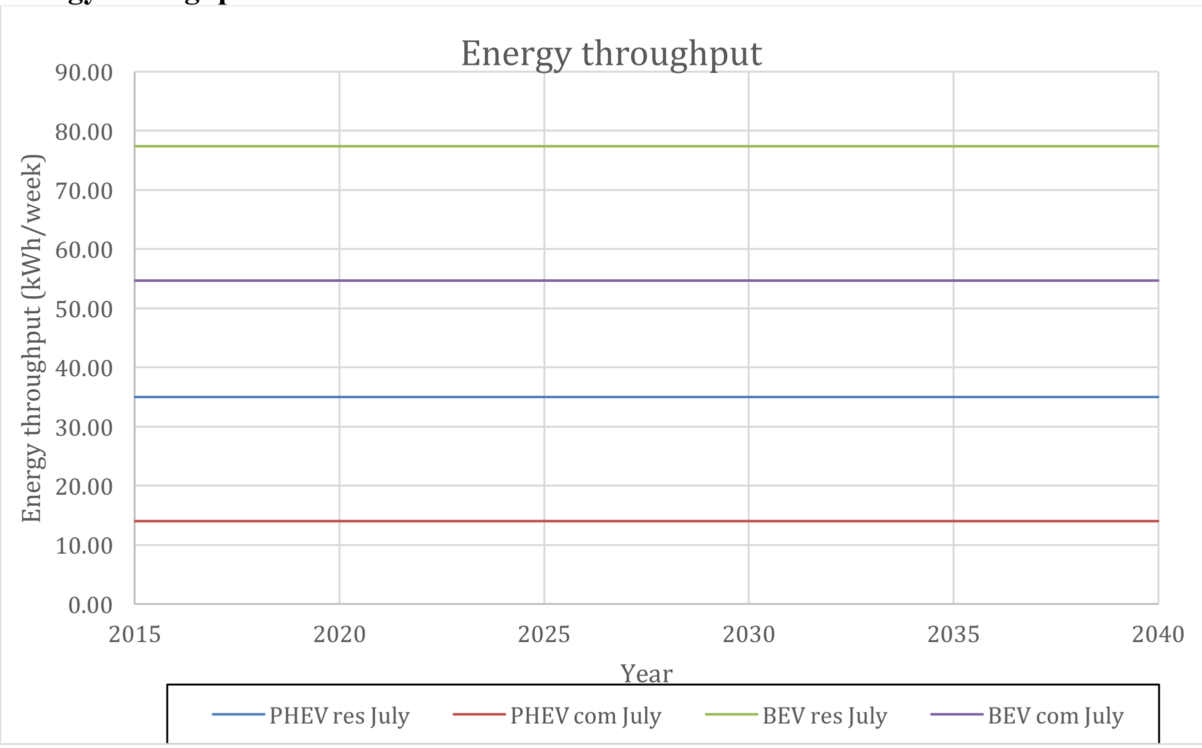

Figure 23. Energy throughput

Key points energy throughput

Figure 23 presents the energy throughput of the four EVs in this model, which is constant for every situation. This is because trips are assumed to remain constant and no V2G services are delivered, therefore no changes in energy throughput are found.

The differences between various EVs is that they all drive different distances using their electromotor. PHEVs drive a part of the trip using their combustion engine and have therefore lower energy throughput. Furthermore, residential type EVs are assumed to make more trips and therefore have higher energy throughput of the battery per week.

Average DOD for discharging

V2G technology would allow EVs to discharge their battery. Because there is no energy returned to the grid in these simulations, the DOD for discharging remains zero the entire time. Therefore, there is no graph presented for this battery degradation indicator.

Average SOC

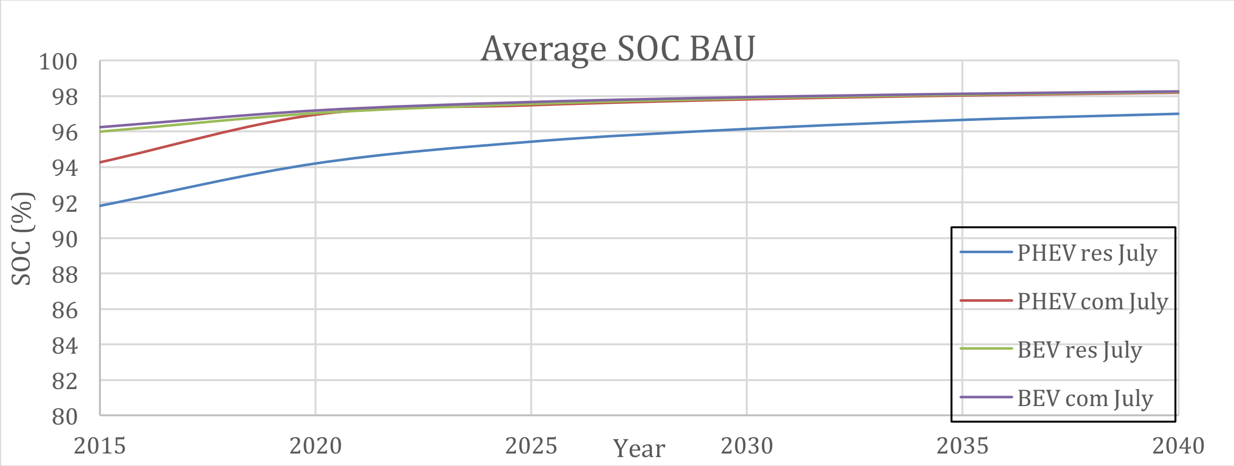

Figure 24. Average SOC BAU, July and January

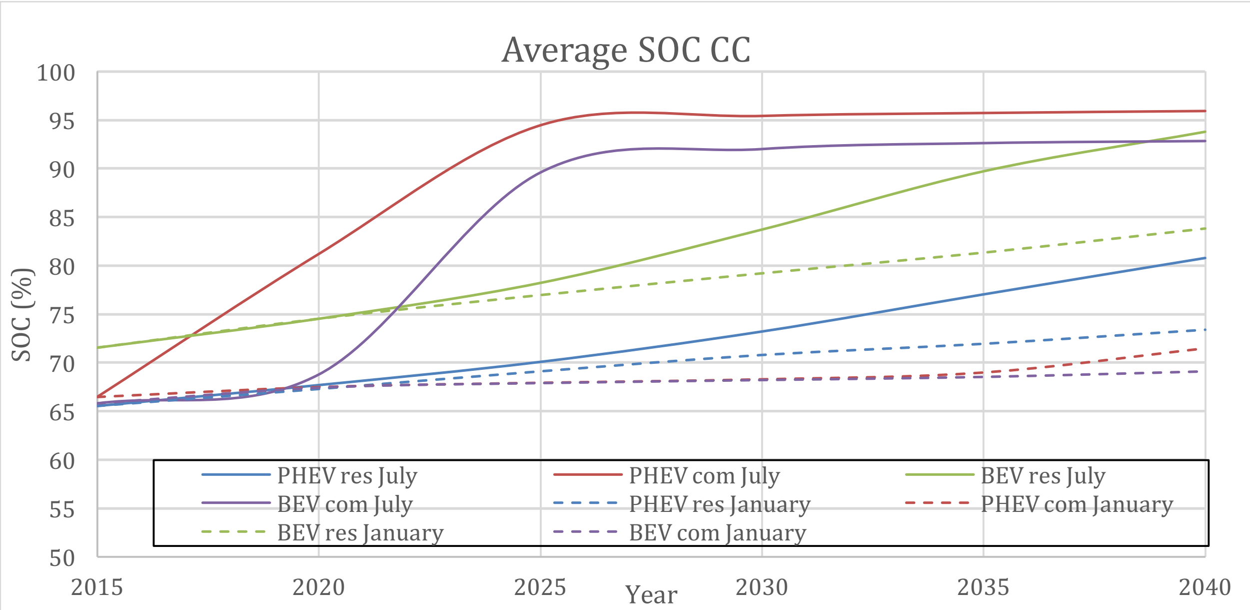

Figure 25. Average SOC CC, July and January

Key points average SOC

With BAU technology average state of charge is constant in January and July, since they both charge what is discharged for a trip. The average SOC increases over time though, because of the increase in battery capacity. The trip distance remains constant over the years and therefore the relative amount of electricity required from a battery decreases. The average SOC is quite high, mainly because an EV charges directly after a trip when possible.

The total amount of energy throughput remains similar as in the BAU situation, since no electricity is returned to the grid. The main reason for the differences between CC and BAU in figures 24 and 25 is that with CC (and V2G) technology in place the required SOC for EVs is 70%, except when there is PV power surplus. Therefore, the average SOC is much lower. With increasing battery capacity, the average SOC of mainly the two commercial EVs since these have more storage capacity for PV power during midday.

6. Discussion

This chapter takes the results from this research and compares it with previous research, discussed theory and used methodology (6.1). Then, it discusses some limitations of this research and ideas how these could be improved (6.2). This chapter concludes with some recommendations and ideas for further research (6.3).

6.1 Discussion

Results
The results as presented in chapter 5 confirm the statement that the discrepancy between PV supply and EV charging demand reduces self-consumption and increases oversupply. Also, as previous research concluded before, overdemand occurs within a couple of years due to a simultaneous occurrence of fixed electricity demand and EV charging demand peaks.

Furthermore, the results have shown that, as mentioned in part 1.1, an increase of storage capacity improves distribution of available assets. This alleviates impact on the LV grid and the use of smart charging technologies is able to facilitate this. Because even increased EV growth does not result in EV failure, these smart charging technologies enable sufficient charging of EVs without disrupting the existing grid while providing sufficient EV charging to make required trips. This is confirmed by McGrath's (2016) statement in part 1.1, stating that if all existing personal transport cars would be replaced by EVs, there would still be sufficient capacity to sufficiently charge these, however a better utilization of the existing assets is required.

Vehicle to grid was expected to help alleviate the LV grid to avoid overdemand. However, since this research assumed controlled charging to work ideally and has not included financial impact on prosumers, V2G was not found to be a requisite from the grid point of view. A research that includes financial impact or that approaches V2G as a part of smart charging infrastructure could present different results on V2G necessities.

The results of this research provide insight on the impact of an energy transition as implemented in the centre of Amsterdam, created by combining data from multiple stakeholders and previous researches in a simulation model.

Methodology
The construction of the model to simulate grid impact has shown to be a good method to answer the research question. It has shown to be able to take all important factors into account and to visualize grid impact in different situations and with an energy system in transition.

However, the assumptions behind the construction of the model that have been made to simulate reality as realistic as possible, have not all been validated thoroughly or are still uncertain. Part 6.2 presents the limitations of these assumptions in more detail.

Previous research
This research refers to some earlier studies which focussed on energy transition or impact of CC or V2G on urban electricity networks. The results from this research best fit the conclusion of the research by Eising et al (2014), who concluded that risk on grid

functionality would occur as soon as 2015 in densely populated parts of Amsterdam. That is sooner than found in this research, mainly because a large amount of different charging stations have been regarded in the research from Eising et al (2014). This in contract to this research, where more average data has been used. Therefore, there could be other vulnerable LV grid in The Netherlands that faces overdemand sooner than the grid in the centre of Amsterdam.

Another research by Westering et al (2016) is less in line with the results of this research concludes that 6% of transformer stations will face overdemand in 2030. The main reason for the differences in the later research and this one is that Westering et al (2016) have assessed about 7000 transformer stations, of which only a small share fits the characteristics of the grid condition in the centre of Amsterdam, as described by Eising et al (2014). Moreover, the growth rate of EV and PV is different than as used in this research. This indicates that there is a high variety in different transformer stations and that assumptions and availability of detailed local information have a large impact on the results.

Another research by v.d. Kam and v. Sark (2015), who looked at V2G services, concluded that V2G would be used a lot in a small smart charging network in order to decrease peak charging demand. However, that research looked at household level and the self-consumption of only that small system was regarded. In that case V2G would occur, however from the point of view of an entire grid this has not been found to be a necessity. Hence, the difference can be explained by a different perspective regarding V2G necessity and impact.

Battery degradation
As seen in chapter 5.4 on battery degradation, there are very different conclusions and opinions on the impact of CC and V2G services on battery degradation. There are as many researchers who expect strong increase of battery impact as there are researchers who found limited impact. Then, there are researchers that either do not make conclusions on feasibility of V2G or who expect that the market will change in such a way that battery degradation will not matter or could be overcome by other financial benefits. Clearly no consensus has been reached on V2G impact on battery degradation, therefore more practical results from pilot projects and knowledge of battery behaviour are required.

The results from the simulations in this research do not provide much insight on battery degradation because V2G did not occur. However, smart charging technologies have the potential to take factors into account that could influence battery degradation and could therefore be programmed to (dis)charge EVs while taking battery demand into account, which could improve battery performance.

6.2 Limitations

Model

- EV simulation

In this model a simplification of EV use is simulated, including four different EV behaviour types. However, in practice every single EV has its own characteristics, resulting in a more diverse EV behaviour. For practical reasons, four EV types have been used and are believed to simulate reality sufficiently accurate, however more individual EV simulations would provide more realistic results.

- Simulation periods

The months July and January have been simulated because these have distinctive solar intensity and fixed electricity demand. Because this research looks at a period of 25 years (2015-2040) this is assumed to be sufficient to create clear insight in the development of grid impact. However, simulations per month or per week would be interesting to find more specific trends within one year.

Data input

- EV trips

Fixed trip time for different EVs is assumed to be constant for all weekdays in different months. Furthermore, some EVs could be located at home for an extended period of time or a lack of charging stations could lead to different problems which has not been taken into account in this research. More detailed insight in factual behaviour of EVs in one neighbourhood would improve representation of EVs. However, due to the size of the neighbourhood it would be very difficult to gain this insight in over a hundred EVs, although it would improve the accuracy of the results.

Focus area

- Neighbourhood composition

A simplification has been made in the simulation of residential and commercial electricity demand. Although every building could have a specific electricity demand, standard average consumption patterns have been used to represent fixed demand. In particular commercial type buildings can vary greatly in consumption patterns and size.

- Exact operation of LV grid in the neighbourhood

This research focussed on the LV grid in an urban area with fixed borders of grid connection. However, in some cases different LV grids could be interlinked and large EV charging stations could be connected to a nearby MV grid in order to overcome LV grid overdemand. More detailed insight and intensive involvement of the local DSO would provide more realistic grid characteristics.

- Uncertainty analysis

The uncertainty analysis in this research has been performed with data simulated for 2035. However, because results differ between various years, an uncertainty analysis for different years than 2035 could be interesting as well. Due to practical reasons and the scope of this research only one year has been used.
Moreover, due to the many changes that are introduced in the field of this research lately, much data that has been used as input values are expected to change over the years. The seven factors used in the uncertainty analysis are entitled most important factors to influence results,

based on the authors opinion. However, every reader could have an opinion on these factors or the changes of these factors over time.

Implementation

- Financial impact

Financial impact has not been taken into account in this research, however, this will influence the impact of CC and V2G technology on prosumers. Hence, including financial impact would identify ways to provide incentive to prosumers to change charging behaviour or allow their EV to perform V2G services. However, it would also add a new dimension to the research and increase the size and scope of this research.

- Controlled charging technology

In this research three situations have been regarded, either with exiting technology, controlled charging or vehicle to grid technology in place. However, a gradual integration of these two smart technologies into the existing grid could be more realistic. Therefore, a partial use of controlled charging and vehicle-to-grid services in the existing grid would present more realistic results on grid impact in the near future.

6.3 Recommendations

Based on this research the following recommendations have been formulated:

- To avoid overdemand and oversupply on the existing LV grid in urban areas, smart charging infrastructure is required on the short term. The electricity grid should be more flexible and feature storage capacity to be able to avoid overdemand and oversupply of transformer stations.
- Smart charging technologies have a limited impact on reducing oversupply of PV power. Therefore, more solutions are required to alleviate the LV grid from increasing shares of PV surplus besides EV storage.
- The PV and EV goals of the government of Amsterdam are ambitious. However, implementation of these targets will impact the existing electricity network and solutions to overcome this impact are not sufficient in place. Besides availability of the required technology, consumer behaviour is an important factor that must function in a certain way to make large adoption of PV and EVs in the centre of Amsterdam possible.

  An increase in EV availability improves the solution that controlled charging provides. An incentive to make personal EVs available has to be created or improved to provide storage capacity on sunny days in the summer.
- PV yield from personal solar panels are used best when shared among the neighbourhood to increase self-consumption and reduce grid impact. Proper infrastructure and financial regulations are required to facilitate this.
- Impact of changing pricing mechanisms for electricity costs on prosumer behaviour should be further assessed. Improved pricing mechanisms could enforce V2G services and better charging behaviour from EV owners.
- This research required large amounts of data, which were in many cases simplified or partially based on assumptions. To conduct similar research with more accurate data enabling a successive researcher to make more valid and specific conclusions about grid impact, intensive cooperation of all stakeholders is required. For example, organisations like the local DSO (Liander), owners of EV charging data (HvA) and policy makers (government of Amsterdam) should cooperate and be closely involved in such research.

7. Conclusion

In this research the impact of an urban energy system in transition on the existing LV grid has been assessed. To do so, a model has been constructed that simulates electricity supply and demand of a typical neighbourhood in the centre of Amsterdam. To assess the impact of this energy transition, goals of the local government on EV and PV growth have been used. Besides looking at impact on the grid as a result of these governmental targets, simulations have been run using two innovative technologies to determine their solution to potential problems occurring in the future. Controlled charging and vehicle-to-grid are two technologies that have been used in an attempt to alleviate the existing LV grid. Besides risk to the grid, also potential EV failure due to insufficient energy content and the amount of PV power that is used in the specific neighbourhood has been assessed. Furthermore, an uncertainty analysis has been conducted to create insight in the impact of different input parameters and to be able to gain insight in the performance indicators in different regions or with improving techniques in the coming years. Finally, potential battery degradation impact due to CC and V2G has been looked into both by regarding existing literature and using the simulation outcomes. To perform this research, the following research question has been used:

What is the impact of increasing shares of EV and PV on the low voltage grid in Amsterdam and what is the impact of controlled charging and vehicle to grid?

The results have shown that overdemand is expected in January 2018. From 2021 these problems have been found to occur in July as well, which is expected to be the period in a year with lowest chance of overdemand. Damage resulting from PV oversupply has been found first in July 2031 and will only occur in months with high solar intensity. This is the case if at least 57,5% of total fixed electricity demand in the area is installed in PV capacity.
Controlled charging presents a good solution in alleviating grid overdemand. With this technology in place overdemand did not occur, while EV requirements have still been met at all times. Furthermore, controlled charging has reduced oversupply and increased PV self-consumption. Vehicle-to-grid technology has presented the exact same results as controlled charging, therefore can be concluded that returning energy from EVs back to the grid is not a requisite to alleviate the grid if controlled charging is already widely implemented. V2G could however be interesting for owners of PV and EVs if pricing mechanisms for electricity change, or be a part of a solution to improve the grid when controlled charging technology is not adequately implemented.

This research has shown that V2G is not a requirement for alleviating the LV grid to avoid overdemand, therefore limited information has been found on battery degradation. CC is expected to reduce battery degradation rates due to controlled use of the battery, which is mainly visible in the increased average state of charge of the battery.
Previous research has shown different results on battery degradation due to vehicle to grid services, however overall it seems that intensive V2G use does have a noticeable impact on battery degradation for the EV owner. More practical results are required to quantify this impact and different business cases could be developed to reward EV owners in order to overcome battery degradation impact.

This research has been performed based on energy transition goals of the government of Amsterdam on EV and PV growth. Based on the results of the uncertainty analysis some conclusions can be drawn regarding the impact of different factors. Increasing EV growth and charging speed will rapidly increase overdemand. Neighbourhoods with space for more EVs, potentially with EVs that charge faster than assumed in this research are expected to face overdemand even sooner. Furthermore, PV growth and charging speed affect overcapacity and self-consumption, which again can be expected in a neighbourhood with more space for PV panels. Finally, neighbourhoods with higher share of commercial type buildings will face less overdemand and oversupply and will have a higher self-consumption share.

Amsterdam will face LV grid problems in the centre of the city if PV and EV shares keep increasing rapidly and smart solutions to alleviate the grid are no implemented within the coming few years. Wide implementation of controlled charging would provide a solution; although it is highly doubtful if decent technology will be in place on such short notice. Changing electricity pricing mechanisms, vehicle-to-grid services or EV charging from the MV grid are potential solutions as well. Battery degradation seems to be limited, however more practical results and pilot projects are required to make final statements about this impact.

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9. Appendices

A. Amount and shares of top-5 PHEVs and BEVs

There are multiple different EV types in the market; Table 8 presents the top 5 of PHEVs and BEVs in The Netherlands (31-03-2016, rvo).

Model	**Type**	**Amount**	**Share** (%)
Mitsubishi Outlander	PHEV	24.572	30,9
Volvo V60	PHEV	14.646	18,4
Volkswagen Golf	PHEV	9.009	11,3
Opel Ampera	PHEV	4.826	6,1
Audi 3	PHEV	4.802	6,0
Other	PHEV	21.771	27,3
Model	**Type**	**Amount**	**Share** (%)
Tesla model S	BEV	4.905	44,8
Nissan Leaf	BEV	1.534	14,1
Renauld ZOE	BEV	1.186	10,8
Nissan E-VN200	BEV	668	6,1
Renault Kangoo	BEV	628	5,7
Other	BEV	2.018	18,5

Table 8. Top-5 amount of PHEV and BEV in The Netherlands per type. Source: RVO, (2016)

B. Top 5 Dutch PHEVs and BEVs

Data on Dutch top 5 PHEVs and BEVs is presented in Table 9. The weighted averages for PHEV and BEVs has been used to represent these vehicles, which are presented bold. Standard EV models are used for data on charging capacity.

Type	**SOC_{min}** (%)	**C_{bat}** (kWh)	**E_{cons}** (kWh/km)	**η_{trans}** (%)	**Range** (km)	**P_{charge}** (kW)	**Share** (%)
Mitsubishi Outl.	20[6]	12[2]	0,196[5]	0,85[4]	52[2]	3,7[2]	30,9[3]
Volvo V60	20[6]	12[2]	0,204[5]	0,85[4]	50[2]	3,7[2]	18,4[3]
Volkswagen Golf	20[6]	8,8[2]	0,150[5]	0,85[4]	50[2]	3,7[2]	11,3[3]
Opel Ampera	20[6]	16[2]	0,229[5]	0,85[4]	60[2]	3,7[2]	6,1[3]
Audi A3	20[6]	8,8[2]	0,150[5]	0,85[4]	50[2]	3,7[2]	6,0[3]
Weighted average PHEV	**20**	**11,57**	**0,190**	**0,85**	**51,69**	**3,7**	**100**
Tesla model S	20[6]	85[2]	0,233[5]	0,87[4]	320[2]	3,7[2]	44,8[3]
Nissan Leaf	20[6]	24[2]	0,137[5]	0,85[4]	150[2]	3,7[2]	14,1[3]
Renauld ZOE	20[6]	22[2]	0,089[5]	0,85[4]	210[2]	3,7[2]	10,8[3]
Nissan E-VN200	20[6]	24[2]	0,128[5]	0,85[4]	160[2]	3,7[2]	6,1[3]
Renault Kangoo	20[6]	22[2]	0,117[5]	0,85[4]	160[3]	3,7[2]	5,7[3]
Weighted average BEV	**20[6]**	**57,09**	**0,181**	**0,86**	**252,7**	**3,7**	**100**

Table9. Characteristics top-5 PHEV and BEV in The Netherlands

[2]www.thenewmotion.com [3]rvo, 2016 [4]Estimations [5]Calculation[6]Appendix D presents explanation of SOC_{min}

C. Dutch EV charging patterns

Spoelstra et al (2014) performed a research on EV charging patterns in The Netherlands based on over 900.000 EV charging sessions between January 2013 and April 2014. The data on these charging sessions provided insight in the start- and stop time of these charge sessions. Figures 26 and 27 present the main results on charging times that are used to create charging patterns of EVs in this research.

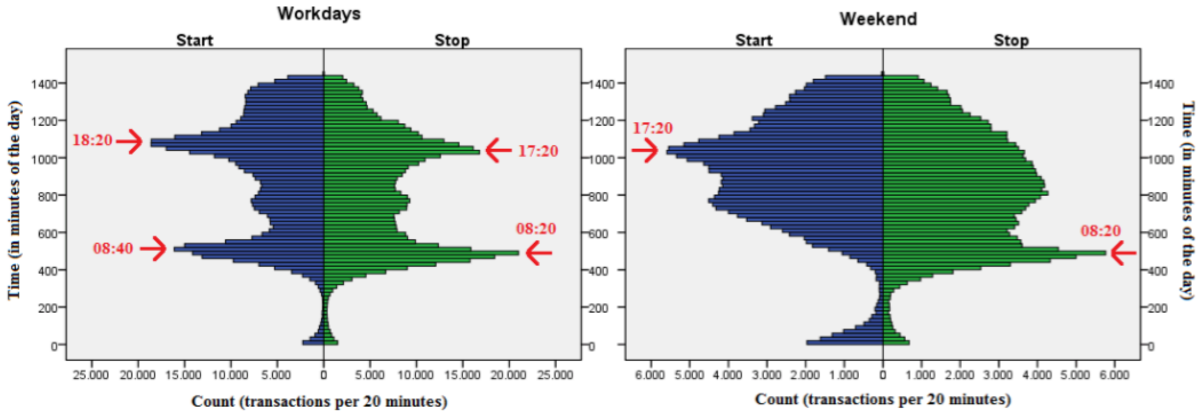

Figure 26. Dutch EV charging patterns during workdays and weekdays

Figure 26 clearly shows a start and stop peak around 8:30, indicating that at that time many people either disconnect their EV to make a trip or arrive at their destination and start charging their EV. The same goes for the evening peaks around 18:00. This has been used in this research to distinguish between residential and commercial type EVs. In the weekend there is a less clear pattern, there are some peaks but these are about four times as small as during weekdays and between peaks there is much more activity.

Figure 27 presents charging sessions, distinguishing between public and semi-public charging stations. Semi-public charging stations are used to create charging behaviour of commercial EVs, that are mainly connected during daytime.

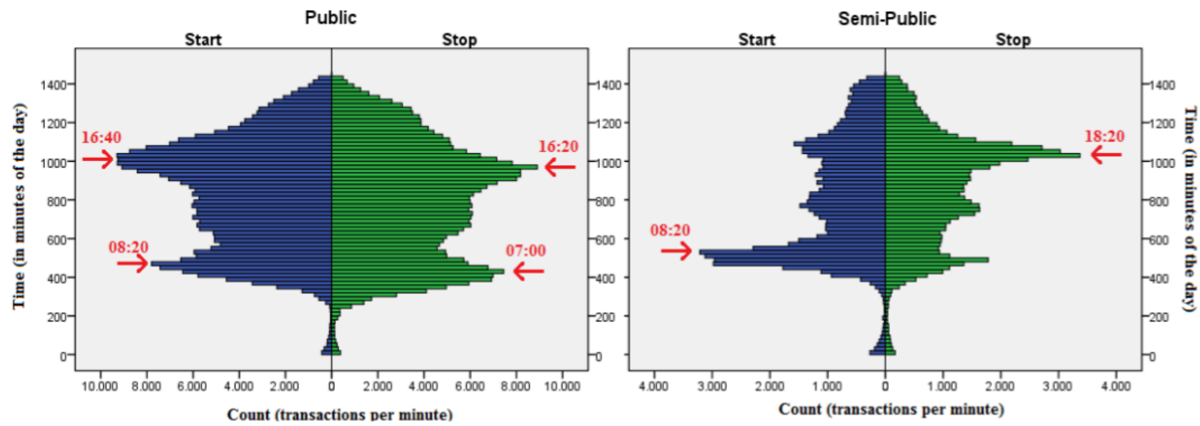

Figure 27. Dutch EV charging patterns for public and semi-public EVs

D. State of charge/depth of discharge

The state of charge (SOC) indicates the amount of energy left in a battery. An SOC of 100% presents a full battery, a SOC of 0% present a totally empty battery. Depth of discharge (DOD) is linked to the SOC: DOD=100-SOC and the other way around. Figure 28 gives a graphical presentation of determination of SOC and DOD.

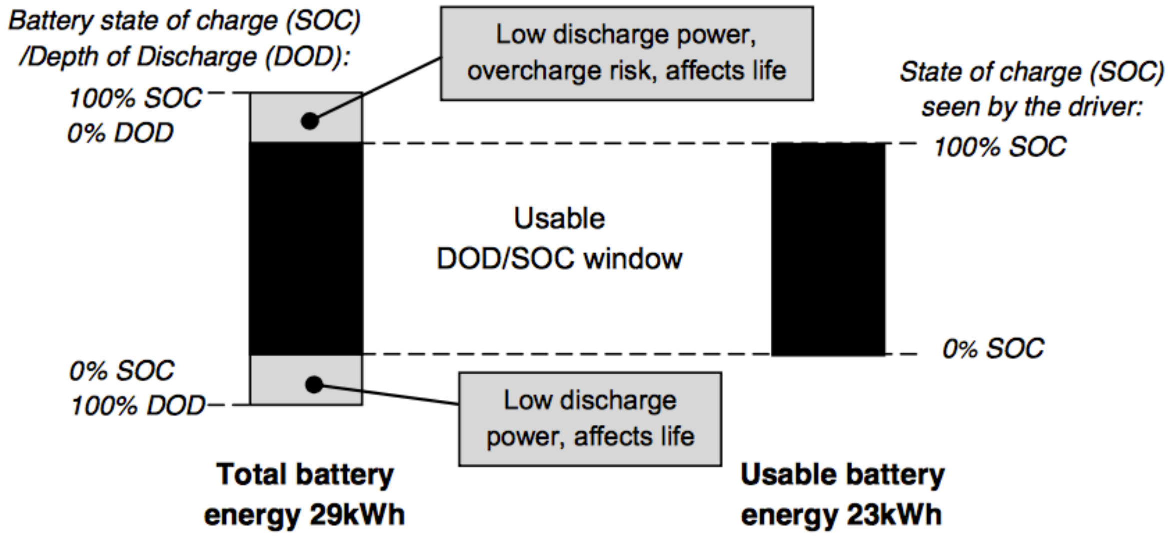

Figure 28. SOC explanation. Source: Element Energy (2012).

Although a SOC_{min} of 30% is used as well (Bishop et al, 2013), this research uses a SOC_{min} of 20%, similar to (Morano et al, 2009); (v.d. Kam & v. Sark, 2015).