TU Delft
Delft University of Technology
Faculty of Architecture
and the Built Environment

Lightyear

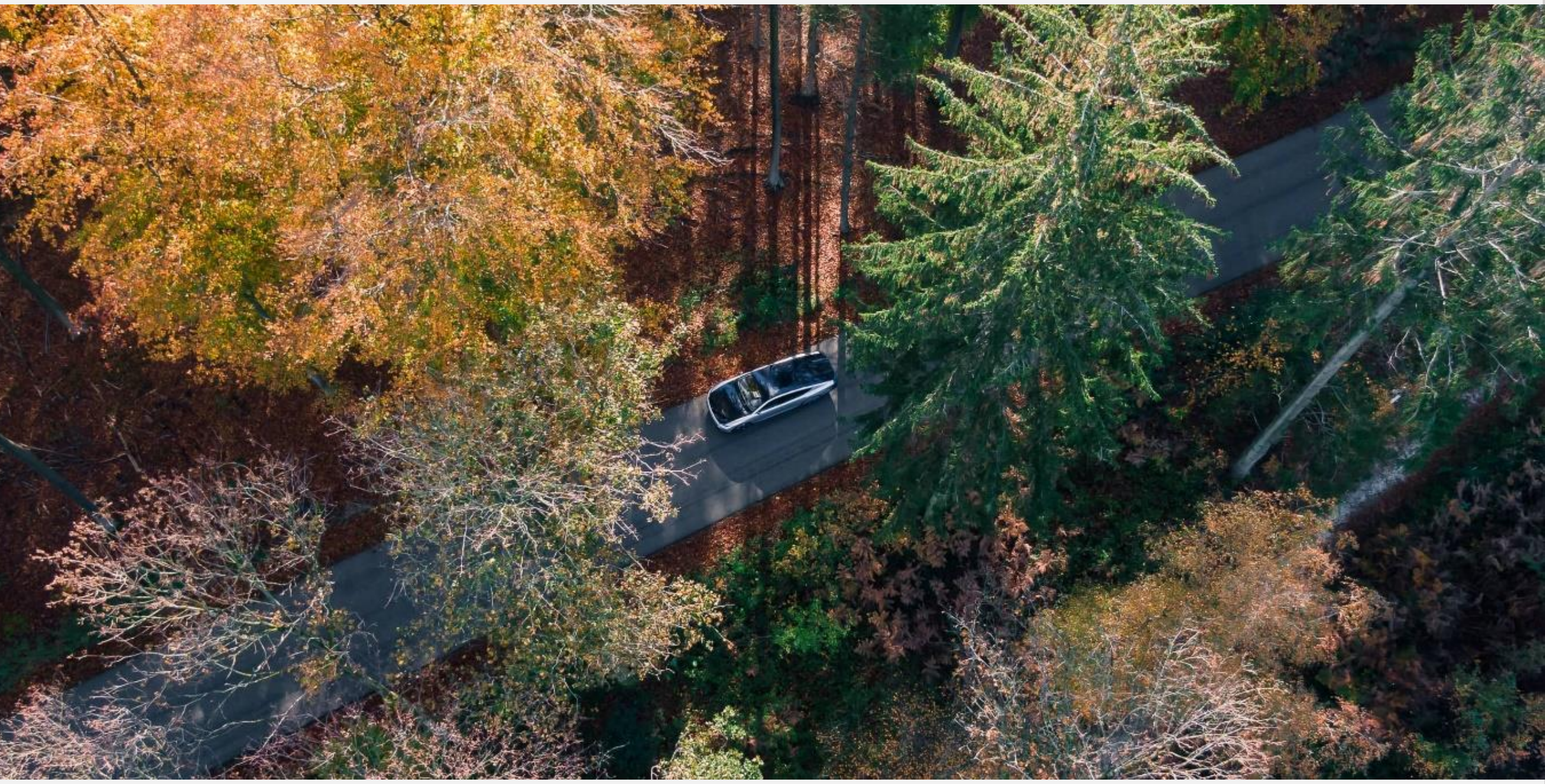
Master Thesis

The system costs of future electric mobility

Comparing battery electric vehicles with solar electric vehicles

Gearte Nynke Noteboom
August 2021

A study based on the electricity and mobility system in The Netherlands.



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August 2021

Master thesis submitted to Delft University of Technology

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in Complex System Engineering & Management at the

Faculty of Technology, Policy, and Management

by

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To be defended in public on August 24, 2021

Acknowledgments

'PER ASPERA AD ASTRA' – THROUGH HARDSHIPS TO THE STARS

This research was conducted as a final assessment for the master program Complex Systems Engineering and Management at the Delft University of Technology. The Latin phrase 'Per Aspera ad Astra' has been very applicable to the process of my thesis. Tackling the complex assignment, I started with in February 2021, has been a huge challenge. I learned a lot from the process and the research on an academic and personal level and I am very grateful that I could have the chance to execute this research.

Therefore, first I would like to thank Daniel Scholten for being my first supervisor on behalf of the TU Delft. Daniel was a continuous and very motivating support during the process. We always had critical discussions about the research, but in the end, he always expressed his confidence in the research. Moreover, I would like to thank Kornelis Blok for being Chairman and second supervisor on behalf of the TU Delft. Kornelis is an inspiration regarding his knowledge about the energy transition. In our conversations, Kornelis always asked the right critical questions. By doing this, the research became much stronger.

Second, I would like to thank Martijn Lammers, my supervisor on behalf of Lightyear. He continuously supported me in our weekly updates, and always highlighted the research from different point-of-views, by asking questions. Martijn translated the research to the practical use of it, which motivated me a lot. In addition, I would like to express my gratitude to Tom Selten and Roy Cobbenhagen of Lightyear, who were very involved during the research.

Third, I want to express my gratitude to Naud Loomans from ZEnMO Simulations. Without Naud, I could not have done this research. Naud taught me about modelling in AnyLogic. He always patiently did this and was always there for me if I had any questions.

Finally, I would like to thank my friends and family, who supported me in several ways.

Gearte Nynke Noteboom

Utrecht, August 2021

Executive summary

While the expected rise of electric vehicles (EVs) in The Netherlands could attenuate climate change, new challenges arise.; one challenge is that large-scale penetration of EVs could increase system costs.

System integration challenge

Specifically addressed in this thesis is the integration of the EV in the Dutch local grid system: (1) the charging infrastructure and (2) the distribution grid. First, to make future electric mobility accessible for everyone, a charging infrastructure roll-out keeping pace with the rising EV fleet needs to be realized. Second, the rising EV fleet is paired with increasing EV electricity consumption peaks, especially threatening distribution grid reliability when no interventions take place. Keeping the electricity supply as reliable and accessible as it currently is, is a concern that triggers distribution grid and charging infrastructure reinforcements, bringing system costs.

The introduction of the SEV

This thesis introduces the highly efficient Solar Electric Vehicle (SEV), the Dutch Lightyear One, as an alternative for the conventional Battery Electric Vehicle (BEV). A SEV has a low energy consumption and generates solar electricity for its use. Therefore, a SEV is expected to be less dependent on the grid and the charging infrastructure than the BEV. Accordingly, this research aimed at exploring to what extent SEVs could reduce the system costs of future electric mobility. Hence, the main question is: *'What are the system costs of SEVs compared to BEVs?'*

Measuring the system costs

The costs for the system exist from the national investments needed for the grid and charging infrastructure reinforcements. The costs are therefore based on the capacity requirements of the system. These national capacity requirements for the charging infrastructure and the grid are extrapolated based on the maximum simultaneity rate of charging and the peak loads found in urban, suburban, and rural areas. A scenario in 2050 is exploited comparing a 100% BEV fleet with a 100% SEV fleet.

Method I: Agent-based model (ABM)

The maximum simultaneity rate and the peak loads were derived from the residential load curve that was approximated in an already existing ABM. The ABM models local electricity load and includes future developments such as *smart charging*, residential PV supply, heat pumps, and the BEV in it. Next to the parametrization of a scenario in 2050, two model contributions were made in this research: (1) adding the SEV to the model and (2) adding different driver personas in the model based on real data.

Method II: Cost-benefit analysis (CBA)

The system costs are calculated via a CBA, including solely the CapEx of the grid assets and the charging stations. No learning effects were considered for both the grid and the charging infrastructure. For the charging infrastructure, an occupancy rate of 80% was considered, significantly increasing the number of required charging points per neighbourhood. Furthermore, the current Dutch charging speed distribution was assumed. Finally, data and methods that were needed to make a rough estimation about the grid reinforcement costs, were gathered, used, and validated by a distribution system operator (DSO) in The Netherlands.

Results & conclusion

The results showed that the charging infrastructure primarily influences the system cost savings that could be realized with a 100% SEV fleet compared to the 100% BEV fleet. In a winter week, the SEV reduces the maximum required charging infrastructure up to ~3 times; a belonging cost difference of ~€8 billion was estimated until 2050. In a week with high solar irradiance, the charging requirement for the SEV could even be 8 times lower than for the BEV. The difference is caused by the prognosed Dutch charging behaviour that is influenced by the smart charging strategy; and the low electricity consumption and electricity solar yields of the SEV accounting for respectively ~66% and ~34% of the cost reduction. In contrast to the charging infrastructure, the difference between the SEV and the BEV in grid impact was slightly visible in the peak loads. The small difference in peak loads was primarily caused by the prognosed charging behaviour that was influenced by the smart charging strategy in combination with the low energy consumption and the solar energy yields of the SEV. However, the difference is not significant enough to require extra grid reinforcements for the BEV compared to the SEV; no difference in costs for the grid was presented. In conclusion, an estimated total system cost saving of ~€8 billion caused by the reduced charging infrastructure requirement, was presented in this thesis.

Discussion

Making a prognosis for future electricity consumption and costs involves uncertainties. This is inherent in a transition. Different developments in technology, politics, the market, and user groups lead to a complex interplay that can change electricity consumption in the future. In this research, many assumptions were made to approximate the future load curve and the system costs of electric mobility. Due to sensitive parameters, the system costs measured are solely applicable to the scenario that is presented in this thesis. The system costs calculations indicated what the cost-difference could be and gave general insight into the effects on the system costs when a SEV or BEV is integrated into the energy system.

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List of abbreviations

ABBREVIATIONS (IN ALPHABETIC ORDER)	
ABM	Agent-Based Model
AW HEAT PUMP	Air-to-water heat pump
BEV	Battery electric vehicle
CAPEX	Capital expenditures
COP	Coefficient of performance
DDZ	DeeldeZon model
DHW	Domestic hot water
EV	Electric Vehicle
GHG	Greenhouse Gasses
HVAC	Heating Ventilation and Air-conditioning
ICE VEHICLE	Internal Combustion Engine vehicle
KNMI	Royal Dutch Meteorological Institute
HV	High Voltage
IEA	International Energy Agency
LV	Low Voltage
MAAS	Mobility as a Service
MV	Medium Voltage
NPV	Netto present value
OPEX	Operational Expenditures
PV	Photovoltaics
CBA	Cost-benefit analysis
SEV	Solar electric vehicle
SOC	State of charge
S2V	Solar-to-vehicle
TCO	Total costs of ownership
V2G	Vehicle-to-grid
VRES	variable renewable energy sources
WW-HEAT PUMP	Water-to-water heat pump
WLTP	Worldwide Harmonized Light vehicle test Procedure

Terminology

It is important to create a common understanding of the terms that are used to avoid ambiguities in the understanding of the research. As multiple terms are used in this thesis a list of the most important terminology is provided below.

System costs
System costs are defined as all the costs of massively integrating EVs into the existing electricity system. These costs exist of costs for reinforcing the charging infrastructure and the grid. Charging infrastructure reinforcement costs are the costs for the public charging infrastructure when EVs are massively integrated into the system. Likewise, grid reinforcement costs are the costs for the distribution grid assets that need to be replaced when EVs are massively integrated into the system.

The battery-electric vehicle (BEV)
A BEV is here referred to as a plug-in battery-electric vehicle entirely powered by electricity from the grid.

The Solar electric vehicle (SEV)
A lightweight, aerodynamic efficient EV of which the electricity consumption is, for a part, covered directly by its solar panels and partly by electricity from the grid. A Solar Electric Vehicle (SEV) does have batteries for propulsion as well as the Battery Electric Vehicle (BEV) but is distinguished from the BEV by its onboard solar generating capability and lower energy consumption.

The electric vehicle (EV)
When the EV is mentioned, both the SEV and the BEV are being referred to.

The occupancy rate
The amount of time that a charging point is occupied by an EV divided by the effective time that the car is effectively charging.

The utilization rate
The amount of time that a charging point is occupied divided by the total available time within a set timeframe.

The simultaneity rate
The share of EVs charging at the same time in a neighbourhood.

The local peak load
The maximum local electricity load measured over time.

Smart charging
Smart charging means that electric cars charge at optimal times. The speed and time of charging are adjusted:
• to the total power demand and the space on the electricity network. This prevents (too) high peaks.
• on the available sustainable energy (solar and wind).
• on electricity prices.
• on the number of cars that charge simultaneously.

Chapter 1: Introduction

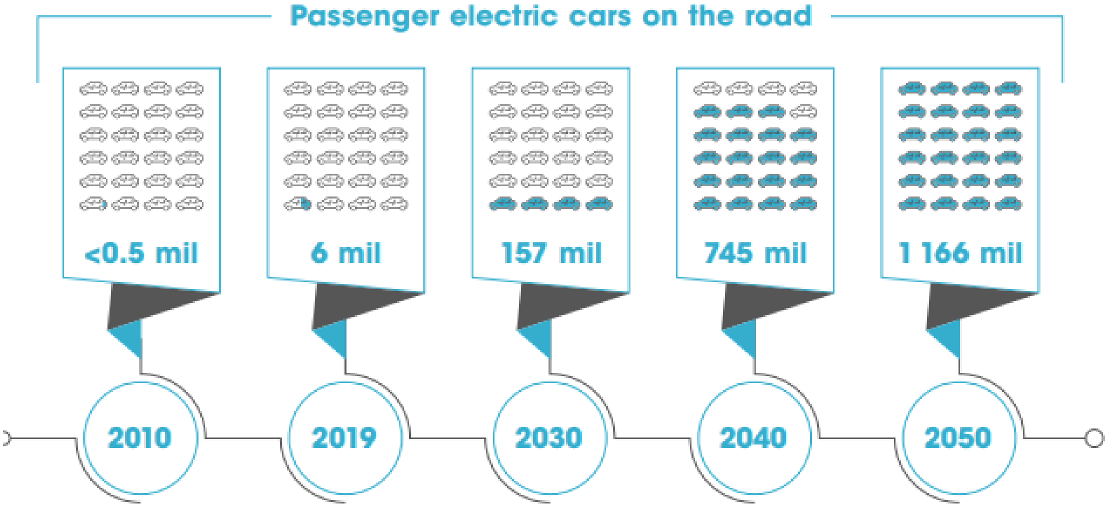


Figure 1.1 Paris agreement-aligned scenario of electric vehicle (EV) deployment between 2010 and 2050.
Source: Adapted from [58].

According to the Intergovernmental Panel on Climate Change (IPCC) [1], global warming is caused by humanity. Climate change is expected to have a global irreversible impact that threatens life on earth. The IPCC [1] suggests that amongst others the bulk production of fossil fuels needs to change to address global warming. In the Paris agreement of 2015, 175 parties agreed on a plan to limit the temperature increase to 1.5 degrees above pre-industrial levels [2]. To accomplish this, amongst others a decrease in greenhouse gasses (GHG) is needed [3]. In The Netherlands, gas, and coal plants are planned to be phased out and the share of variable renewable energy sources (vRES) is aimed to increase nationally and locally until 2050 [4]. Part of the gas appliances, such as heaters and gas stoves are planned to be electrified instead [5] [6] [7] [8]. Moreover, part of the vRES electricity is planned to be generated decentral [9]. On the other hand, the trend of growing electricity demand is expected to continue with predictions of for example 30% - 50% extra demand in 2050 [7] [10].

A sector that is responsible for 23% of the global energy-related GHG emissions is the transport sector [3]. To attenuate climate change there is a global need for electrification of transport means that do not use fossil fuels. For the replacement of the internal combustion engine (ICE) passenger vehicle, there is a growing public conviction for the use of battery electric vehicles (BEVs), through their potential zero-carbon character and dropping prices [11]. The promising perspective of BEVs has caused the authorities in The Netherlands to provide tax incentives and to pursue the elimination of non-electric vehicles from 2030 [11][3]. Accordingly, the mobility sector aims to reduce GHG emissions by at least 60 percent, compared to 1990 [12]. Hence, it is expected that the adoption of BEVs will increase rapidly in the coming years[1] [13].

[1] *Assuming that the electricity generation transition from fossil to renewable sources will be sufficiently matching the increasing demand of electric power.*

1.1 Problem statement

While the rise of BEVs could attenuate climate change a new challenge arises; large-scale penetration of BEVs could leave a negative societal impact when looking from a system point of view [14]. The focus of this thesis is on the impact of integrating BEVs in the Dutch local electricity system regarding the technical capacity limits of the charging infrastructure, the distribution grid, and the paired costs.

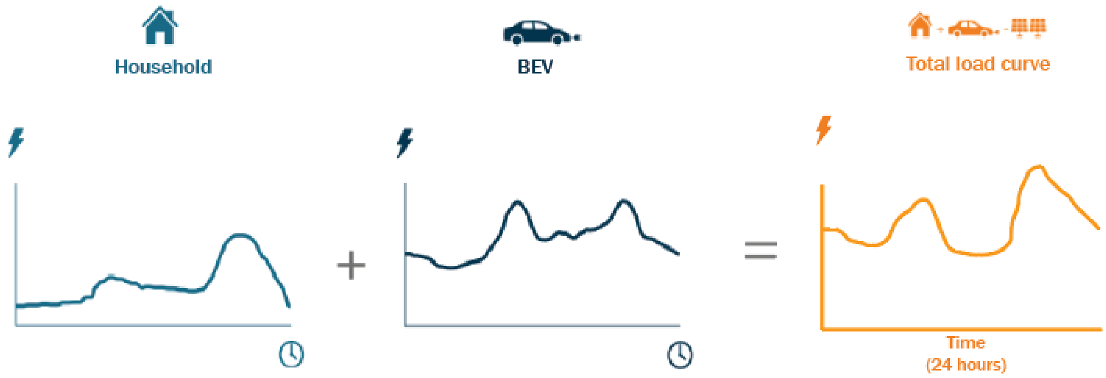


Figure 1.2 The impact of the BEV on the residential load curve.
Source: Adapted from [9].

The rise of BEVs will cause high peaks in the load curve, especially on a local scale. The cause is two-sided. First, people tend to charge their car simultaneously for example at the end of the working day or when they arrive at work [15]. Second, BEVs consume a considerable amount of electric power; one BEV might double or even triple the peak load of a household [15] [16]. Figure 1.2 illustrates the effect that takes place in the load curve when many BEVs are adopted in a neighbourhood. It can be derived from this graph that the peaks of the moment of charging correspond to the peak loads of the households, increasing the already existing peak loads even more. The bigger the BEV fleet, the higher the impact of the BEV on the electricity demand curve. In the electricity system, balancing the supply and demand of power in the grid is indispensable since energy cannot be sufficiently stored in the network yet [17]. When there is a discrepancy between demand and supply interventions take place or a black-out may occur [17]. In The Netherlands as in many other countries, society has become greatly dependent on electricity; the grid needs to be able to meet demand at any time. Hence, balancing electricity demand and supply is essential for the functioning of the entire society, and grid reliability is considered a great good. Historically, the grid's capacity is designed on the forecasted maximum peak load [18]. One of the problems that arise takes place when the peak loads caused by the BEV exceed the technical capacity limits of the grid. When exceeding the capacity limits of the grid, grid assets such as cables and transformers cannot supply the electricity that is demanded and therefore needs to be replaced, bringing system costs [17] [9] [19]. To avoid expensive reinforcements, it is necessary to flatten the load curve to maintain the current reliability and safety level of the grid. However, interventions flattening the peak loads caused by charging, such as storage technologies, are often expensive or yet technologically impossible [20] [18]. While the energy transition is accompanied by many challenges, the focus of this research is on the capacity needs for the grid and the charging infrastructure when the BEV becomes dominant in the future mobility system.

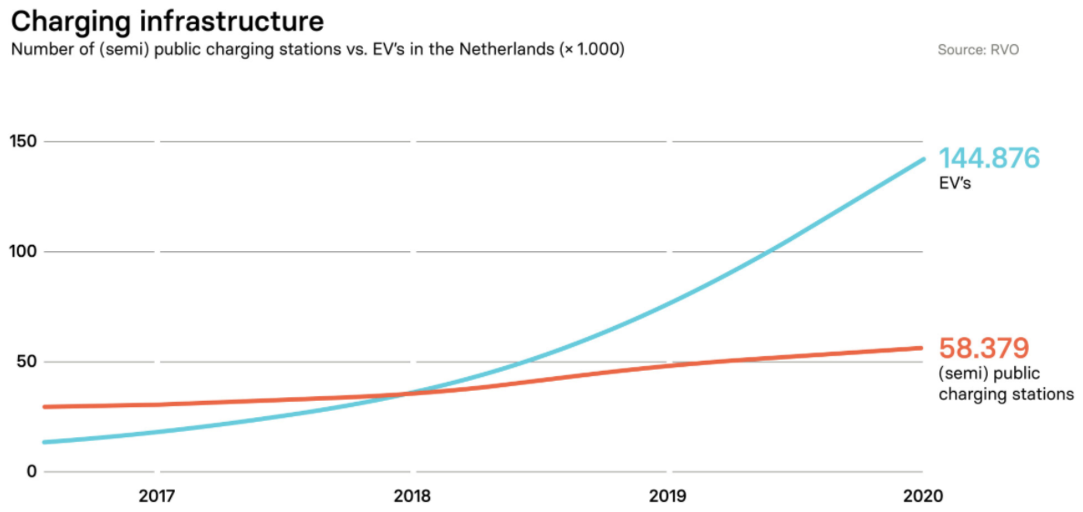


Figure 1.3 Historical number of (semi-)public charging stations vs electric vehicles in The Netherlands.
Source: Adapted from [21].

The popularization of the BEV is accompanied by another challenge that is related to the increased electricity demand of the BEVs: a massive charging infrastructure roll-out is needed to satisfy the future charging need and to enable electric mobility to be accessible for everyone [13]. Favourably, the charging infrastructure capacity, meaning the number of charging points available, can meet customer demand at all times [22]. The tendency of people to charge simultaneously is just like for the grid, also a concern for planning the charging infrastructure capacity requirements; the more BEVs are charged at the same time, the more charging points are needed to satisfy the users' demand at all times [23]. Subsequently, many charging points need to be installed to support the rise of the BEV, bringing high costs for the system. The impact of the BEVs on the required charging infrastructure is closely related to the required grid capacity. Therefore, the focus is on both system challenges: the long-term impact of the BEV on the investment need for the charging infrastructure and the grid in The Netherlands.

Figure 1.4 Stella Lux, the solar car of Solar Team Eindhoven, participating in the World Solar Challenge 2015.

A Dutch invention, which could potentially flatten the load curve and decrease the system investment need is the hybrid highly efficient solar electric vehicle (SEV): such as the developed Dutch Lightyear One. Lightyear is a start-up that is established by the team members of Solar Team Eindhoven, a Dutch student team that participates in the biannual Bridgestone World Solar Challenge in Australia. In this world championship, solar cars are challenged to drive 3000 km through the outback primarily on onboard generated solar power [24]. While these grid-independent solar cars are not intended for commercial purposes yet, hybrid electric vehicles, such as the Lightyear One, are already being developed and commercially sold [25]**.** The Lightyear One is on the one hand a vehicle with solar cells integrated into it. On the other hand, to limit the SEVs dependency on the grid, the Lightyear One's weight and energy consumption are minimized. Accordingly, a SEV consumes less electricity and generates part of its electricity from the sun. Therefore, the vehicle becomes less grid-dependent than most other EVs implying that fewer charging moments are needed for the SEV user. It appears that the potential of SEVs unburdening the grid and the charging infrastructure is unexplored yet in the current body of literature.

1.2 Research objective and questions

This research aims at uncovering differences between the SEV and the BEV to explore to what extent SEVs could reduce the system costs of BEVs in the future energy system. To understand the impact of the SEV compared to the BEV on system costs, the main research question is formulated and answered.

Research objective*:* Uncovering differences between the SEV and the BEV to explore to what extent SEVs could reduce the system costs of BEVs in the future energy system.

Main question: '*What are the system costs of SEVs compared to BEVs?*'

The sub-questions

1. *How can the system costs of future electric mobility be measured?*
2. *How to approximate the future residential load curve?*
3. *How to determine the system costs of future electric mobility?*
4. *To what extent would mass adoption of SEVs influence the system costs of electric mobility?*

To get a complete overview of the rise of the BEV, the developments of the energy transition, and its belonging impact, a scenario in 2050 is elaborated in this thesis; for 2050 internationally many plans and goals have been made and set for realizing the energy transition [5]. One of those goals is to massively deploy a smart charging strategy in the future energy system in The Netherlands [19]. Accordingly, when answering our main research question, we go out from a smart charging strategy in 2050. Finally, to estimate the system costs and limit ambiguities, this research makes a comparison between two extreme scenarios: the adoption of 100% BEVs or SEVs in The Netherlands. Other mobility options such as the ICE vehicle, autonomous driving, and shared driving are hereby left out of the scenario.

1.3 Research design

This thesis answers the main question by answering the sub-questions formulated above. Here below a short description is given of the research design.

Chapter	**"How can the system costs of future electric mobility be measured?"**
2	Chapter 2 seeks to provide a comprehensive overview of the current knowledge on the future system costs of electric mobility. It answers the first research question. The knowledge and the insights gained on the SEV, and the BEV is used to provide an analytical framework that maps out the relation of the independent, dependent, and moderating variables in section 2.4. Chapter 2.5 concludes with the research flow.
	"How to approximate the future residential load curve?"
3	The research analysis uses two research methods. In chapter 3, the focus is on the first step: modelling the residential load curve using an agent-based model (ABM). It explains what an ABM is and why it is chosen as the approach for determining the residential load curve in 2050. Afterward, the model logic and main assumptions are explained. This chapter answers the second sub-question.
	"How to determine the system costs of future electric mobility?"
4	This chapter explains how the system costs of future electric mobility are derived from the load curve and answers sub-question 3. The system costs are employed by a cost-benefit analysis. The steps and assumptions that are necessary are explained in this chapter. Note that this chapter merely examines the method of operationalizing the system costs of future electric mobility. In Appendix G the real calculations following the steps in this chapter are illustrated.
	"To what extent would mass adoption of SEVs influence the system costs of electric mobility"
5	This chapter describes the general results that have been acquired during this research by going through the steps in chapter 4. It first describes the model outcomes and afterward explains the belonging costs for the system. The chapter concludes with a sensitivity analysis testing the validity of the research.
	"What are the system costs of SEVs compared to BEVs?'
6	This chapter provides a discussion of the results and methods in this thesis. First, a critical review is provided on the main results of the thesis. Afterward, the implications of the results for the academic world and society are discussed.
	"What are the system costs of SEVs compared to BEVs?'
7	This chapter provides an answer to the main research question and explores possibilities for further improving and extending the research. Moreover, policy and company recommendations are given.

Chapter 2: Analytic framework

This chapter seeks to provide a comprehensive overview of the current knowledge on the future system costs of electric mobility. It answers the first research question: "How can the system costs of future electric mobility be measured?" This knowledge is used to provide an analytical framework that maps out the relation of the independent, dependent, and moderating variables in section 2.4.

2.1 BEVs and SEVs

There are already many types of BEVs ranging from the Tesla Model S to a BMW i4. To measure the system costs of the SEV compared to the BEV, it is of great importance to first define the reference BEV and SEV and their belonging technical characteristics. Because there are already many BEVs in the market, not a single BEV model has been selected, but an average BEV was defined. To make a realistic comparison with the SEV some selection criteria are applied to the wide range of BEVs that is derived from a Dutch EV database [26]. First, the BEVs were filtered by the release date and country. Only BEVs that are available in The Netherlands from 2021 were selected. All BEVs that were released before 2021, were not considered, as these might give an unfair image of the technical characteristics of the future BEV. After all, the Lightyear One (SEV) is expected to be commercially available in 2024 and generally has better technical characteristics than a BEV that was released earlier. Finally, to make an equal comparison, only BEVs that are in the same price range as the SEV were selected. The BEVs selected are within the price range of €25.000 - €40.000. This price range is in line with the price of the SEV, which is estimated to be €30.000 - €35.000. After filtering the BEVs that are released from 2018 in The Netherlands within the mentioned price range 5 BEVs were selected. The technical characteristic of which the average is considered is the WLTP energy consumption. WLTP stands for Worldwide Harmonized Light vehicle test Procedure and is a test procedure that enables equal comparison of the energy consumption of light vehicles [27]. Hence, the average WLTP energy consumption of the BEVs of 152 Wh/km was considered. To enable a good comparison, the battery capacity for both the BEV and the SEV was set to 60 kWh. The technical characteristics of the BEV are presented on the next page. Accordingly, in this thesis two types of electric vehicles (EVs) are distinguished:

- The average Dutch Battery Electric Vehicle (BEV): an EV entirely powered by electricity from the grid.
- The Lightyear One (SEV): A lightweight, aerodynamic efficient EV of which the electricity consumption is, for a part, covered directly by its solar panels and partly by electricity from the grid.

For the reference SEV, the Lightyear One is chosen. The Lightyear vehicles are characterized by highly efficient powertrains, smart batteries, and the integration of solar cells in their low-weight body. The Lightyear One HVS is being referred to when the term "SEV" or "Lightyear One" is used in the remainder of this report. The 5m^2 solar roof of the Lightyear One already could add 60 km to the total range on a summer day, accounting for 60 km of grid independence. The SEV moreover accounts for low energy consumption due to its aerodynamic design and lightweight character [28]. Compared to the BEV the SEV has a lower energy consumption amounting to 83 Wh/km. The range of 395 km of the BEV is significantly lower than the SEV using a comparable battery capacity [26]. Accordingly, the hypothesis is that the SEV is less grid-dependent than the BEV, leaving the question "how much" open for the analysis.

The characteristics of the SEV and the BEV

Characteristics Lightyear One (SEV)	
Price (€)	€30.000 - €35.000
WLTP range	725 km (not including solar energy)
Battery capacity	60 kWh
WLTP energy consumption	83 Wh/km
Solar panel surface	5 m^2
Solar cell efficiency (2024 - 2050)	21% - ~25%
Drivetrain efficiency	91%

Figure 2.1 Lightyear One

Characteristics reference BEV	
Price (€)	€25.000 – €40.000
WLTP range	395 km
Battery capacity	60 kWh
WLTP energy consumption	152 Wh/km

Figure 2.2 An example of a BEV: the Nissan LEAF.

2.2 The system costs of electric mobility

When no intervention takes place, the integration of both the SEV and the BEV, could cause grid and charging infrastructure reinforcements that are paired with costs for the system. System costs are defined as all the costs of massively integrating EVs into the existing electricity system [29]. These costs exist of costs of reinforcing the charging infrastructure and the grid. Charging infrastructure reinforcement costs are the costs for the public charging infrastructure when EVs are massively integrated into the system. Likewise, grid reinforcement costs are the costs for the distribution grid when EVs are massively integrated into the system [29]. System costs are often seen as part of societal costs. Societal costs are often broken down differently in literature. Clerck and Christensen [30] differentiate societal costs into product-level costs and external costs. Here it is argued that it is needed to differentiate these costs into not two but three categories: (1) product-level costs, (2) system costs, and (3) external costs. This division is based on a research of Samadi [29] analysing the societal costs of electricity plants.

Other societal costs than system costs are left out of scope during the research. However, they are described shortly in Appendix B. Product-level costs are defined as the total costs of ownership (TCO) including the private costs associated with the production and lifetime of an EV. Appendix B shows that earlier research was executed, investigating the TCO of both the SEV and the BEV. Hence, TCO is not analysed in this thesis. External costs are defined as the costs of electric mobility not accounted for in the market price, causing an externality [29]. When comparing the SEV and the BEV, the (future) societal costs of the externalities are not expected to differ significantly. For scoping the research, the external costs were therefore not considered during the analysis either.

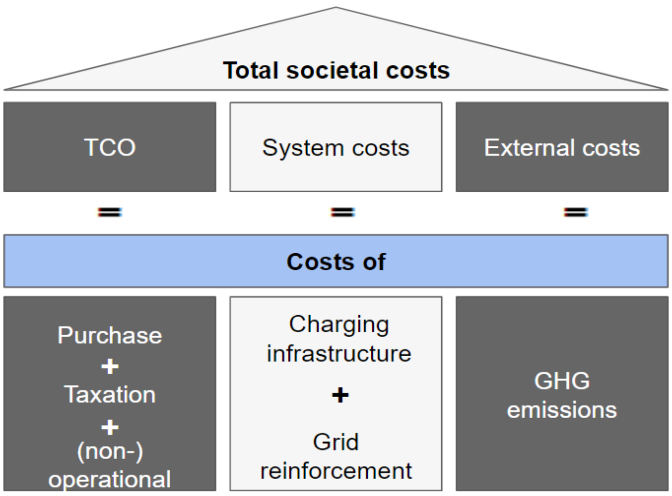


Figure 2.3 Schematic overview of total societal costs.

Consequently, the costs for the system exist from the national investments needed for the grid and charging infrastructure reinforcements. The costs are therefore based on the capacity requirements of the grid and the charging infrastructure in 2050. In this section, a comprehensive overview of the current knowledge on the grid and the charging infrastructure is provided. It is explained that the capacity that is required for the charging infrastructure and the grid is based on respectively: (1) the maximum simultaneity rate of charging on a local scale and (2) the local peak load. It is also explained that metrics could be derived from EV's electricity consumption over time that could be derived from the distribution load curve.

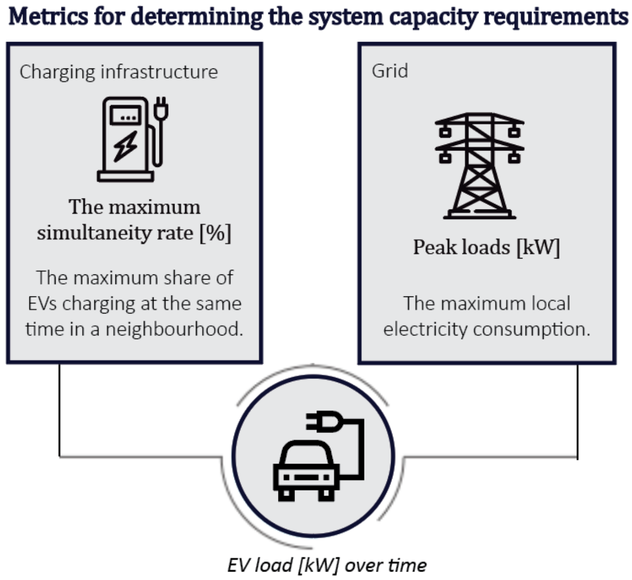


Figure 2.4 The determination of the system capacity that is required due to the rise of the EV.

2.2.1 Charging infrastructure

The need for charging infrastructure increases when conventional cars are being replaced by electric cars, bringing system costs. To explore the system costs that EVs could bring until 2050, it is necessary to know how many charging stations are needed. However, in the literature, there are different thoughts about how the future charging infrastructure capacity requirement must be determined. For example, the maximum goal of 9.5 EVs per charging point was set by the European Commission. This goal does not distinguish between the different types of EVs [13]. Moreover, it does not differentiate in the different charging speeds; the spatial distribution; the charging behaviour, the composition of the mobility fleet, the availability of charging stations, and the limited compatibility of charging sockets with the existing EVs. Therefore, the metric of the European Commission is not found specific enough for the analysis.

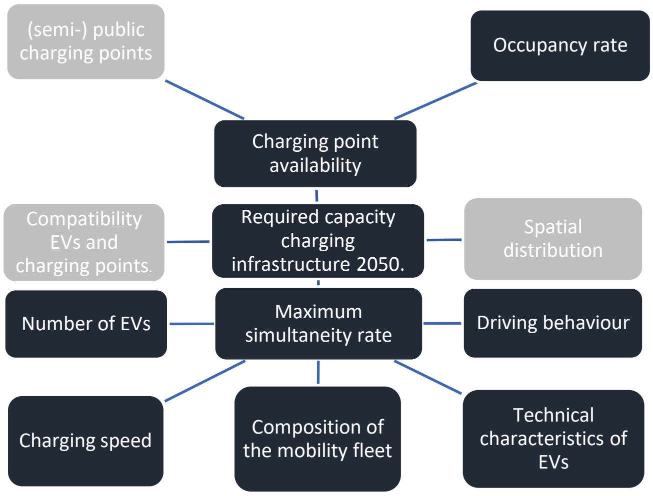


Figure 2.5 The factors that influence the required capacity of the charging infrastructure in 2050. (blue = considered in the analysis, grey = left out of scope).

All aspects in figure 2.5 are considered important for a good estimation of the capacity requirement of the charging infrastructure in 2050. However, not all aspects are considered for the comparison between the SEV and the BEV in the analysis. As in this thesis, the charging infrastructure capacity requirement for the BEV and the SEV are compared, it is of importance to consider a roll-out strategy that can distinguish between both types of EVs. Moreover, it is found important to consider the utilization rate [2]. The literature review later in this chapter showed that Torensma [12], Hoed [31] and Vervoordeldonk [32] recommend focusing on the utilization rate when determining the dimensions of the charging infrastructure. As the utilization rate differs significantly per hour of the day, it is even better to monitor the charging stations per hour per neighbourhood, to make informed decisions about the capacity requirement of the charging infrastructure locally. It gives a more detailed view of the local availability of charging infrastructure than when considering average utilization rates. Therefore, the determination of the charging infrastructure capacity requirement will be considered bottom-up by first approaching the question from local areas. As there is no insight into the charging infrastructure in 2050, the utilization rate for one hour specifically is in this thesis referred to as the simultaneity rate; the ratio of the EVs charging simultaneously in an hour to the total EV amount. When dimensioning the infrastructure based on the simultaneity rate, a maximum utilization rate can be pursued as a goal, translated into the number of charging points that need to be placed. It is here argued that it is favourable for customers to be able to charge their car at any time when it is needed. Therefore, the *maximum* simultaneity rate in neighbourhoods, the maximum share of cars charging at the same moment, is considered for setting a capacity goal. The maximum simultaneity rate is dependent on the technical characteristics of the EV, the number of EVs, the charging speed, the composition of the mobility fleet, and the driving behaviour. Therefore, the metric considers many factors that are found in the literature to be important to consider when dimensioning the charging infrastructure. The maximum simultaneity rate can be derived from the local load curve of electric mobility as the

[2] The amount of time that a charging point is occupied divided by the total available time within a set timeframe [31].

EV's electricity consumption over time and the charging speed indicate the number of EVs that are charging simultaneously. In addition, the occupancy rate[3] separately is considered in determining the future charging capacity requirement as Wolbertus [33] showed that a significant number of the time an EV is occupying a charging station, the EV is not charging. The spatial distribution, the existence of semi-public charging points, and the compatibility of charging sockets and EVs are not considered in the analysis. On a local scale, the spatial distribution is not expected to influence the need for future charging infrastructure. Besides, semi-public charging points are limited available. These types of chargers are for simplification reasons and for the sake of time not considered during the analysis. Finally, to scope the research it is assumed that in 2050 a standard for the charging sockets is developed, making all sockets compatible with all types of EVs. Therefore, this factor was also not considered during the analysis.

2.2.1.1 Driver behaviour

The simultaneity of charging appears to be largely dependent on the charging behaviour of EV users [34]. The behaviour of the car users gives insight into the simultaneity and intensity of the needed electricity. It provides insight into the moment of the peak loads. As the case is now, peak loads take place around 5 pm as people tend to charge their car at the end of the day [35]. The hypothesis is that the car efficiency of an EV influences the charging behaviour of the user of the car. This has been demonstrated in an internal study by Lightyear. It compares a BEV (Tesla model 3) with the SEV and calculates how many charge moments in a year are needed for different personas. After a simplified calculation, it is expected that the difference between the number of charge moments varies per persona.

# Charge moments	*BEV*	*SEV*	*Difference*
Persona 1	39	19	51%
Persona 2	59	31	47%
Persona 3	179	147	18%

Table 2.1 Fictional personas and the corresponding difference in charging behaviour.

The BEV needs to charge respectively 51%, 47%, and 18% more than the SEV with persona 1, 2, and 3. While the exact percentages of this calculation must not be taken too narrow, the cars show a difference in charging behaviour per persona. Hence, it is considered valuable to look into different real existing personas in the research when considering the load curve.

2.2.1.2 Charging speed

When people choose to charge their EV they can choose between different types of chargers. The implications of the different types of chargers are mainly noticeable in the shape of the load curve. EVs are charged with Direct Current (DC) and Alternating Current (AC) chargers. The difference between DC and AC is mainly noticeable in the power level, which influences the charging speed and the electricity demand from the grid. The power (in kW) of a charger represents how many kWh of electricity could be charged in one hour. Direct current (DC) charging is often referred to as fast charging. As the power setting of fast chargers nowadays is sometimes more than 50 kW, fast chargers have mostly too high power levels for the distribution grid [11]. When 10 BEVs in one neighbourhood use a fast charger of 50 kW at the same time, the demand increases with 500 kW. The charging peak is lower and spread out over a longer period when using chargers with lower power. Moreover, there is a higher chance of EVs charging at the same time, as the charging sessions last longer. Hence, AC chargers form the dominant charging station type on the distribution grid. Common AC chargers can deliver between 3.5 kW and 22 kW. Next to the home environment, these AC chargers are often also used at work and leisure locations [36].

[3] The amount of time that a charging point is occupied by an EV divided by the effective time that the EV is charging

2.2.2 The Dutch Electricity grids

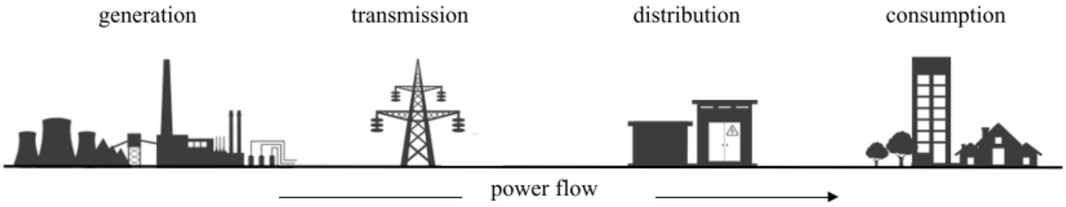


Figure 2.6 A schematic representation of the Dutch Electricity grid.
Source: Adapted from [18].

Electricity is transported to the consumers through the electrical grid. Four levels of electrical grids are interconnected to form a linked electricity supply system [36]:

- **The transmission grid** operates at 220 and 380 kV and is used to transport electricity over large distances in The Netherlands and Europe.
- **The transport or high voltage (HV) grid** operates at 50, 110, and 150 kV and transmits electricity at a regional level.
- **The medium voltage grid** operates at 3 – 30 kV and supplies large users, such as an industry and connects with the local distribution network.
- **The distribution or low voltage (LV) grid** operates at 239 and 499 V and connects the grid to small enterprises and households.

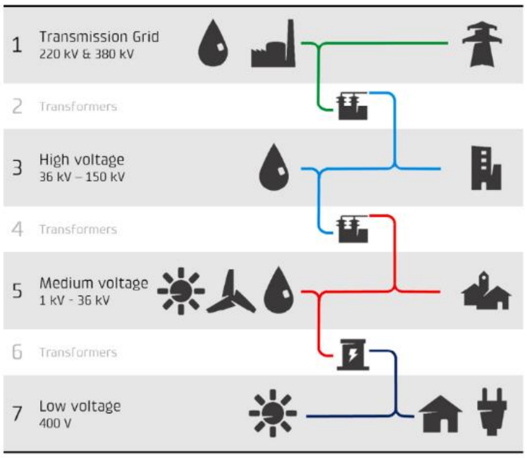


Figure 2.7 Overview of high voltage and low voltage grid.
Source: Adapted from [37].

The transmission grid uses very high voltage levels to minimize electrical losses. The cables of the transmission grid are the spine of the Dutch power grid and connect large power plants to the HV grid. The HV grid transmits power at a provincial level and links the transmission network to the medium voltage grid. The medium voltage grid distributes the electricity on a regional scale and is connected to the HV and LV grid by transformers. The LV grid is the main point of focus during this thesis. In the remainder of this thesis, the LV-load curve is being referred to when the term “load curve” or “distribution-load curve” is used.

The distribution grid distributes the electrical energy on a local scale among all connected parties, such as households and shops [38]. In The Netherlands, the distribution grid consists of underground cables and operates with often 3-phase 230/400 V. It is connected to an MV network by an LV transformer. When the capacity limit of either a transformer or a cable is exceeded by the residential load curve, grid reliability is threatened and even a black-out may occur. Blackouts, especially the ones with long downtimes have high costs, as a society and the economy have become heavily dependent on electricity. In addition, blackouts may damage grid assets that must then be repaired or replaced at high costs [39]. Reinforcing transformers and underground cables could decrease reliability problems but comes with costs.

Favourably, the distribution grid is always able to handle the peak loads to provide grid reliability. Accordingly, the required grid reinforcements are needed depending on the current status of the grid, and the predicted peak loads (kW) that the grid is subject to [18]. The peak loads could be derived from the local electricity load. The electricity load is logically not only dependent on the charging need, but it is also influenced by other factors, such as the need for electricity in the commercial sector and the electricity needs of households. The electricity need of households in many countries is expected to grow until 2050 [18]. The residential load is historically forecasted based on a load of households and a load of commercial buildings primarily [18]. Due to the developments of the energy transition part of the gas appliances are electrified, and the rise of decentral vRES production is being introduced. These developments need to be considered when approximating the future load curve. The future load curve is moreover dependent on the behaviour of people in the residential areas. This behaviour needs to be considered when approximating the future load curve.

The current structure of the grid is necessary to explore when making an indication of the needed grid reinforcements caused by the rise of electric mobility. The typical number of households connected to the MV/LV transformer is 80. The structure of distribution grids often differs between countries, regions, and even towns [40]. In some older urban areas, LV grids have a meshed structure. These networks are better in voltage management and electrical losses, but experience high short-circuit voltages in case of an outage. Hence, most LV networks have a radial design, which is shown in figure 2.8. This design has no-fault reserves, when a cable fails the power must be restored by maintenance work. In The Netherlands, these cables have a standardized diameter, and the new cables are made out of aluminium. As the economic life of an LV grid is more than 40 years and has not been replaced everywhere within this time, the LV grid in The Netherlands is only partly standardized. The other part still exists of a historical design; cables used to be built out of different types of cable [36].

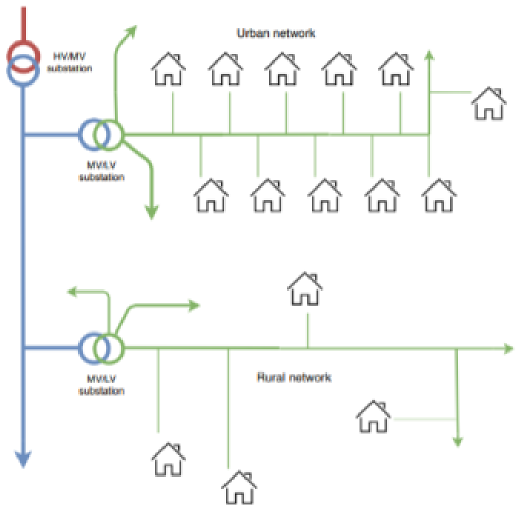


Figure 2.8 Radial topology of LV grid and the corresponding cables (in green).
Source: Adapted from [36].

2.2.3 System interventions

There are system interventions that could potentially limit required grid reinforcements and charging infrastructure reinforcement. In this research, only the smart charging intervention is considered. Smart charging enables power distributors to influence charging behaviour by time-of-use electricity tariffs and can decrease the peaks in the load curve [41]. When prices are high, EV drivers are encouraged to not plug in their EVs and vice versa. From the literature review that is held in section 2.3, it appears that many scientists recognize the potential of smart charging and even the Dutch government is planning to implement smart charging on a large scale [19]. Moreover, smart charging could help to unburden the grid and the need for the charging infrastructure and is therefore found very relevant in its potential to reduce system costs. The notion of smart charging is often defined differently. This research includes the definition of smart charging that is already part of the grid and defined by 'het nationale laadonderzoek [42]'.

The notion of smart charging [42]:
Smart charging means that electric cars charge at optimal times. The speed and time of charging is adjusted:
• to the total power demand and the space on the electricity network. This prevents (too) high peaks.
• on the available sustainable energy (solar and wind).
• on electricity prices.
• on the number of cars that charge simultaneously.

Other interventions are left out of scope such as vehicle-to-grid (V2G) technology, battery storage systems, and solar-to-vehicle (S2V) technology, which also could unburden the grid or the charging infrastructure. These are described in Appendix B.

2.3 BEVs experience and SEV expectations

Before determining the analytical framework and the research design a literature review is conducted on the system costs of the BEV and the SEV. As explained before, the system costs are derived from the capacity requirements of the grid and the charging infrastructure. These capacity requirements could be derived from the maximum simultaneity rate and the peak loads that both could be derived from a local load curve. The core concepts that are selected for the literature review are the BEV and the SEV that are defined in section 2.1. To keep a broad view both concepts are not only evaluated on their impact on the system costs but also their impact on, the load curve, and the capacity requirements of (1) the charging infrastructure and (2) the grid. The articles were found via the Scopus, Google Scholar, and ScienceDirect databases. Selection criteria were the presence of a combination of keywords covering the field of the two core concepts such as "distribution grid", "charging infrastructure", "solar electric vehicles (SEV)", "battery electric vehicles (BEV)/ plug-in electric vehicles (PHEV)" and "system impact/costs". Most sources were found by snowballing. A maximization criterion in the selection of the articles was the year, in which the article was written (the newer the better).

2.3.1 BEVs, the grid, and the charging infrastructure

After a thorough literature analysis, it is found that the literature agrees that the BEV will bring high system costs regarding the development of a charging infrastructure [12] [13] [19] [42] [19]. The system costs of the BEV on the charging infrastructure in this thesis are operationalized in the national capacity requirement for the charging infrastructure; the number of charging stations needed for the mass deployment of EVs. Following the national Agenda of Charging Infrastructure (NAL) [42], The Netherlands is facing a massive challenge regarding the development of the public charging infrastructure. National Agenda Charging Infrastructure (NAL) [42] expects that in 2030 the BEV fleet in The Netherlands is sizing 1.9 million vehicles. Following NAL this corresponds to a charging requirement of 7,100 gigawatt-hours (GWh) during peak hours, requiring 1.7 million charging points, of which 70% should be public charging places [42]. According to a first estimate, approximately €5 million in implementation costs per year are involved in the NAL. For determining the dimensions of the charging infrastructure the EU has set the maximum goal of ~9.5 EVs per charging point [13]. However, literature does not always agree on the way how the charging infrastructure requirement is determined. Therefore, there is also no clear insight yet on the long-term costs for the charging infrastructure in The Netherlands. Mathieu [13] found that there is currently a need for ~1.3 million charging points EU-wide and close to 30 million in 2030. He argues that it is of great importance to consider the charging speed when determining the national charging infrastructure capacity requirement. Another aspect that could be considered when setting the requirements for the charging infrastructure is the utilization rate of charging points. Torensma [12], Hoed [31] and Vervoordeldonk [32] recommend focusing on the utilization rate when determining the dimensions of the charging infrastructure. The utilization rate is defined as 'the amount of time that a charging point is occupied divided by the total available time within a set timeframe [31]'. Hoed [31] states that the utilization rate differs largely per hour of the day and neighbourhood. He states that it would be even better to monitor the occupancy of charging stations per hour per neighbourhood and take informed decisions about the capacity requirement of the charging infrastructure locally. Contrarily Bakker [19] does not distinguish between the different hours of the day and bases the public charging infrastructure requirement on the aggregated charging power per day in kWh. Wolbertus [33] found that 80% of the time that an electric car is at a charging station, it is not charging. He pleads that this influences the availability of the charging infrastructure, and that the occupancy rate influences the capacity requirement of the charging infrastructure. The occupancy rate is here defined as the amount of time that a charging point is occupied by an EV divided by the effective time that the car is charging. Moreover, better interoperability of the charging infrastructure and EVs could promote efficient capital investment, by requiring fewer charging points. Currently EVs and charging sockets are not standardized and therefore not always compatible, causing that more charging points are needed when no standard is introduced [43]. Finally, a report of Ecofys [19] argues that amongst others the composition of the mobility fleet, the technological characteristics of EVs, and the charging point availability play an important role in determining the capacity requirement of the charging infrastructure in the future [19]. In conclusion, there are already plans to scale up the charging infrastructure until 2050. However, different thoughts are elaborated towards the determination of the charging capacity requirement for 2050. The aspects that are considered during this thesis are illustrated and explained in section 2.2.1.

What are the system costs for the grid in case of the mass deployment of BEVs? It was already shown that the rated capacity of the grid assets must be equal to or higher than the peak loads the assets are subject to. After a literature analysis, it is found that the literature agrees that a growing BEV fleet has an impact on the national and distribution grid costs when no intervention takes place. However, the results of the literature review are ambiguous when looking into the size of the impact. Layzell [15] argued that BEV growth in Germany nationally adds about 1 to 4 percent by 2050 requiring additional grid and generation capacity of about 20 GW. Meanwhile, Lutander [44] found that the total Swedish national electricity consumption rises by 17.1% during critical weeks at a 100% BEV fleet. Klettke [45] states that the overall increase of the electricity demand in Europe rises by 10% at a BEV-penetration rate of 34% until 2050. She continues this statement by arguing that the energy system will not be able to meet the demand at all times anymore when no measures are taken [45]. Moreover, Lenzen [46] states that the current Australian national grid can support a maximum of 10% BEV fleet. Where the size of the effect of the impact of the BEV differs, the rise of the BEV will have an impact on the national grid anywhere. However, it is also noted that the rise of the BEV is often only considered as part of the cause of the rise of the imbalance of the grid on a national scale. For example, following Netbeheer Nederland [9], the rapid development of decentral electricity production solely forces the Dutch grid operators to invest in reinforcing the high voltage and medium voltage grid. Besides this, reinforcements are needed for the system integration of vRES, demand growth, and electric transport [7][9][10]. Hence, the developments of the energy transition, including the rise of the BEV, incite the transmission system operator (TSO) in The Netherlands to invest €7.8 - €8.7 billion in the high voltage (HV) grid between 2020 and 2029 [47]. Where Tennet plans to invest in grid upgrades for the developments of the energy transition, the future situation of the distribution grids in The Netherlands is uncertain [18]. Accordingly, the focus of this thesis is on the distribution grid.

On a local scale, a BEV seems to have a more significant impact on the system costs than on a national scale [15] [16] [18] [48] [49] [50] [35] [39] [34] [23]. Given that one BEV could double [15] or even triple [16] the peak consumption of an individual household the impact of BEV adoption on the costs for the distribution grid is expected to be relatively higher compared to the impact on the national grid costs. Jochem [16] and Garcia [49] confirm the challenge of mass penetration of BEVs on a local level specifically and state that the high peaks are caused by on the one hand the high electricity consumption of BEVs and on the other hand the simultaneousness of BEV charging. Garcia [49] reports that when no intervention takes place, transformers and lines are overloaded; an increase of CO_2 intensity takes place, and that electricity costs increase. Subsequently, he states that there is a need to reinforce the grid due to the peak loads that become higher caused by the mass penetration of BEVs. Ulffers [39], agrees with Garcia and states that the increase in electricity demand can lead to overloading and voltage violations. Layzell [15] showed that for a typical German residential circuit of 150 homes, of which 25% of the households own a BEV, the local peak load increases by 30%. Jarvis [50] even reported an increase of even 60-110% in the power load in neighbourhoods in Texas, in case of respectively 15 – 30% BEV penetration. Lousberg [35] predicted in Dutch agent-based modelling (ABM) research the current load curve of a residential area in a winter week at 100% BEV penetration (figure 2.9). The graph shows that the peak growth increases largely caused by the charging need of BEVs.

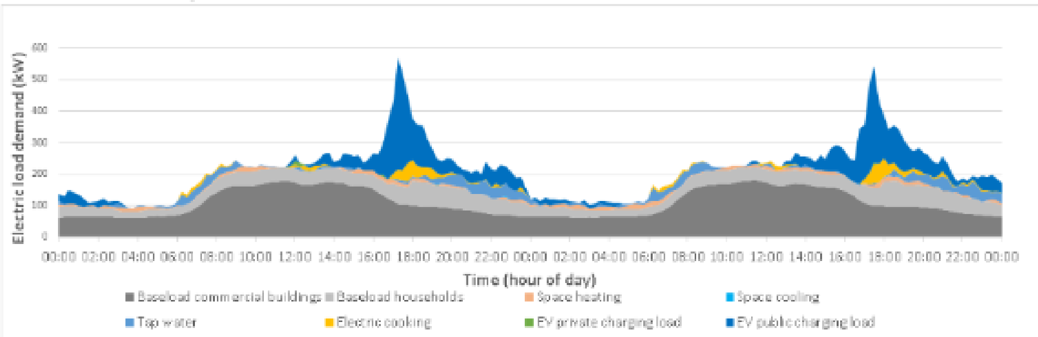


Figure 2.9 Residential electric load demand prediction during winter.
Source: Adapted from [35].

Where literature is internationally ambiguous on the extent of the BEV impact on the distribution grid, the authors have a common expectation: the peak loads on a local scale are growing significantly when the number of BEVs in a residential area grows. The distribution grids are not designed for the high peak loads that the BEV brings, they are automated to a limited extent and are restricted to capacity limits [18]. For example, Pillai [51] assessed the capacity of three distribution grids in Denmark and concluded that distribution grids can handle 6% of EV charging load during peak hours. Following this train of thought, the report of IPPC [52] argues that the Dutch distribution grid needs to be strengthened to secure the reliability of the electricity supply system.

The literature review results so far only show what is known about the impact of the BEV on the required system reinforcements, based on uncontrolled charging strategies, meaning that no intervention takes place to schedule the demand. However, it could be concluded that the body of literature is fairly unanimous about the potential of smart charging strategies balancing the charging load curve [7] [16] [18] [19] [25] [49] [50] [35] [51] [53] [54] [40] [55]. Besides balancing the load curve, the required charging infrastructure could decrease on the condition that the charging load is more distributed during the day, in this case, fewer charging points are needed [12] [19]. A study by McKinsey [15] claims that when smart charging is applied, the local demand peak would grow 14% less than with a simple charging strategy. Refa [11] claims that the impact is even higher resulting in 47% lower energy demand during the evening peak. The RVO [56] even argues that by applying a smart charging strategy no extra measures are needed regarding the grid infrastructure reinforcements. Also, Asensio & Aperribay [49] claim that smart charging is the key to achieve large-scale penetration of EVs. The different impacts that are reported by the different authors seem to be a result of the different definitions of the smart charging strategy and the different thoughts about the future energy system. For example, Refa [57] defines smart charging as "optimizing the charging session by alignment of time, speed, and charging method with the EV-owner's preferences and given both electricity market and grid conditions". In contrast, Lousberg [35] does not consider the charging speed in its attempt to explore the impact of the BEV on the grid. The different concepts of smart charging, so far recognized, are shown in figure 2.10.

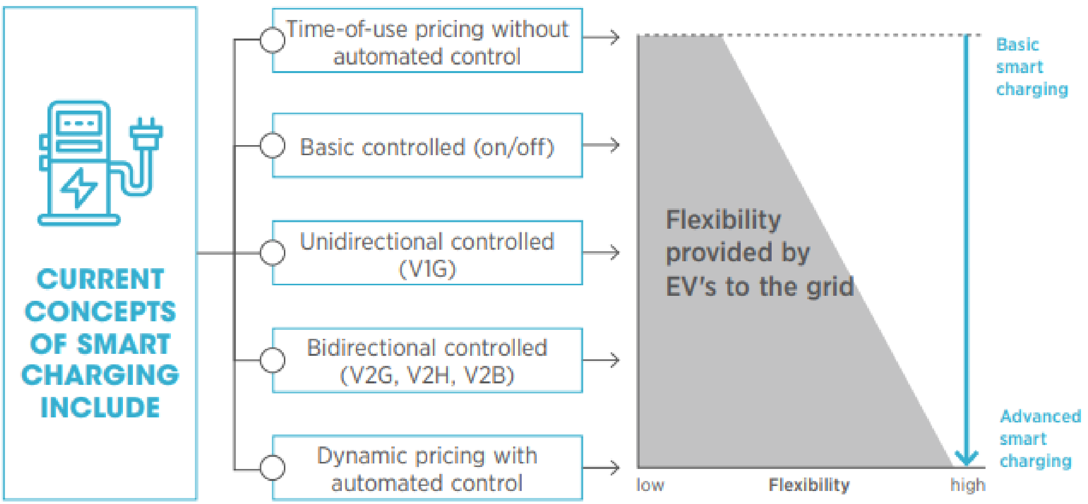


Figure 2.10 Current concepts of smart charging following IRENA.
Source: Adapted from [58].

Next to the potential of smart charging the literature review revealed that there is a difference of perception about the main cause responsible for overloading the distribution grid asset capacity. Where we so far found that the BEV fleet could cause grid reinforcements to be needed, some argue that the reinforcements costs are mainly caused by local photovoltaic (PV) production or the penetration of electric heat pumps in the future energy system. A Swiss study by Gupta [7] indicated that the peak load could increase 2-3 times in 2050, caused by electrification of transport, household appliances, and the reverse power flow of solar energy of people feeding solar energy back to the grid. Typical issues of decentral commercial generation are (1) voltage and frequency fluctuations and (2) the overloading of the distribution cables by a negative peak flow [59] [7] [44] [60] [61]. The peak supply of solar panels is around noon as the solar irradiation is the highest then. Luthander [44] stated that 71% of solar PV during summer needs to be limited when the PV generation replaces the electricity consumption of households. Meanwhile, Bilton [60] claims that when PV penetration on a local scale becomes higher than 25% - 30%, grid reinforcements are needed. Finally, Verschueren [59], claims that if 80% of the 63 households in a residential area are in the possession of PV panels, 45% must be switched off to prevent voltage violations and grid instabilities.

Next to the decentral supply of PV panels, the possibility of the electrification of heat appliances also raises concerns about how the distribution grid must handle this. Multiple scientists state that the arrival of the heat pump is likely to be largely responsible for the grid reinforcements on a local scale [9] [60] [47]. Currently, in The Netherlands, the seasonal peaks in heat demand are mainly met by the provision of natural gas. This is changing with sustainable heat alternatives that are in some cases powered by electricity: the electricity grid will absorb part of this peak in heat demand [9]. Accordingly, in the future electricity system, the share of heat pumps and induction hubs is expected to grow [5] [6] [7] [8]. To what extent heat pumps will be deployed in society is still uncertain. A study by Bilton [60], showed that with 20% heat pump penetration in households the peak electricity load increases by 72%. It reported that significant grid reinforcements were needed for the penetration of heat pumps. Moreover, the International Energy Agency (EIA) stated that the electrification of space heating and cooling is carefully estimated to account for roughly half of the energy consumption in buildings in 2050 [62]. Rüdisüli [63] found that when the share of electric heating in Switzerland rises by 75% and, the demand increases by 10 TWh. Including a share of 20% electric mobility, the total electricity demand increased by 25%. Netbeheer Nederland [9] also expresses her concerns about the potential electrification of gas appliances and states that when a home becomes fully electric, additional measures are needed to reduce the energy demand. It proposes better efficiency and better insulation to prevent high peak loads. Finally, Veldman [18] states that the developments of the energy transition, considering the decentral electricity production of solar panels and the expected increased demand for heat pumps and BEVs, will make it increasingly challenging to maintain the balance between supply and demand. Veldman [18] stresses the uncertainty and unpredictability of the future load curve caused by the uncertainty of all the developments that are set up to live up to the energy transition. The distribution grid needs to be adapted to continue to meet the growing demand and the variable electricity supply of vRES.

2.3.2 The expectations of the SEV

The body of literature gave some non-specific insights on the potential of SEVs compared to BEVs flattening the future load curve and reducing the capacity requirements of the system. However, specific details about the impact of SEVs on the Dutch future load curve and the system costs are not explored yet. The technical characteristics of the SEV were presented in section 2.1. Here it was explained that the SEV has a lower energy consumption and generates electricity by its integrated solar panel. Accordingly, it is expected that the SEV has a fewer impact on the grid and charging infrastructure costs. A lower number of charging events is expected by a decreased electricity need of the SEV. Moreover, the electricity consumption of the SEV is expected to be lower than the electricity consumption of the BEV. Therefore, the SEV is also expected to play a role in unburdening the grid by decreasing peak loads. Even though literature does not elaborate yet about the SEV, the hypothesis is that the SEV is less grid-dependent than the BEV, leaving the question “how much” open for the analysis.

2.3.3 Literature gap

The energy transition is accompanied by many challenges, the focus of this research is on the capacity needs for the grid and the charging infrastructure and the paired system costs when the SEV compared to the BEV becomes dominant in the future mobility system. The results on the system costs of the SEV are missing in the literature. For the BEV, the reviewed literature agreed on the need to flatten the load curve and limit the simultaneity of charging to make large-scale BEV penetration possible and prevent expensive interventions. Especially for the distribution grid, peak loads are expected to become significantly high when no intervention takes place. Many scientists for example see potential in unburdening the grid and the charging infrastructure by the implementation of smart charging, a strategy that could help to distribute the charging electricity consumption over time. A smart charging strategy might also be applied to reduce the costs for the future charging infrastructure. However, this depends on the way how the charging infrastructure requirement is determined, and the effectiveness of the smart charging strategy. However, no clear consensus has been found about the method for designing the future infrastructure capacity requirement. Finally, there is no clear consensus in the literature about the main cause for local grid reinforcements. The rise of residential solar PV and electric heat pumps could also play a driver in the grid reinforcements. While considering the latter developments, the focus of this thesis remains on the system cost of electric mobility.

2.4 Analytical framework

The knowledge and the insights described in this chapter are used to provide an analytical framework that maps out the relation of the independent, dependent, and moderating variables. The analytical framework reflects on the variables and relations that are considered during the analysis of this research. The variables and relations are briefly explained below. The grey area reflects the relations and variables which are subject to analysis during the research. The white area is left out of scope but is still an important factor in the system cost calculations.

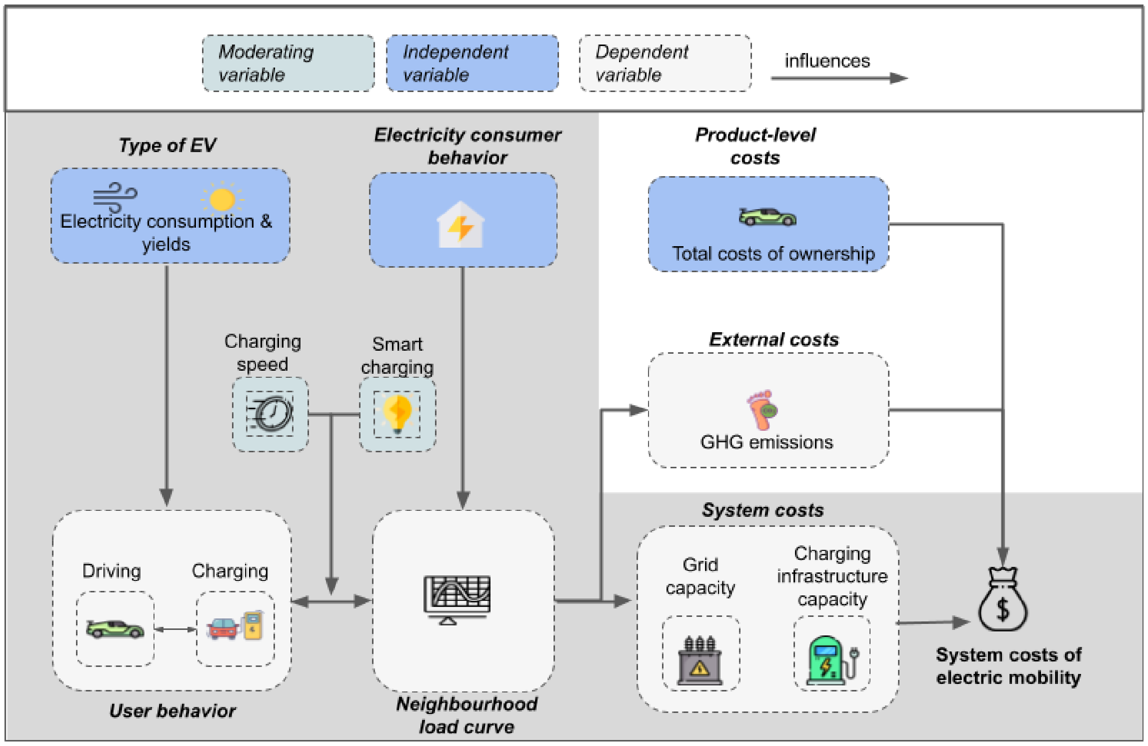


Figure 2.11 Analytical framework.

The societal costs exist of product-level costs, system costs, and external costs. However, the focus of the analysis is on the system costs during this research. The system costs are determined by the capacity requirements of the system. Capacity requirements for charging infrastructure and the grid are based on (1) the maximum charging simultaneity rate [48] and (2) the peaks in the local load curve [18]. These can be both derived from the residential load curve. The load curve is dependent on the EV users driving behaviour and the electricity consumer behaviour. The driving and charging behaviour is dependent on the fundament of the thesis: the technical difference between the BEV and the SEV. The impact of the EV user behaviour on the load curve is moderated through the system intervention smart charging. Moreover, the speed of the future charging points changes the shape of the load curve.

2.5 Research methods and flow

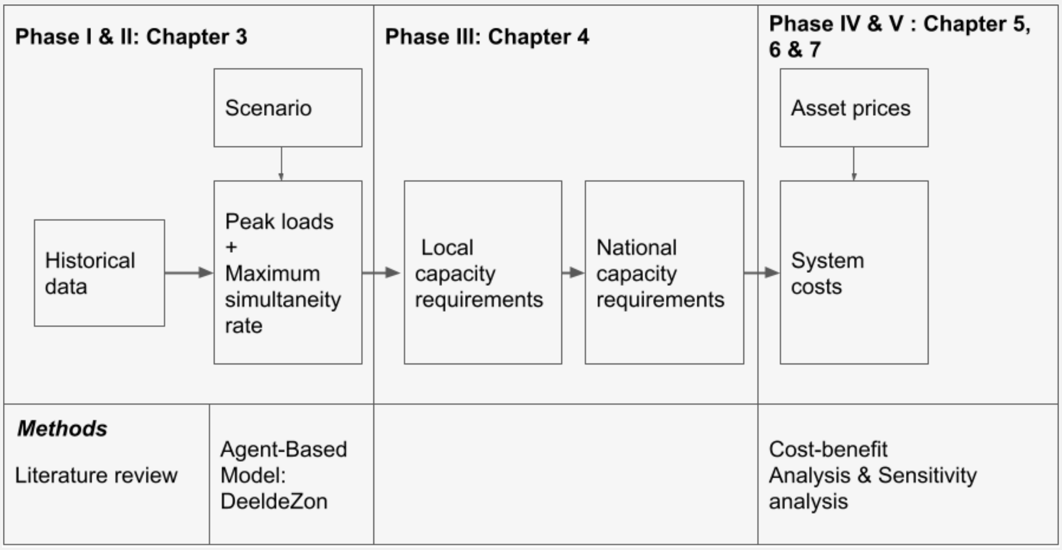


Figure 2.12 Research flow.

Now the analytical framework is presented, the research flow is determined. In figure 2.12 a research flow diagram is shown. It shows the steps which were taken to answer the main question. It distinguishes four phases of the core research, the belonging chapters, and methods. The steps of this research flow diagram are briefly explained in the text below. The choices for the methods are explained in chapters 3 and 4.

Phase I: Scenario

A scenario in the year 2050 is mapped for the 100% penetration of the SEV and the BEV separately. All planned electricity demand and supply developments such as residential PV supply and heat pumps on a local scale are processed here. EV charging and driving profiles are also exploited in this scenario.

Phase II: approximation load curve

Based on the scenario the current load curve per hour over a year on a local scale is simulated via an Agent-Based Model (ABM). Historical load profiles of commercial buildings and households of 2018 are used as a base for the load curve. A distinction is made between the BEV and the SEV in two simulations.

Phase III: Capacity requirements

Based on the shape of the load curve in phase II the local capacity requirements of the grid and the charging infrastructure are determined. The local capacity requirements are extrapolated to national capacity requirements by distinguishing between rural, suburban, and urban areas.

Phase IV: System costs calculations

Based on the national capacity requirements the system impact of electric mobility is determined. Besides the costs of the infrastructure reinforcements are calculated in cost-benefit analysis (CBA).

Phase V: Validation

A sensitivity analysis is performed to validate the fundament of the research. This analysis tells which parameters significantly affect system behaviour and/or the model outcomes [64].

Chapter 3: Modelling the residential load curve

Chapter 2 concludes with the research flow. The research analysis uses two research methods: ABM and CBA. In this chapter, the focus is on the first step: modelling the residential load curve using ABM. It is explained what an ABM is and why it is chosen as the approach. Afterward, the model logic and main assumptions for the 2050 scenario are explained. This chapter answers the second question: "How to approximate the future residential load curve? "

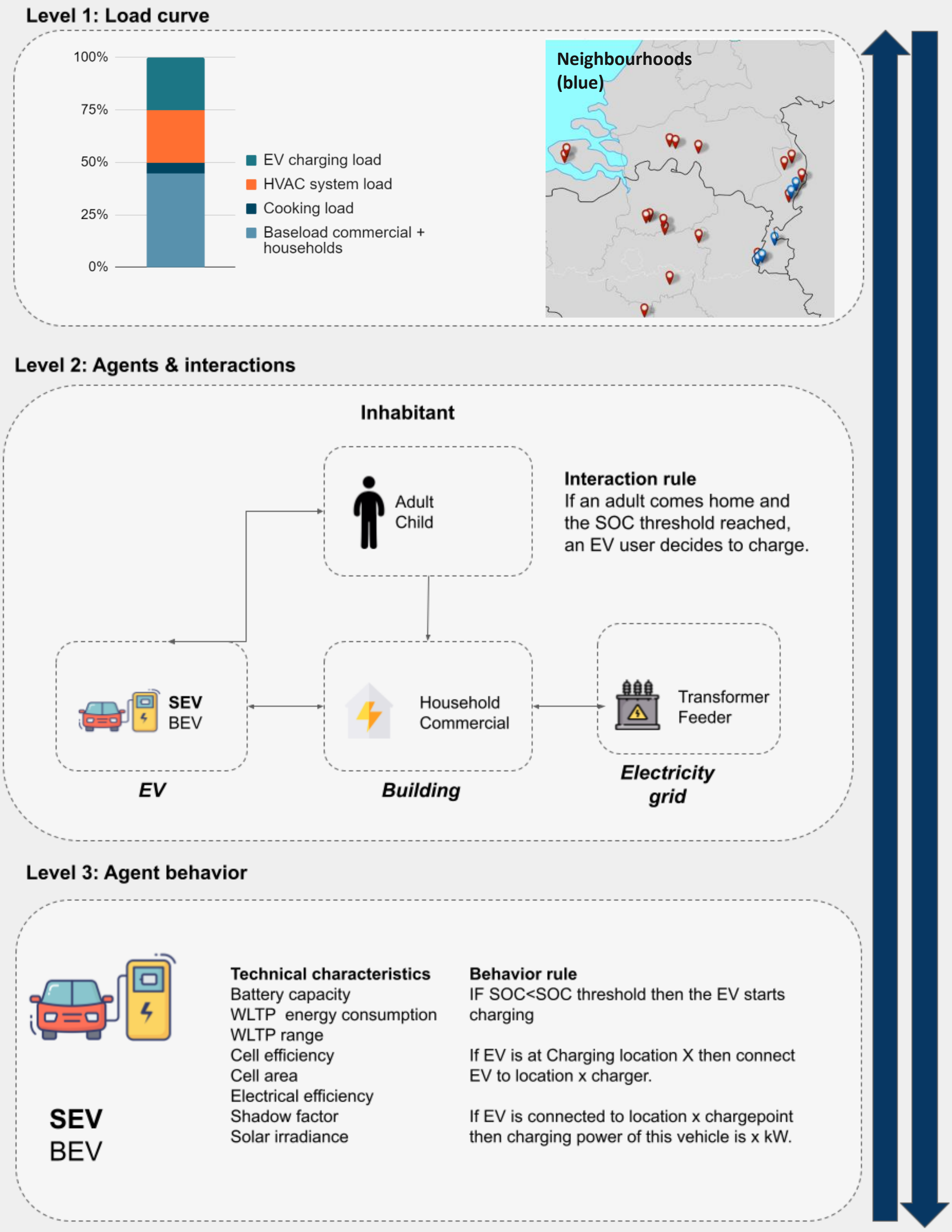
3.1 Agent-Based modelling (ABM)

The best way to determine peaks in the load curve is via direct measurements or historical data. As the aim of this study is to find out the system costs of electric mobility in 2050, the sole use of direct measurements is not considered practical for this study. Radical changes in the demand for residential areas make the future load curve hard to predict. The residential load curve will not incrementally change as it is dependent on the way people handle the new appliances such as heat pumps and electric stoves. A forecasting method is therefore also not considered to be accurate for this research purpose; calculations in forecasting methods are based on trends and incremental autonomous changes [65]. Another method to calculate the power demand of BEVs is using a statistical method to estimate the simultaneity rate. In this method, the simultaneity rate is calculated by the total charging power of all Dutch EVs together, divided by the vehicle's rated charging power. Research by Ulffers [39] found that local weak spots in LV cables often cannot be identified when using this statistical method. It led to an underestimation of the reinforcement costs [39]. To incorporate human behaviour of the complex adaptive energy system of a neighbourhood an ABM is used. An ABM is a quantitative model that simulates agents with behaviour affecting each other over time [35]. An ABM aims to make models as close as possible to the real world, without making use of empirical data. The ABM discipline distinguishes itself by counteracting the thought of old-fashioned model methods assuming that the market works perfectly and that the behaviour of actors in the system is always rational [3]. The uncertainty of the future energy system proves that a "simple" modelling study is not enough, and that actor behaviour needs to be considered. The use of an ABM in this research fits the complexity and adaptiveness of the energy supply system as it simulates a dynamic network of a neighbourhood; many agents that are acting in parallel constantly act and react to what other agents are doing. The overall behaviour of the system is the result of a huge number of decisions made every moment by the different actors in the system and is so-called 'highly decentralized' [66]. This overall behaviour of the system is considered here as the residential load curve. A big disadvantage of an ABM study is that it is very extensive and therefore not easily applicable. However, there already exists an ABM of the residential load investigating the load impact of BEVs on a local scale. ZEnMo simulations tried to counterfeit the reality of the future local electricity system and the role of the BEV in it. It calculates load profiles by adding up parts of the load curve which are originating from individual consumers. Where ABMs normally do not use empirical data the model of ZEnMo does use some empirical data to predict the household load and the commercial load. Therefore, it is questionable to what extent this model is an ABM. However, the point of focus of the research analysis is the electricity demand of EVs specifically. The EV electricity demand is not based on empirical data in the model and is based on behaviour. Hence, it was considered valuable to approximate the future load curve via the ABM of ZEnMo to define the maximum simultaneity rate and the maximum peak loads caused by the rise of the EV. Accordingly, the existing model of ZEnMo is expanded in this research to answer the main question. The ZEnMo model is developed in AnyLogic, a program that is based on the JAVA language.

3.2 The DeeldeZon model

Accordingly, this research uses and extends the existing model of ZEnMo, called the DeeldeZon Model (DDZ). DDZ is an ABM in which human behaviour within a neighbourhood is simulated. This behaviour takes place within the homes and mobility options that people have, resulting in specific energy demand at any time. The load curve is a result of many decisions of actors in the model. The operational decisions and strategies of the single actors are governed by institutions structuring the interaction in the model [67]. A schematic overview of the model is given on the next page. Only the EV is considered as the agent in the scheme. Note that this is not the only agent that is part of DDZ.

DDZ model schematic representation



DDZ represents five different neighbourhoods in the south of The Netherlands: Maastricht Sphinxtuin, Venlo Zuid, Sittard-Geleen, Belfeld, and Wolder. The different neighbourhoods have different characteristics and distinguish commercial buildings from normal households. Subsequently, the households are divided into the categories presented in Table 3.1. Besides, shops, offices, education, healthcare, sport, and industrial buildings are considered separately for the electricity demand and are part of the commercial load. The five residential areas in The Netherlands are characterized by their inhabitants, households, road network, and electricity grids. The human agents considered are adults and children. They control reactive agents such as households, EVs, and the electricity grid.

HOUSEHOLD TYPE	Apartment	Terraced	Corner	Semi-detached	Detached	Commercial
MAASTRICHT	127	1	2	0	0	14
SITTARD-GELEEN	0	0	0	19	24	2
VENLO-ZUID	29	44	9	2	1	9
WOLDER	56	7	6	0	8	13
VENLO BELFELD	50	0	0	8	12	7

Table 3.1 Type of buildings per neighbourhood in the DDZ model.

The individual agents interact with each other and evolve in the residential load curve. Children and adults at home have different options of using electricity, electric cooking, and heating or cooling water and space. All households together form the household load. Adults belonging to the households can possess a BEV with a chance of 48% [68]. If no other adult of the same household is using a BEV, adults can drive to work, bring their children to school, or go on a trip to for example a leisure location. When an EV is not driving, and its state of charge (SOC) is lower than a certain threshold an adult decides to charge its EV. The charging point has different speeds, influencing the time needed to charge the battery and influencing the driver's behaviour, and vice versa. The household load, commercial load, and EV charging load are aggregated in the grid and evolve in the load curve per hour. The smart charging algorithm reacts to this total by drawing up a schedule in which EVs will or will not charge. New EVs that are also going to charge respond to this schedule by adjusting their charging schedule to the total load curve. The elements forming the main pillars of the distribution load curve are given in equation 3.1 and illustrated in the graph in figure 3.1.

$$\boldsymbol{Residential\ load\ (h)}: Load\ hour\ (h) = Commercial\ load\ (h) + Household\ load\ (h) + heat\ pump\ load\ (h) + Electric\ cooking\ load\ (h) + water\ tapping\ load\ (h) + EV\ charging\ load\ (h) - solar\ PV\ load\ (h) \qquad \textbf{(3.1)}$$

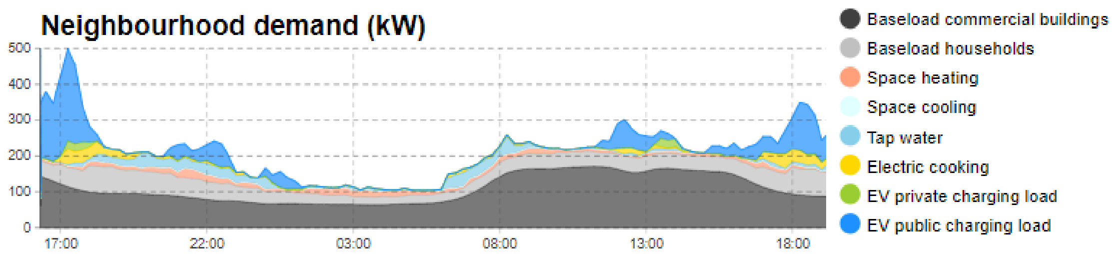


Figure 3.1 A graphical representation of the neighbourhood demand in kW.
Source: Adapted from [35].

The residential load originating is subdivided into five categories [35]:

- The historical baseload: a load of households and commercial buildings.
- Electric cooking load: load originating from electric cooking.
- Thermal loads: heating, ventilation, and air conditioning (HVAC)-systems dependent on the behaviour of people and weather conditions.

- The PV supply load: the load residential households generate with the solar panels placed on their roofs.
- The EV private and public charging load.

The design of the model is based on geographical data (GIS) and building registers [69]. The data provided by building registers includes the location, floor area, and type of commercial buildings. Electrical load consumption patterns of commercial and residential buildings are provided by data from NEDU [70]. The technical features of the electricity grid are based on publicly available data of a Dutch distribution system operator (DSO). Weather data, including the hourly solar intensity and temperature, is provided by data from the Royal Dutch Meteorological Institute (KNMI) [71]. The chances of doing a particular activity are based on general CBS distributions. The number of electric vehicles and inhabitants is determined by the number of households and the different types of households. Every household has a maximum of two adults and three children. Finally, each household can have a maximum of two EVs depending on the number of adults living in it and the willingness of them to buy an EV.

The remainder of this chapter first shows the choices for every part of the load curve made. Hereafter: the choices made for the model contributions of phase II are argued.

3.3 Phase I: The residential load curve in 2050

As explained the residential load curve is subject to change until 2050. In this section, a scenario in 2050 is mapped. Relevant model assumptions are evaluated and, if necessary, adjusted to a scenario in 2050. The assumptions are divided into level 1 and 2 assumptions, giving the assumptions on a general model level (level 1) and an agent level (level 2). The level 1 assumptions are considered in this section. The level 2 assumptions and formulas are considered and explained in Appendix C.

3.3.1 Historical household and commercial baseload

To model the future residential load curve as realistic as possible the residential and commercial demand of electricity is derived from a historical load curve [70]. As the residential demand is expected to grow in the future [7] a yearly growth rate is considered. However, CBS [72] found that despite increasing use of electricity the household load did not grow significantly over the past few years. This is explained by the development of lower energy-consuming appliances and the insulation of buildings. The biggest growth in electricity demand originated from the arrival of the refrigerator and the computer. As comparable developments in the future are considered separately, no growth rate per year is considered in this load curve.

Model assumptions	*Data*	*Level*
• *Baseload profile buildings based on historical data of 2017.*	[70]	1
• *Baseload households based on historical data of 2017.*	[73]	1
• *No growth rate is considered for the commercial and residential load curve in 2050.*	[72]	1
• *The future developments from 2017 until 2050 impacting the load curve contain the use of HVAC systems, solar PV, electric stoves, and electric transport.*	DDZ	1
• *The data of the profile factor in a year is gathered via NEDU. From the different load profiles, an average load profile of a company with less than 2000 working hours is chosen for the non-food sector (E3A). For the food sector, an average load profile of a company with more than 5000 working hours is chosen (E3D).*	[70]	2
• *Buildings in the food and non-food sector consume respectively 467 kWh and 81 kWh per square meter per year.*	[74]	2
• *Power consumption of different types of households per year.*	[73]	2
• *The load variation is incorporated to let the household demand profile vary per household and is uniformly distributed between 0.6 and 1.*	DDZ	2

Table 3.2 Model assumptions made to calculate household and commercial load. Level 2 assumptions are explained in Appendix C.

3.3.2 HVAC system load

The electrification of space heating and cooling is uncertain for 2050. However, very careful estimation of the International Energy Agency (IEA) states that heat pumps could account for roughly half of the energy consumption in buildings in 2050 [62]. However, the share of electric heating in 2050 is largely unknown. As the gas system changes drastically, some of the homes and businesses will be using fully electric heat pumps, while others will be heated by heat networks or using hybrid heat pumps powered by green gas or hydrogen. In the Dutch regional and national scenarios, the adoption of hybrid heat pumps is expected to be 20% by 2050. Following Netbeheer Nederland fully electric heat pumps will account for ~43% in 2050 [5]. Despite the uncertainty about the share of the electric heat pump in the future energy system, an assumption is made that the number of heat pumps in households is 43% in 2050.

DDZ distinguishes between air-to-water (AW) and water-to-water (WW) heat pumps. The AW heat pump uses the temperature outside to compress it to warmth and condenses this to water. A WW heat pump uses water from for example a lake and warms it with a heat exchanger. While both types of heat pumps are conceptually different, the operationalization costs are almost equal. AW pumps are more popular than WW heat pumps. Soil drilling needed for the installation of the WW pump in many places has become prohibited, because of the damage it brings to the environment and in particular groundwater [75]. Hence, in the research scenario of 2050, only the AW heat pump is considered in the model experiments [76]. Another distinction made in the DDZ model is the use of a single-stage or variable-stage heat pump. A single-stage heat pump has only one power setting. Accordingly, it switches on and off when the temperature is for example 5 degrees below or above the desired temperature, respectively. A variable-stage heat pump can operate at multiple power levels depending on the desired temperature. As flexibility in the energy system is becoming more and more scarce, the flexibility of the system of the variable-stage heat pump promises much for the future energy system. Besides, it provides better comfort as the temperature remains more stable, it can also be highly valuable for advanced demand response. Accordingly only the variable stage heat pump with a typical maximum power of 4kW is considered during the model experiments [77].

As the heating of households, heating water is currently largely dependent on the gas infrastructure in The Netherlands. Alternatives for the heating of water are the application of an AW or WW heat pump or by a domestic hot water heat pump (DHW). The DHW uses outdoor air to provide hot water. Unlike AW heat pumps, DHW only provides domestic hot water for showers, dishwashers, sinks, and other appliances where water needs to be heated for humans. DHWs work by delivering hot water through a centralized boiler or storage tanks separate from water [78]. For the sake of decreasing the number of parameters in the DDZ model, it is assumed that electricity demand for heating water is done by AW heat pumps only. Accordingly, the electricity consumption of heating of water is not considered separately in the DDZ model and incorporated in the Heat pump electricity demand.

While the gas consumption gradually stops until 2050, the current gas consumption is a good indicator for the electricity demand for the use of heating and cooling of space in 2050. Hence, in DDZ historical data of the gas supply from 2019 is used to project the future electricity demand for heating and cooling in households [79].

Model assumptions	*Data*	*Level*
• *Data for projecting the electricity demand for space/water heating and cooling in 2050 is derived from historical data of the gas consumption in 2019.*	[73]	1
• *Fully electric heat pumps are situated in 43% of the households by 2050.*	[5]	1
• *AW heat pumps account for all the different heat pumps in a neighbourhood.*	[75]	1
• *All heat pumps are variable-stage heat pumps operating at a thermal energy level of 4kW. For the heat pump, this is the same for cooling and heating and varies between 2.3- and 6-kW thermal energy depending on the type of household and its belonging gas consumption.*	[77]	1
• *Coefficient of performance (COP) WW and AW heat pump derived from historical data.*	[80]	2
• *Ambient temperature based on historical data of 2018.*	[71]	2

Table 3.3 Model assumptions made to calculate the load of HVAC systems. Level 2 assumptions are explained in Appendix C.

3.3.3 Electric cooking load

Contrarily to the heating of space and water, electric cooking is completely dependent on the behaviour of people in the neighbourhood. It is expected that electric stoves will replace gas stoves in 2050 [5]. Therefore, a scenario of 100% electric cooking in 2050 is assumed in this research. The power of the electric stove is dependent on the number of pits. The mean power of an electric stove now varies between 2 and 5 kW dependent on the number of pits in use [81]. As earlier argued, the energy consumption of electric appliances is likely to become lower due to the development of more energy-efficient equipment. Hence, it is assumed that 1 kW of power is consumed per pit in use. As the number of pits in use and the chance distribution of cooking per hour is not expected to be significantly different in 2050 the current belonging values of these aspects are adopted from the existing DDZ model.

Model assumptions	*Data*	*Level*
• *100% of the stoves become electric in 2050.*	[5]	1
• *Chance distribution of inhabitant behaviour.*	DDZ	2
• *Per pit in use, it costs 1 kW of power.*	[81]	2
• *Chance distribution cooking per hour.*	DDZ	2
• *Chance distribution number of pits in use.*	DDZ	2

Table 3.4 Model assumptions made to calculate the behavioural load. Level 2 assumptions are explained in Appendix C.

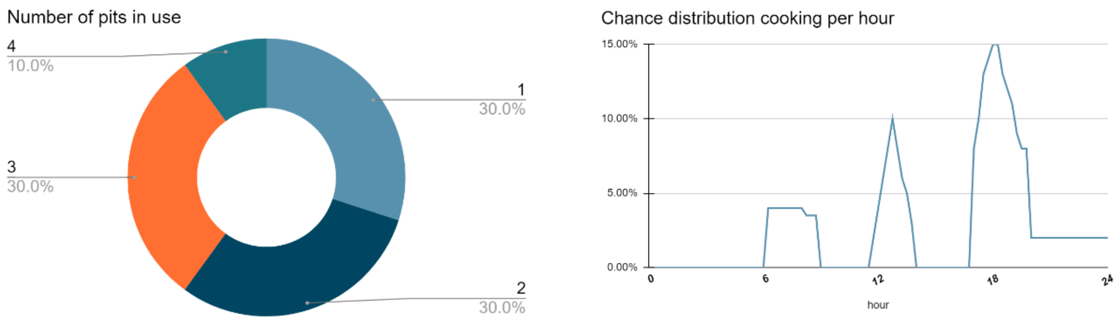


Figure 3.2 Behavioural load input distributions in the DDZ model.

3.3.4 PV Load

In the past years, the installed capacity of off-grid solar PV has grown more than ten times [82]. A large part of electricity produced by solar energy originates from PV panels installed on roofs of houses [18]. IRENA mapped that the share of wind and solar energy could theoretically meet 86% of the power demand [83]. On a local scale, Tennet expects that in 2050 126 GW will be generated from renewable sources and 84 GW of that will be originating from locally generated solar energy. From the 86% of renewable energy, it is assumed that 57% of the generation will be originating from solar energy. We here assume therefore that 57% of the households will have solar panels on their roof by 2050 [10]. This assumption is a rough estimate, as it neglects the commercial decentral production of solar. The solar contribution is dependent on amongst others the efficiency of the solar cells and the solar irradiance [71]. The International Renewable Energy Agency (IRENA) [82] predicts that solar cell efficiency will grow in the future. It does, however, not give any prediction about the future efficiency of the solar cells. The PV efficiency is set to 22% in the 2050 scenario, where it is now 18% on average. The PV panels in the model can only generate power for the belonging houses. In chapter 2 the concept of PV panels feeding energy back into the grid, was noted. For scoping reasons, this concept is not considered in the model. The solar peak is mostly around noon and the peak in the load curve is mostly around the end of the day. Subsequently, the solar peak is not expected to have a significant influence on the peak on the load curve caused by the EV.

Model assumptions	*Data*	*Level*
• *57% of the households will have solar panels installed on their roof by 2050.*	[10]	1
• *The mean PV efficiency on household roofs in 2050 is 22%.*	[82]	1
• *The PV irradiance per hour is originating from the historical data of KNMI.*	[71]	2
• *The installed area of PV is dependent on the size of the roofs of households. The area of the roof is different per building and derived from GIS data of The Netherlands.*	[31]	2

Table 3.5 Model assumptions made to calculate the PV load. Level 2 assumptions are explained in Appendix C.

3.3.5 EV charging load

The electricity demand of EVs depends on the state of charge (SOC) of the EV, the charging strategy, the charging power, and the time of the next planned trip. EV owners can charge their EVs at home or in public. Model assumptions regarding the SOC and the time of a trip are explained in chapter 3.4.2 involving driving behaviour. The peak load is originating from the moment and speed of charging of all individual cars. The charging speed is dependent on the location where the EV is. An EV can park at different places having different types of chargers shown in figure 3.3. Hence, the location of the EV is related to a certain charging speed in the model. The charging speed and the moment of charging determine how much power is used for charging the specific EV.

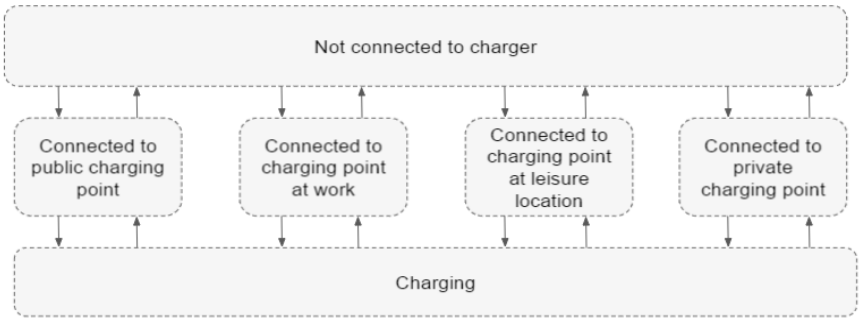


Figure 3.3 A schematic overview of the different destinations an EV can have in DDZ.

As the design of charging infrastructure in 2050 is still unclear, the assumptions are based on the current charging point power distribution in The Netherlands. Charging points at work and leisure locations are often also considered as private chargers; companies usually install charging points for use by visitors or employees [84]. When looking at the database of public chargers in The Netherlands now, for public charging 19%, 67%, 13%, 1% of the charging points respectively are charged by charging points with a power of 3.7kW, 11kW, 22kW, 50kW [36]. Private charging points have speeds differing from 3.7, 11, and 22 kW. As there is no specific information about the distribution of charging speed of the private charging points in The Netherlands, uniform distribution with a charging power of 3.7, 7.8, and 11 kW is used in the model [13]. Finally, the model contains unlimited charging points, as the goal is to find out what the charging need is. When having a constrained number of charging points, the charging need is not mapped out well.

The charging strategy that is adopted in the model is smart charging. Chapter 2 already highlighted that smart charging is assumed to be an integral part of the future energy system as it is largely recognized in the literature. Different concepts of smart charging were shown. As currently, smart charging is only a limited part of the mobility system, it is chosen to base the smart charging strategy solely on time-of-use electricity tariffs without automatic control. This is the most 'basic' smart charging strategy, that is not automated but based on human behaviour and financial incentives. The charging speed that is sometimes considered in the design of a smart charging strategy is not considered in the ABM. Where it is tempting to apply a 100% effective smart charging strategy, it is questionable if a 100% effective smart charging strategy is realistic as human behaviour stays the main driver of the load [57]. The RVO measured that the share of people that are actively applying a smart charging strategy is 20%. However, this was partly caused by the fact that not all people are yet familiar with smart charging. Moreover, the incentives for smart charging are limited. Accordingly, in the future system, it is expected that more people are familiar with smart charging and that more efficient incentives are created. In The Netherlands, research of E-laad [57] resulting from a pilot in which people actively participated in a smart charging strategy reported that 69% of the total charging sessions applied smart charging. Accordingly, in this thesis, it is assumed that 69% of charging sessions use a smart charging strategy.

Model assumptions	*Data*	*Level*
• *The electricity demand of EVs depends on the state of charge (SOC) of the EV, the charging strategy, the charging power, and the time of the next planned trip.*	[10]	1
• *For public charging 19%, 67%, 13%, 1% of the charging points respectively are charged by charging points with a power of 3.7kW, 11kW, 22kW, 50kW*	[82]	1
• *The private, leisure, and work charging power amount to 33% of the charging sessions 3.7, 7.8, and 11 kW.*	[13]	1
• *Apartments have no access to private parking places; EVs belonging to an adult who lives in an apartment are charged via a public charging point.*	DDZ	1
• *No limit is set on the number of chargers in the model, to find out what the charging need of the consumers is.*	-	1
• *Of the EV users, 69% of the charging sessions use a smart charging strategy and are incentivized to charge during off-peak hours.*	[57]	1
• *The smart charging strategy involves that the moment of charging is adopted to the off-peak hours and the charging schedule of other EVs.*	-	

Table 3.6 Model assumptions made to calculate the EV charging load. Level 2 assumptions are explained in Appendix C.

3.4 Phase II: Model contributions

Now that the assumptions about the 2050 scenario have been substantiated, the model contributions and their belonging assumptions are explained in this section. First, the SEV is added to the current DDZ model. Second, a deeper layer is applied by modelling different driver behaviour patterns.

3.4.1 The SEV modelled

The lower energy consumption and energy yields of the SEV can influence the state of charge (SOC); the SEV owner, in general, has less incentive to charge its EV than the BEV owner.

Technical characteristics SEV and BEV	*SEV*	*BEV*
• *Battery capacity [kWh]*	60	60
• *Energy consumption (WLTP) [Wh/km]*	83	152
• *Range [km]*	725	395
• *Cell efficiency is 2050[%]*	25%	-
• *Cell area [m2]*	5	-
• *Drivetrain efficiency [%]*	91%	-
• *Shadow factor [%]*	30%	-
• *Solar irradiance [Wh/m2]*	[71]	-

Table 3.7 Technical characteristics SEV and BEV.

The SOC (%) of an EV is initially randomly distributed, ranging between 0 and 100% per EV. For both the SEV and the BEV the battery capacity is 60 kWh. The SOC decreases when an EV is driving. The SOC decreases depending on the distance driven and WLTP energy consumption (Wh/km). The WLTP energy consumption for the SEV and BEV are different depending on their technical characteristics. The SOC per hour is determined in the following formula:

$$\boldsymbol{SOC_{BEV}}\ (\boldsymbol{h}+\ \boldsymbol{1}) =\ \boldsymbol{SOC_{bev}}\ (\boldsymbol{h}) - \frac{\mathbf{D(h)} * E_{BEV}}{\mathbf{B_{BEV}}} \qquad (3.2)$$

Symbol	Definition
SOC (h)	*State of charge [%] per hour (h)*
D (h)	*Drive distance [km] per hour (h)*
E	*WLTP Energy consumption [Wh/km]*
B	*Battery capacity [wh]*
S	*Solar range [km]*
Si	*Solar irradiance [Wh/m2]*
De	*Drivetrain efficiency*
Sa	*Solar cell surface in m2*
EI (%)	*Electrical efficiency (%)*

Table 3.8 Symbol definitions of formulas used for modelling the SEV.

The SOC is a parameter that changes over time; accordingly, the h represents the hour of the day. The SOC formula is different for the SEV. The solar range, the extra range gained from solar electricity, gives the extra SOC gained by solar energy. The SOC is limited to a battery capacity of 100% in the model as a higher SOC is not possible.

$$\boldsymbol{SOC_{SEV}}(\boldsymbol{h}+\boldsymbol{1}) =\ \boldsymbol{SOC}(\boldsymbol{h})_{\boldsymbol{SEV}} - \frac{(\boldsymbol{D}(\boldsymbol{h}) - \boldsymbol{S}\ (\boldsymbol{h})[km]) * E_{SEV}}{\mathbf{B_{SEV}}} \qquad (3.3)$$

Data of the KNMI [71] from 2018 is used to determine this solar irradiation per hour. The assumption here is that solar irradiation will not change significantly from 2021 up to 2050. The efficiency of the electric drivetrain and the shadow factor determines how much solar irradiation is converted into kinetic energy. Cobbenhagen [85] found that on average 30% of solar irradiation is blocked by buildings. Accordingly, the shadow factor, meaning the percentage of time that the SEV is in the shadow is set to 30%. Finally, a cell efficiency of 25% is used, which is higher than the current cell efficiency of 22%. Like the solar PV installed on the roofs of households, solar cell efficiency is expected to grow. It is here assumed that solar cell efficiency increases by at least 3% up to 2050. The solar range is determined by equation 3.4:

$$S = Si\ (h) * \mathrm{Sa} * \ De * Sa * (1 - \ shadow\ factor)/\mathrm{E} \qquad \textit{(3.4)}$$

In this calculation, the drivetrain efficiency plays a role. This is determined by the cell efficiency and the drivetrain efficiency of the SEV.

$$De = Cell\ efficiency * EL\_efficiency \qquad \textit{(3.5)}$$

The values of the cell efficiency and drivetrain efficiency are presented in Table 3.7.

Model assumptions	*Source*	*Level*
• *Data from the KNMI from 2018 is used to determine this solar irradiation [kWh/m2/hour]. The assumption here is that solar irradiation does not change significantly from 2021 up to 2050.*	[71]	1
• *The shadow factor, meaning the percentage of time that the SEV is in the shadow is set to 30%.*	[85]	1
• *It is assumed that solar cell efficiency will grow by at least 3% up to 2050.*	LY	1

Table 3.9 Model assumptions made to compare the SEV with the BEV in DDZ.

3.4.2 Driving behaviour modelled

Optimizing the use of the charging infrastructure requires a better understanding of how to distinguish user groups, establishing their charging profile, and how this differs to the extent of the average Dutch driver. For example, what additional charging demand is expected when 2% of the inhabitants are extreme travellers, charging their car at home? Studying the charging behaviour of different user groups helps to plan in sufficiently maintaining the capacity of the grid and charging infrastructure. In this research the following user behaviour characteristics are distinguished:

- **The trip chance:** The chance of a certain trip taking place.
- **The departure time:** The moment of home departure.
- **The trip distance:** The distance of a trip.
- **The duration of a trip:** The time between the moment of home departure and arrival.
- **The SOC threshold**: The value of the SOC that incentivizes the user to charge its car when the SOC is below this value.

Before defining the different user groups the average Dutch driver (resident) is described and forms the base of the population in the model. Subsequently, additional charging profiles are sketched, based on data that could be found to define deviant user groups. Therefore only 53% of the population in DDZ is defined as the average driver. The other 47% exists of deviating user profiles, extreme commuters, Ride-hail drivers, and long-distance drivers.

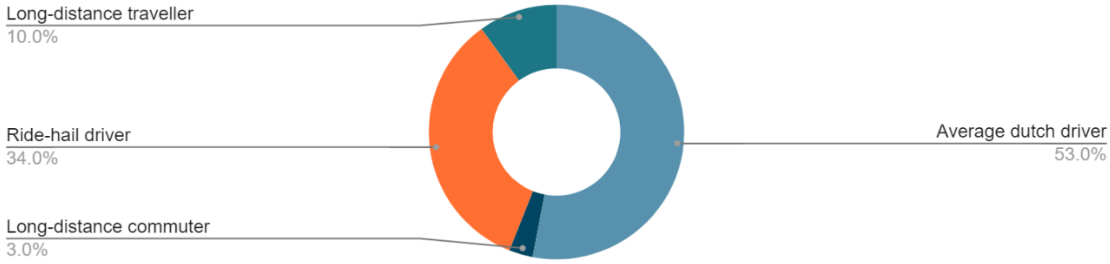


Figure 3.4 Distribution of different types of EV users.

3.4.2.1 Data

After a thorough literature analysis, it was concluded that no precise predictions could be executed. A report of Transport & Environment [13] stated that "data on the distance travelled, departure/arrival times and trip duration are very scarce for cars and even more for BEVs nowadays". Where data about the EV charging behaviour is lacking in the public body of literature, some contradictory findings of the EV user behaviour were shared. On a European level, the average km per year is 12.000 km for ICE vehicles, the BEV drives on average about 20.600 km per year, 42% more than the average ICE vehicle in 2019 [13]. However, sensitive data from LeasePlan proved the opposite. As the results of the BEV user behaviour characteristics are contradictory, the data of the ICE vehicle user behaviour is used for this research. General data about the average distance and departure times of Dutch ICE vehicles is found via sources of the CBS [24]. However, not all required information could be found for the typical Dutch driver. Hence, a source studying the drive cycle behaviour of states in America presented by the National Renewable Energy Laboratory (NREL) of the US is additionally being used. In this research, the state of California is taken as the most representative as its population density (632 inhabitants per m_2) is the most comparable to the Dutch population density (508,2 inhabitants per m_2) [86] [87]. Finally, the SOC threshold is derived from a statistical analysis of EV charging behaviour executed in the UK, as no Dutch information about this type of driver behaviour was found beforehand.

3.4.2.2 Average Dutch driver

The average Dutch driver characteristics that account for 53% of the people in the adults in the model are revealed in this section. The driver characteristics mentioned before differ per type of trip. The DDZ model distinguishes between, weekend, day, evening, and work trips. The distributions and the driver characteristics that are different depending on the trip type are presented in Table 3.10 The assumptions and reasoning made for this distribution are described in Appendix D. The personas that deviate from the average Dutch driver are described below.

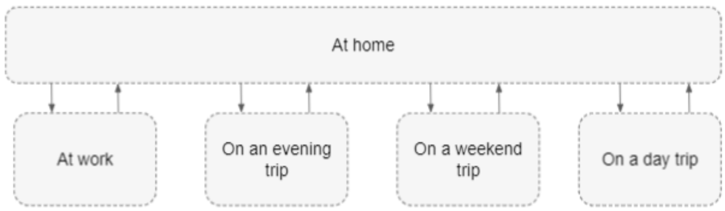


Figure 3.5 Different types of trips defined in the DDZ model.

	Chance distribution of going on a trip	*Trip duration distribution [hours]*	*An average distance [km]*
Work	37%	Uniform (6 – 8)	24 [24]
Evening	31%	Uniform (0.25 – 1.5)	16.3 [24]
Weekend	31%	Uniform (0.25, 3)	13.5 [24]
Day	31%	Uniform (0.25, 3)	16.3 [24]

Table 3.10 Driver characteristics differing per type of trip in the DDZ model.

Long-distance commuter (10%)

The first group is the Long-distance commuter. About 10% of the passenger car drivers drive more than 125 km per day [36]. These cars are charging frequently during weekdays. For this group, the driving distance distribution is adapted to the distribution in figure 3.6. During the weekend, day, and evening trips they are assumed to have the same charging behaviour as the 'average Dutch driver' defined earlier.

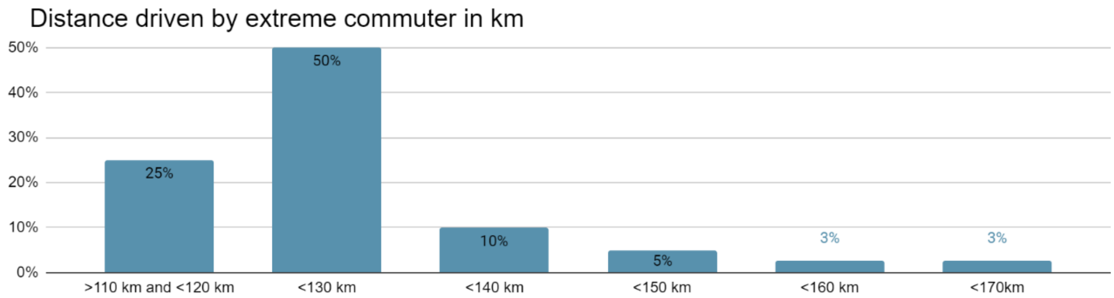


Figure 3.6 Distance distribution for the Long-distance commuter.

Ride hail drivers (3%)

Another user group, representing 7% of all charged sessions and 3% of the population, are ride-hail drivers [31]. This group represents electric taxis and comparable mobility services like Uber and Lyft. Taxis are often connected to fast chargers with a peak during lunchtime. Given that the average taxi driver drives ~132 km per day and the average driving distance for a Dutch driver is 18 km, it is here assumed that a taxi driver drives 132/18 = 7 trips per day [88] [89]. For ride-hail services, such as Uber and Lyft, the cars are often charged overnight, as the cars belong to the drivers themselves. The share of ride-hail services is growing rapidly [90]. Accordingly, for the year 2050 only ride-hail drivers are considered in this research.

Long-distance travellers (34%)

The third user group is the long-distance traveller; a person that frequently goes on a trip of more than 180 km. In The Netherlands, 85% go on holiday, of which 75% travels across borders [91]. As earlier defined 53% of the adults possess a car. For the sake of simplicity, it is assumed that all people possessing a car go by car on their long-distance trip. The share of people traveling abroad by car three times per year is then ~34%. The average long-distance trip estimated by NREL is 367 km [92]. It is here assumed that the trips across borders are (almost) always more than 180 km driving [92]. Therefore, the share of people traveling abroad is considered as a valid indication of the share of the user group of long-distance travellers.

Model assumptions	Data	Level
1. *59% of the population in DDZ is defined as the average driver. The other 41% exists of deviating user profiles, Long-distance travellers, Ride-hail drivers, and long-distance commuters.*	DDZ	1
• *The data of the ICE vehicle is assumed to be sufficient to indicate the Dutch EV user behaviour.*	-	1
• *Departure time is based on departure time data Ovin.*	[89]	2
• *The SOC threshold is fixed to the same distribution for all types of users in this research. 70% of the people decide to charge when the SOC is between 25% and 75% and the other 30% charge when the SOC is above 75%.*	[93]	2
• *There are four types of trips: weekend, day, evening, and work trips.*	DDZ	1
• *When an adult possesses a car and does not go to work, it can go on a day or weekend trip.*	-	2
• *In The Netherlands, ~54% of adults possess a car.*	[94]	2
• *From the Dutch inhabitants, 68,7% go to work of which 50% go by car.*	[94]	2
• *About 10% of the passenger car drivers drive more than 125 km per day.*	[36]	1
• *About 3% of the population are ride-hail drivers, driving on average 132 km per day in 7 trips.*	[31] [88]	1
• *The share of people traveling abroad by car driving more than 180 km in one trip is ~34%.*	[71]	1

Table 3.11 Model assumptions made about the EV driver behaviour. Level 2 assumptions are explained in Appendix C.

3.5 Model verification

An important question when using a model is "did we build the thing right?". Due to the complexity of the ABM, verification in the modelling process has been continuously executed during every change in the model. The complexity is originating from the different agents, different interactions, and different states the agents can be in. Furthermore, the fact it has been searched for an emergent pattern not known in advance makes verification inexplicable in the research. The verification has been done continuously step-by-step for every change in the model, following steps of the methodology of Deguchi [67]. This methodology and part of the application of the verification steps in this research are further explained in Appendix E.

3.6 Model experiments

Multiple experiments are simulated for the week of the 21st of January. This week specifically has been chosen as it reflects the coldest day of the year 2017 [70]. As the temperature is expected to be strongly related to the electricity consumption it is expected that the coldest week of the year will trigger the extremes in the load curve. Moreover, a scenario is simulated with the highest solar irradiance to see the impact of the solar panel during sunny conditions.

Extreme weather conditions 2017		
Min temp [°C]	*-8,7*	*21-jan*
Max solar irradiance[kWh/m₂/h]	0.194	30 May

Table 3.12 Maximum and minimum temperature in 2017.
Source: Adapted from [70]**.**

“Never trust a single run of an ABM”, was the lesson of Igor Nikolic a professor at the TU Delft, who specialized in agent-based modelling. As the behaviour in the model is unpredictable the model is run 10 times for each experiment. Accordingly, it is derived to what extent the model outcomes differ. This variation is considered in the final system cost estimation in the results. An average of the peak loads and the maximum simultaneity rates measured per run of the experiment is used for the system costs calculations. Accordingly, experiments 0, 1, and 2 were executed, representing the experiments differing between an urban, suburban, and rural neighbourhood. All additional experiments and their parameter settings can be found in Appendix F.

Experiments configuration	Experiment 0	Experiment 1	Experiment 2
urbanization degree	urban	suburban	rural
strategy	smart charging	smart charging	smart charging
Number of EVs (a, b)	100% BEV/100% SEV	100% BEV/100% SEV	100% BEV/100% SEV
Persona (Commuter; Ride-hailer; Traveller)	10/3/28%	10/3/28%	10/3/28%
public charging power 3.7; 11; 22; 50	19/67/13/1 %	19/67/13/1 %	19/67/13/1 %
private charging power 3.7; 7.8; 11 kW	uniform	uniform	uniform

Table 3.13 Parameters, variations, and the base scenario.

3.7 Summary

This chapter answered the question: “How to approximate the future residential load curve? “. To enable this an existing ABM that is made by ZEnMo Simulations is extended. The model approximated the future load curve when there is 100% BEV penetration. Two model contributions were added during this research. First, the SEV was modelled in the DDZ model. Second, the Dutch driver behaviour was revised and based on data of Dutch drivers. Also, deviant personas were added to amplify the effect of the individual behaviour on the emerging load curve. Finally, where most of the model assumptions were unsubstantiated by governmental plans or literature first, this research sketched a scenario to base the model assumptions on some of the plans for 2050 in The Netherlands. As the time span until 2050 is long, many uncertainties are still included in the scenarios.

Chapter 4: The cost-benefit analysis

Based on the shape of the load curve in phase II the local capacity requirements and national capacity requirements of the infrastructure are determined. Subsequently, the third research question is answered: "How to determine the system costs of future electric mobility?". Note that this chapter merely examines the method of determining the system costs of future electric mobility. In Appendix G the real calculations following the steps in this chapter are illustrated. In chapter 5 the results are presented.

4.1 A cost-benefit analysis (CBA)

To determine the system costs of the BEV and the SEV separately a cost-benefit analysis (CBA) has been executed. A CBA is a tool often used for policy analysis that attempts to monetize all costs and benefits of a proposed action to determine the net benefit [95]. It gives insight into the positive and negative effects of this proposed action on the welfare of society [96]. In this research including the SEV in addition to the BEV in the future energy system is the "proposed action". A CBA provides insights into the social welfare effects of the change expressed as the balance minus the costs (in euros). The advantage of a CBA is that the effects of various scenarios are compared and evaluated. The disadvantage is that CBAs deal with the uncertainty of the future and that not all effects are easy to quantify. In practice, there are often effects we cannot determine with any accuracy at all [95]. However, a CBA is useful to present what is known about the effect on system costs of different mobility types.

4.2 Phase III: From local to national capacity requirements

After modelling the future load curve and the impact of the BEV and the SEV on it in chapter 3, the local capacity requirements were determined.

4.2.1 Local capacity requirements

Chapter 2 concluded with the research flow. One of the steps that are described is the determination of the local capacity requirements. Chapter 2 also showed that the local capacity requirements are based on the maximum simultaneity rate and the peak loads for the charging infrastructure and the grid. Both metrics are derived from the approximated local load curve that is described in chapter 3. The calculation of the local capacity requirements is explained in this section.

4.2.1.1 The charging infrastructure

For the charging infrastructure capacity requirements, it is necessary to know how many charging points are required in 2050. Chapter 2 explained that the local capacity requirements in this research are based on the ratio of EVs charging at the same time to the number of EVs in a neighbourhood; the maximum simultaneity rate [39]. The maximum simultaneity rate is derived from the approximated load curve and was calculated by equation 4.1a. The number of charging points required is equal to the maximum simultaneity rate of charging times the number of EVs in a neighbourhood and the occupancy ratio. In the CBA the different prices of charging points with different charging speeds are distinguished. Moreover, the occupancy factor representing the ratio between the real occupancy of the charging point and the effective time of charging influences the local number of charging stations needed. Following Wolbertus [33] an EV in The Netherlands on average charges 20% effectively of the time that it is connected to a public charging station. Therefore, the occupancy ratio is set to 5. Private charging stations were not considered, as these are considered in the estimation of the product-level cost, which is not part of the analysis. The local capacity requirements calculation is given in equation 4.1.

$$The\ maximum\ simultaneity\ rate\ per\ charger\ type\ (S(x)) = \frac{E}{P(x)} * T(x) \qquad \textbf{(4.1a)}$$

$$Local\ charging\ capacity\ requirement\ per\ neighbourhood = \sum_{x=1}^{4} S(x) * N * O \qquad \textbf{(4.1b)}$$

Parameter definition
S (x) = The maximum simultaneity rate per charger type (x)
x= 1….4 for charging points 3.7 kW, 11 kW, 22 kW and 50 kW
E = The maximum electricity consumption of the EVs measured over a week.
P(x) = The speed of charger type (x)
T(x) = The share of available chargers of type (x)
x= 1….4 for charging points 3.7 kW, 11 kW, 22 kW and 50 kW
N = number of EVs
O = Occupancy ratio

Example charging infrastructure capacity requirement
From the DDZ model it is derived that in a year the maximum charging simultaneity rate is 20% for the BEV and 10% for the SEV in an urban neighborhood. The average distribution of the use of different chargers is uniformly distributed over 3.7, 11-, 22- and 50-kW chargers. The extra local charging capacity needed of the BEV compared to the SEV is 10 charging points in total as there are 100 EVs operational in the urban neighbourhood. As all types of chargers are used 25% of the time, the needed charging requirement per charging type is 2.5 per charging type. However, as the charging stations are occupied 5 times more than effectively needed, the charging requirement is set to 12.5 per charging station type, resulting in a requirement of 50 charging points in the neighbourhood (note that this block presents an example, not a result.)

4.2.1.1 The grid

The grid infrastructure is dimensioned in a way that the rated capacity of the grid assets is equal to the energy demand it is subject to. Accordingly, the capacity requirement of the grid is based on the peak loads that are predicted in 2050. The peak loads are derived from the ABM described in chapter 3. Similar to the former MV grid reinforcement system cost calculations of Verzijlbergh [40], this research distinguishes between LV transformers and cables as the main assets for the system cost calculations. The total load on LV transformers is measured in apparent power in Volt-Ampere (VA). The apparent power in kVA is the active power in kW divided by the Reactive Power (cos(ϕ)=0.9) [36]. A transformer is replaced by a type with a higher capacity when the threshold value is violated by the maximum peak load. A replacement by a heavier type of the same component is assumed here. The transformer capacities given by Enexis are clustered in 5 different transformer capacities of 100, 160, 250, 400, and 630 kVA. Following the Dutch Electricity act of 1998 grid operators are required to have sufficient reserve capacity [45]. Accordingly, a safety margin of 10% is included in the calculation of the capacity requirements of the grid. In this safety margin, the average energy loss of the grid of approximately 5% is also considered [97].

Example transformer capacity requirement calculation
The current transformer of Maastricht Sphinxtuin has a capacity of 100 kVA. The peak load in the year 2050 for a consumption of 100 households appears to be 119 kW. Taking a safety margin of 10% the capacity requirement increases to 131 kW. Converting 131 kW to the apparent power (kVA) the capacity requirement of the grid equals 130/0.9 = 145 kVA. The apparent power of the transformer must be higher than 162.5 kVA. Accordingly, the transformer is replaced by a transformer of 240 kVA. (Note that this block presents an example, not a result.)

Before calculating the local grid capacity requirements, it is necessary to know the status of the Dutch LV grid. Therefore, grid asset information of internal research of different DSOs in The Netherlands has been used. Data of 5000 transformers and 88.000 cables are used. Currently, there are in total 13.000 transformers and 600.000 cables for the electricity distribution in The Netherlands [5] [98].

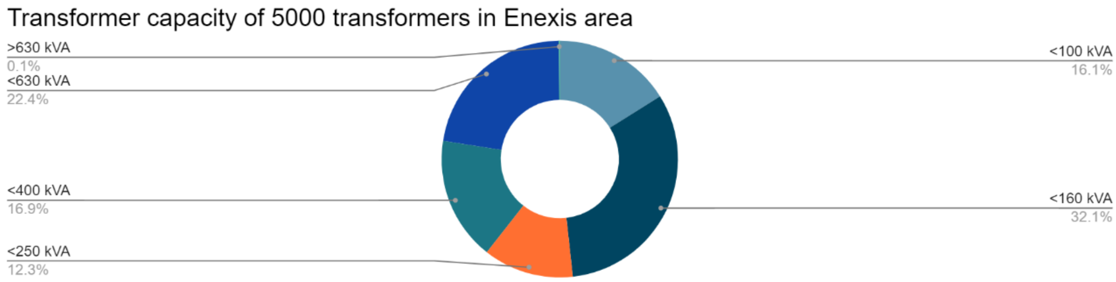


Figure 4.1 Transformer capacity distribution of 5000 transformers in the Enexis area.
[Information obtained via internal data Enexis (2007)]

To conclude about what assets need to be replaced and by what kind of assets it is necessary to know more about the grid current asset capacity. However, no more detailed information than figure 4.1 illustrates the current capacity of the transformers in The Netherlands was available. Hence, current capacities are estimated based on the former grid design method. While this method has changed over the years, here we assume that the capacity of the currently operational transformers is based on a method of ten years ago [4]. The method bases the capacity requirement on the historical peak load and the yearly peak load growth of 1% [18].

$$Current\ transformer\ capacity = f(x) = H(x) * 1.01^{l} * (1 + s) \qquad \textit{(4.2)}$$

Parameter definition
H (x)= The historical peak load of neighbourhood x.
x = 1, 2, 3 for urban, suburban, and rural neighbourhoods.
S = safety margin
l = lifetime of a transformer

Equation 4.2 is applied in the ABM that was described in chapter 3. The historical peak load H was measured in apparent power (kVA), in urban, suburban, and rural areas. The historical peak load is taken in the year 2010 and the lifetime l is set to 40 years [40]. A safety margin of 10% is assumed. Moreover, the planned capacity of the transformer that is placed in 2010 is considered in this research to be representative of all transformers in The Netherlands. While this is a strong assumption, it gives the first estimation of the current level of the transformer capacity.

Next to the capacity requirements of the transformers, the capacity requirements for the cables in the grid are considered in the cost calculations. The capacity requirements of cables exist of (1) the total length of the cables and of (2) the cable capacity measured in active power (kW). When the capacity limit of a cable is exceeded, cables are, like the transformers, replaced with a higher capacity type over the entire cable segment that was overloaded. It is assumed here that the replaced cable is always of aluminum type 150 (AL 150). When AL 150 is overloaded it is replaced by 240 AL [36]. Due to the network complexity of the cables as sketched in section 2.2.2 a full insight into the Dutch LV grid capacity is lacking [99]. Most LV cables in The

[4] It appears that the design method has changed in the past ten years due to the increasing fluctuations and unpredictability of the load curve because of the nascent energy transition.

Netherlands have unique properties and vary in cable type, cable length, and the number of connections to the cable [36]. It is considered too detailed to use all different cable types and thicknesses for this research. Moreover, following the interview with an asset manager of a DSO in The Netherlands, no link has been established between the different types of cables and the urbanization degree. Hence, this research uses former Ph.D. research [98] of Nijhuis that has been used, that clustered 88.000 cables in the network of a Dutch DSO into 26 common clusters accounting for 71.3% of the total LV network of this specific DSO. The top 5 of the clusters accounting for 35% of the Dutch distribution network are used to sketch the different cables in the distribution network. The distribution of cable types in figure 4.2 shows the distribution used for the system cost calculations in The Netherlands in this research.

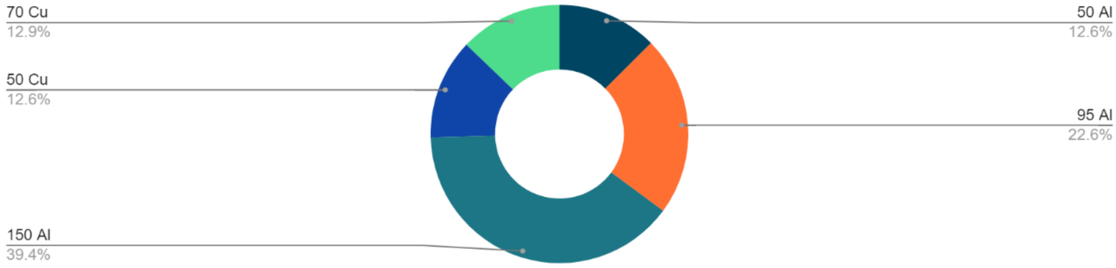


Figure 4.2 Cable capacity distribution of 88.000 cables.
Source: Adapted from [36].

The cable capacity is calculated in terms of the active power in kW. It is assumed that only 3-phase connections are placed in the neighbourhoods as this is currently the standard type of connection [36]. For 3-phase connections, the active power in kW is equal to current (A) times the voltage (V), divided by 1000. Like the transformer for the cable capacity, a safety margin of 10% is assumed.

TYPE	CAPACITY [A]	CAPACITY [KW]
50 AL	115	26.4
95 AL	175	40.25
150 AL	230	52.9
50 CU	125	28.7
70 CU	155	35.65

Table 4.1 Cable properties.
Source: Adapted from [38] [36].

Now there is an estimation about the status of the grid and the capacity requirement, it is necessary to know how the dimensions of the cables are determined. The average number of customers per cable is 23 households [36]. Hence, the number of cables is estimated by the number of households in a neighbourhood divided by 23. The total electricity grid in The Netherlands alone consists of 600.000 cables that account for 300.000 km of LV cable and 8 million connections [98]. As in the ABM model, the number of households per type of neighbourhood varies, the average length of the cables per household is determined by dividing the number of connections divided by the total km of the cables in The Netherlands: 37.5 meters per household. A senior asset manager at a DSO in The Netherlands stated that the length of the cable differs per type of degree of urbanization; the cables are longer in rural areas and shorter in urban areas (see Table 4.2). The length of the total cables per neighbourhood is the number of household connections times the average length of the cable per neighbourhood. When an urban neighbourhood has 129 grid connections the cable length is estimated at 3870 meters.

Cable dimensions	*number of households*	*Number of cables per neighbourhood*	*meter cable per household (m)*	*meter cable needed in the neighbourhood (m)*
Urban	129	5.6	25	3870
sub-urban	85	3.7	37.5	3187.5
rural	43	1.9	50	1935

Table 4.2 Cable dimensions per type of neighbourhood.
Source: Adapted from [98].

Example cable capacity requirement calculation
In Maastricht Sphinxtuin, the peak load in the year 2050 for a consumption of 130 households appears to be 185 kW. The number of cables is 130/23 = 5.6. This means that the capacity of the cables in total is calculated by multiplying the capacity of the cable's times 5.6. In this case it is assumed that the capacity of all the 50 AL cables for all urban areas in The Netherlands is exceeded as the 50 AL cables have a capacity of 26.4 * 6 * 1.10 = 174.2 kW including the safety margin of 10%. This means that in urban areas, 12.6 % of the 50 AL cables need to be replaced, by a 150 AL cable with a capacity of 214 kW. (Note that this block presents an example, not a result.)

4.2.2 National capacity requirements

Now the method of determining the local capacity requirements is defined, the requirements are extrapolated to national capacity requirements. Three neighbourhoods are simulated distinguishing between rural, suburban, and urban characteristics. The characteristics of these areas are stated below in Table 4.3 [100]. Looking in the DDZ model; Maastricht Sphinxtuin, Venlo-Zuid, and Venlo Belfeld are respectively belonging to the areas that are called urban, suburban, and rural, having 130, 88, and 43 households, respectively.

Urbanization category	*People per km$_2$*
Urban	<1500
Sub-urban	< 1000 and >1500
Rural	<1000

Table 4.3 The definition of rural, suburban, and urban defined by the CBS.
Source: Adapted from [100].

The assumption here is that specific reinforcement costs per different neighbourhoods are representative of the rest of The Netherlands. While this is a strong assumption, it gives the first estimation on the range of system costs needed to promote the mass deployment of BEVs and SEVs in The Netherlands. The system costs per neighbourhood are extrapolated to the ratio between the different types of areas in The Netherlands shown in figure 4.3.

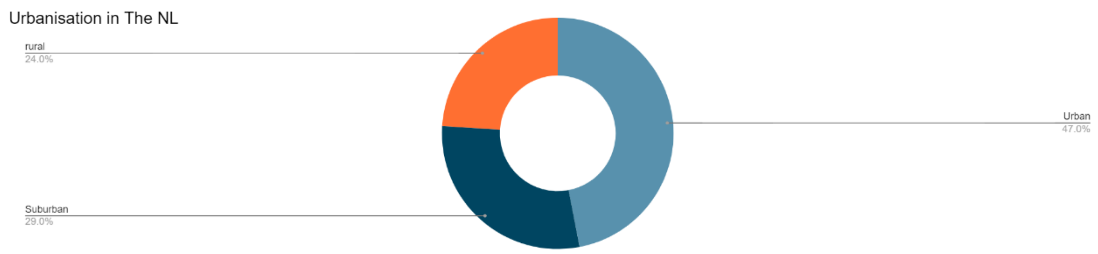


Figure 4.3 Division between rural, suburban, and urban areas in The Netherlands.
Source: Adapted from [101].

As there are currently ~8 million households in The Netherlands the number of urban, suburban, and rural neighbourhoods could be determined [101]. Subsequently, the capacity requirements are scaled up proportionally to national requirements.

Neighbourhoods in The Netherlands	
The number of households in The Netherlands.	8M
The average number of households per neighbourhood.	96
The number of neighbourhoods The Netherlands.	85.000
The number of neighbourhoods urban (47%).	40.000
The number of neighbourhoods suburban (29%).	25.000
The number of neighbourhoods rural (24%).	20.000

Table 4.4 The number of urban, suburban, and rural neighbourhoods in The Netherlands.
Source: Adapted from [101].

4.3 Phase IV: The system costs

Out of the national capacity requirements, the system costs are calculated. Therefore, the system costs for both the SEV and the BEV are indirectly derived from the DDZ model. Here the final equations used for calculating the system costs are explained.

4.3.1 Charging investment need

The capital expenditures (CapEx) of the charging infrastructure are mainly dependent on the costs for the charging points and the installation of the charging points. The costs vary according to the power of the type of charger. Equation 4.3 shows how the charging investment costs are determined of which the x is defined in Table 4.5.

$$Charging\ investment\ need = \sum_{n=1}^{3} \sum_{x=1}^{5} S\ (x)\ *\ Nev * C(x) *\ N(n) \qquad \textbf{\textit{(4.3)}}$$

Parameter definitions
S (x) = The maximum simultaneity rate per charger type (x)
Nev = The number of EVs that are available in a neighbourhood
C (x) = Costs in € per charger type (X).
x= 1….5 for charging points 3.7 kW, 11 kW, 22 kW and 50 kW.
N (n) = The number of type n of neighbourhood on national scale.
N = 1, 2, 3 for urban, suburban, and rural neighbourhoods.

The asset costs of the different chargers are derived from Transport & Environment [13] and are illustrated in Table 4.5. Only the capital expenditures (CapEx) of the charger are considered expressed in installation, equipment, and grid connection costs. The operational expenditures, such as maintenance costs, are not expected to be different for the use of the BEV and the SEV and are not considered. The life length of a charging spot is estimated at 10–15 years [102]. Hence it is assumed that the status of the charging infrastructure is not necessary to consider when calculating the costs of the charging infrastructure. Finally, no learning effects were considered in these prices.

x	Charger	CapEx 2020 [€]
1	Public 3.7 kW	€3400, -
2	Public 11 kW	€3950, -
3	Public 22 kW	€4500, -
4	Public 50 kW	€31000, -

Table 4.5 Costs of different charging stations.
Source: Adapted from [13].

The costs of the leisure location and the weekend trip chargers are assumed to be equal to the chargers at work.

4.3.2 Grid investment need

Capacity requirements of the grid have historically been dependent on the expected peak demand [18]. The total costs of the grid are the replacement and energy loss costs of all grid assets. Similar research of Lukzo [40] calculating the system costs for the MV grid, used equation 4.4 for the calculation of the system costs of the grid. In this research study equation, 4.4 has been derived from Lukzo's research [40]. Only the energy losses are not considered, as these are considered in the safety margin of 10% that was validated by a senior asset manager of a DSO in The Netherlands.

$$Grid\ investment\ need = \sum_{n=1}^{3}(C_{trans} + l_{cable}\ C_{cable}) * N(n) \qquad \textbf{(4.4)}$$

Parameter definitions
C_{trans} = The material and installation costs of a transformer. [€]
C_{cable} = The material and installation costs for one kilometre of cable [€]
L_{cable} = Length of a cable [km]
N (n) = The number of type n of neighbourhood on national scale
N = 1, 2, 3 for urban, suburban, and rural neighbourhoods

The transformer and cable costs are given in Table 4.6 and Table 4.7 and are derived from the internal data of a DSO in The Netherlands. The costs of the 150 AL cables are estimated at €47, - €42, - and €37, - per meter for urban, suburban, and rural areas. These are determined in response to an interview that was held with a DSO in The Netherlands. If the 150 AL cables have been overloaded these 240 AL cables are replaced at additional costs of €12, - per meter. As the charging infrastructure, only the CapEx is considered in the cost calculations.

Costs of transformer reinforcement

Trafo category	Material & installation material	Installation costs	Total (excl.)	Taxes (10%)	Total (incl.)
[kVA]	[€)	[€)	[€)	[€)	[€)
100 kVA	€ 4,000	€ 1,000	€ 5,000	€ 500	€ 5,500
160 kVA	€ 6,000	€ 1,000	€ 7,000	€ 700	€ 7,700
250 kVA	€ 7,000	€ 1,000	€ 8,000	€ 800	€ 8,800
400 kVA	€ 11,000	€ 1,000	€ 12,000	€ 1,200	€ 13,200
630 kVA	€ 16,000	€ 1,000	€ 17,000	€ 1,700	€ 18,700

Table 4.6 Costs of transformer reinforcements.
[Information obtained via internal information of a DSO in The Netherlands.]

	Costs per meter material (AL 150)	Extra costs (AL 240)	installation costs per meter	extra costs per meter	total costs per meter (50AL)
Urban	€12	€12	€20	€15	€47
sub-urban	€12	€12	€15	€15	€42
rural	€12	€12	€10	€15	€37

Table 4.7 cost breakdown cables.
[Information obtained via internal information of a DSO in The Netherlands.]

4.3.3 The total system costs

The value of money changes during the years until 2050 and is considered in the calculation of the system costs. Based on this the NPV value is calculated with an of 1.65%, the current Dutch interest rate [40].

$$TSC_{system} = \frac{TSC}{(1+r)^{t-t_0}} * P_{growth} \qquad \textbf{(4.5)}$$

Parameter definitions
TSC = Total system costs. [€]
R = Dutch interest rate [%]
P_{growth} = growth of the population [%]

In the equation, 4.5 t is 2050 and t_0 is 2017 as the simulated scenario is 2050 and the data for calculating the load curve has been derived from data of 2017. The NPV has been calculated for both the SEV and the BEV. Consequently, the TSC_{system} is calculated for the SEV and the BEV. Finally, the growing population is considered in the analysis. A report of Netbeheer Nederland [9] states the number of connections is expected to rise by around 19% until 2050. Hence the TSC is calculated with a population growth factor (P_{growth}) of 1.19.

4.4 Summary

A CBA is used to determine the system costs of electric mobility. Where a CBA is a good tool for comparing the effects of various scenarios, it is also recognized here that the long-time span of the research and the belonging assumptions causes the system costs to be unpredictable in the future. However, the CBA is considered useful to present what is known about the effect on system costs of different mobility types. Subsequently, a considerable number of assumptions were made to enable system cost calculations. These calculations are shown in Appendix G. Here below a summary of all then belonging assumptions is given:

Cost calculation assumptions	*Source*
• *The local capacity requirements are here based on the share (%) of the number of the maximum EVs charging at the same time, also called the maximum simultaneity rate of charging. In this research, it is assumed that EV owners need to be able to charge their EV at any moment.*	[13]
• *The grid infrastructure is dimensioned such that the rated capacity of the grid assets is equal to the energy demand they are subject to, including a safety margin of 10%.*	[18]
• *The specific reinforcement costs per different neighbourhood (urban, suburban, and urban) are representative of the rest of The Netherlands. The system costs are extrapolated proportionally to the number of urban, suburban, and rural neighbourhoods in the NL.*	-
• *An occupancy ratio of 5 is assumed, reflecting the ratio of the average time that an EV user is occupying a charging point to the effective time the EV is charging.*	[33]
• *This research uses grid asset information of internal research of different DSOs in The Netherlands. Data of 5000 transformers and 88.000 cables are used.*	-
• *The capacity of a transformer currently operational is based on a method of ten years ago. The planned capacity of the transformer that was placed in 2010 is assumed in this research to be representative of all transformers in The Netherlands. This method is based on the yearly demand, the lifetime of a grid asset, and a growth rate of demand of 1%. The electricity demand of heat pumps, EVs, and electric cooking appliances is not considered here.*	-
• *A transformer is replaced by a type with a higher capacity when the threshold value is violated by the maximum peak load. A replacement by a heavier type of the same component is assumed here.*	-
• *The capacity of cables currently is based on a Ph.D. research of Nijhuis that clustered 88.000 cables in the network of a Dutch DSO into 26 common clusters accounting for 71.3 % of the total LV network of this specific DSO.*	[98]
• *Only 3-phase cable connections of 150 AL are placed in the neighbourhoods. If these are overloaded on the first instance 240 AL cables are placed.*	[36]
• *As in the ABM, the number of households varies, the average length of the cables per household is determined by dividing the number of connections divided by the total km of the cables in The Netherlands: 37.5 meters per household. The cable length varies depending on the neighbourhood (urban, suburban, or rural).*	[98]
• *The asset costs of the different chargers are derived from Transport & Environment. No learning effects are considered in these prices.*	[13]
• *The asset costs for the grid are derived from a DSO in The Netherlands.*	-

Table 4.8 Summary of all assumptions for operationalizing the system costs of electric mobility.

Chapter 5: Results

'To what extent would mass adoption of SEVs influence the system costs of electric mobility? This chapter describes the general results that have been acquired during this research by going through the two methods that are described in chapter 3 and 4. The results are presented in a backward order of the steps presented in the research flow diagram in Figure 2.12. First, the system costs are presented. Second, the local and national capacity requirements and the results that were retrieved from the ABM are shown and explained. Afterward, three factors that were determined in the scenario and have a high impact on the system costs are presented. Finally, nuance was made on the system cost estimations and a sensitivity analysis was performed. The exact CBA calculations are presented in Appendix G.

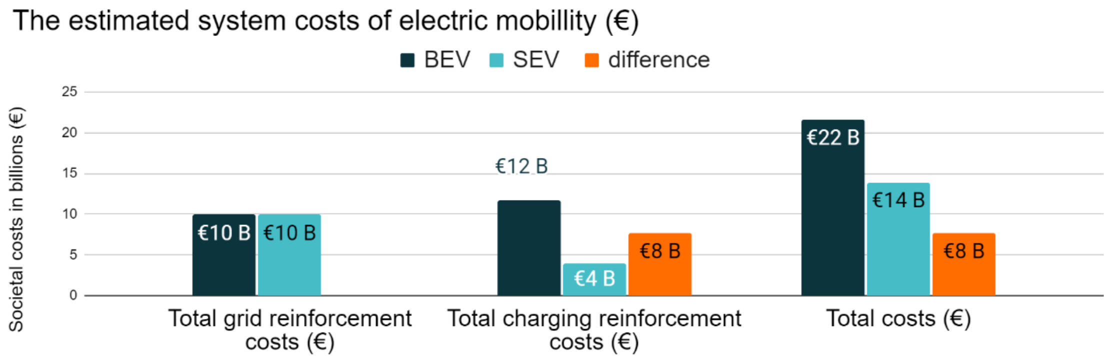


Figure 5.1 The estimated system costs of electric mobility.

The results in figure 5.1 show that the mass adoption of the SEV would save ~65% of the system costs for the charging infrastructure until 2050. In the cost overview, it is shown that the charging infrastructure primarily influences the cost savings that could be realized when the SEV takes a dominant position in the future mobility system. A difference in costs of up to ~€8 billion is estimated in 2050. The results show that no additional grid reinforcements are needed until 2050 when the BEV dominates the future mobility system.

The estimated system costs of electric mobility

National system costs	100% BEV	100% SEV	difference
Grid reinforcements costs	€10 B	€10 B	€0
Charging reinforcement costs	€12 B	€4 B	€8 B
TOTAL	€22 B	€14 B	€8 B

Table 5.1 System costs of electric mobility at 100% BEV and SEV penetration level.

Cost-breakdown per neighbourhood				
Experiment 0: urban				
Grid reinforcements		*100% BEV*	*100% SEV*	*difference*
	Transformer	€0	€0	€0
	Cables	€7 B	€7 B	€0
Charging infrastructure reinforcements	*Charging points*	€6 B	€2 B	€4 B
TOTAL		€13 B	€9 B	**€4 B**
Experiment 1: suburban				
Grid reinforcements		*100% BEV*	*100% SEV*	*difference*
	Transformer	€0.1 B	€0.1 B	€0
	Cables	€2 B	€2 B	€0
Charging infrastructure reinforcements	*Charging points*	€4 B	€1 B	€3 B
TOTAL		€6 B	€3 B	**€3 B**
Experiment 2: rural				
Grid reinforcements		*100% BEV*	*100% SEV*	*difference*
	Transformer	€0.1 B	€0.1 B	€0
	Cables	€1 B	€1 B	€0
Charging infrastructure reinforcements	*Charging points*	€2 B	€1 B	€1 B
TOTAL		€3 B	€2B	**€1 B**

Table 5.2 Total system costs of electric mobility for urban, suburban, and rural neighbourhoods.

5.1 The capacity requirements for the system

Chapter 4 explained that national system capacity requirements indicate the system costs in 2050. These national system capacity requirements are based on the local capacity requirements and are roughly extrapolated based on the number of urban, suburban, and rural neighbourhoods in The Netherlands. The local capacity requirements are based on two metrics that were retrieved from the approximated local load curve modelled in the ABM. These two metrics are the peak loads and the maximum simultaneity rate, indicating the local grid capacity requirement and the number of charging stations required locally. This section presents the local and national capacity requirements of the grid and explains this by showing and explaining the peak loads and the maximum simultaneity rate that were retrieved from the ABM.

5.1.1 The charging infrastructure

System cost reduction presented in Table 5.1 and Table 5.2 originates from a decrease of required charging stations for the SEV fleet compared to the BEV fleet. In chapter 4 it was explained that the capacity requirements for the charging infrastructure were derived from the maximum simultaneity rate in a neighbourhood. The modelled simultaneity rate over time is presented in figure 5.2. The maximum simultaneity rate per neighbourhood is shown in Table 5.3 and corresponds to the number of charging stations that are found necessary to place in the belonging neighbourhoods. The number of charging stations is extrapolated to the national capacity requirement, proportional to the number of urban, suburban, and rural neighbourhoods in The Netherlands (see Appendix G). The results show that the difference in the required number of charging stations for neighbourhoods is estimated to be nationally up to 3 times lower for the SEV compared to the BEV. Consequently, it was found that there are ~3 and 1 million charging stations needed in case of mass deployment of the BEV and the SEV in the mobility fleet of 2050.

Max simultaneity	Number of cars per neighbourhood	100% BEV	100% SEV	Required number of charging points BEV nationally	Required number of charging points SEV nationally
Urban	100	8.5%	2.8%	1.700.000	500.000
Sub-urban	65	11.7%	4%	900.000	300.000
rural	33	12.7%	4.9%	400.000	200.000

Table 5.3 The charging requirement in a neighbourhood and nationally.

The absolute simultaneousness of charging

Note: *The graphs in Figure 5.2 show an average of the ten runs, that were executed per experiment. Accordingly, the average of the maximum simultaneity rates of the ten runs that are used for the system costs calculations lie higher than the peaks that are illustrated in the graphs in Figure 5.2.*

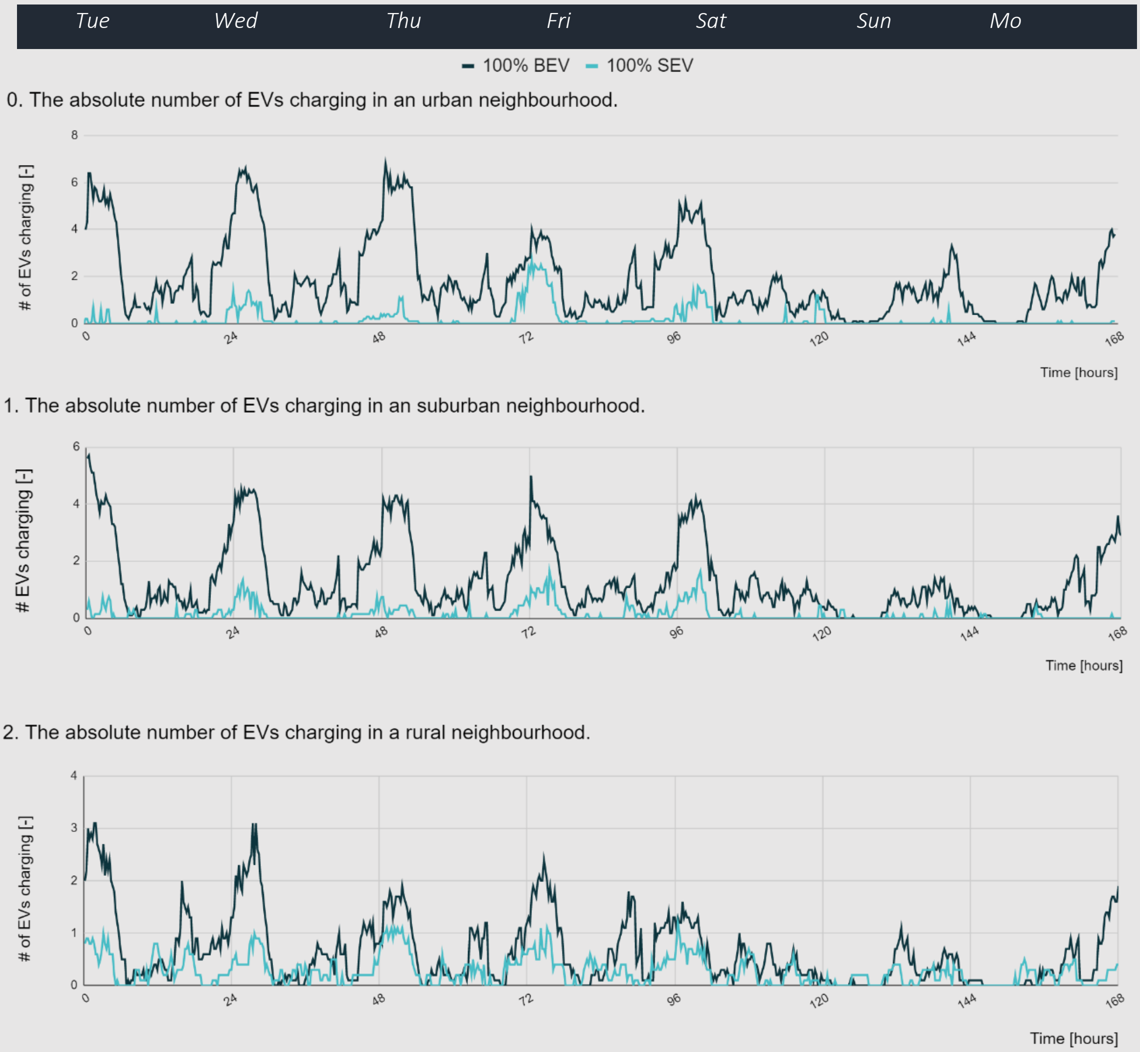


Figure 5.2 The absolute number of EVs charging at the same time on average in different neighbourhoods.

5.1.1.1 *Specific difference SEV vs BEV*

The first results show that the SEV has a maximum electricity consumption that is almost three times less than that of the BEV. This specific difference mainly originates from the driving behaviour that is influenced by the energy yields of the solar roof and the lower energy consumption of the SEV, combined with a smart charging strategy. According to a simple hand calculation, the cumulative solar electricity generated and the high efficiency of the SEV were good for already ~61% of the reduction in electricity consumption in a week. Following the results, the reduction of the required number of charging stations for the SEV is presented to be 65%. The 4% discrepancy specifically is caused by the charging behaviour that is caused by the integrated solar panels of the SEV. The longer a SEV user waits until the next charging moment, the higher the solar electricity that is generated between the charging sessions. The amount of solar electricity generated before each charging moment is therefore also dependent on the driving behaviour of the SEV driver. The distance driven per day for example influences how fast the SOC threshold is reached and how much solar electricity could be stored in the vehicle's battery. Next to the trip distance and the SOC threshold, the moment of departure is important for the electricity consumption of a SEV user. The SOC threshold theoretically could be lower for the SEV, when there is an insight into the future solar irradiation and the future moment of departure and driving distance. The optimal situation is that the cumulative electricity consumption of the SEV is equal or lower to the cumulative income of the solar panel ensuring that the state of charge (SOC) always remains above its threshold. Besides, the importance of the factors above section 5.1.1 explains that the cost reduction is also influenced by the smart charging strategy. Recapitulatory, the specific model outcomes discussed here are primarily dependent on the driving behaviour, the efficiency of the EV, the solar irradiation, and the smart charging strategy.

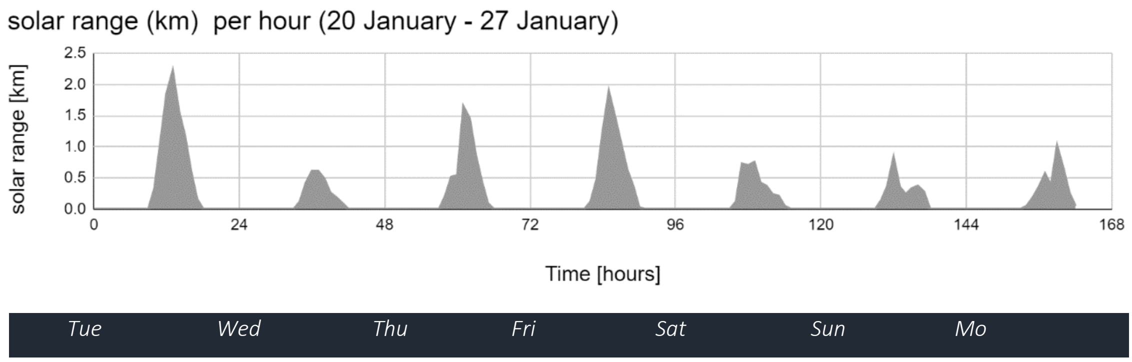


Figure 5.3 Solar range (km) per hour in the coldest winter week.

In contrast to the mentioned differences between the BEV and the SEV, the similarities are explained in Appendix H.

5.1.2 The grid

Tables 5.1 and 5.2 showed that no difference in system costs was found for the grid in the case of 100% BEV penetration compared to 100% SEV penetration. The costs of the grid are determined by the share and costs of grid assets that need to be replaced until 2050. Chapter 4 explained that the grid infrastructure is dimensioned such that the rated capacity of the grid assets is equal to the energy demand they are subject to. Two ingredients were necessary to estimate the costs of integrating an EV into the system: (1) the current status of the grid assets and (2) the peak loads the grid is subject to in 2050. Table 5.4 shows the peak loads that the grid is subject to in 2050 according to the model results of the ABM. Table 5.5 subsequently shows the herewith share of grid reinforcements that are needed based on the current status of the grid. The status of the grid was estimated based on a method and data of a DSO in The Netherlands, utilizing the ABM. This is described in Appendix G.

Max peak load [kW]	*100% BEV*	*100% SEV*
Urban	318 kW	280 kW
Sub-urban	165 kW	150 kW
rural	88 kW	82 kW

Table 5.4 The capacity requirements of the grid in different neighbourhoods.

Even though there is a difference measured in the peak loads, the SEV does not cause more grid assets to be overloaded than the BEV. The relatively small difference between the peak loads, causes the BEV and the SEV to be in the same range of capacity requirements for the grid assets. Hence, no difference is measured in system costs for the grid. The predicted overloaded grid assets per neighbourhood are illustrated in Table 5.5. The results show that many grid assets need to be replaced in different areas. The calculations show a rough estimate as there was little information available about the current level of the grid assets in The Netherlands.

Grid assets to be replaced in 2050 (%)	*Transformer*	*cables*
100% SEV/BEV		
Urban	0%	100%
Suburban	72.3%	60.6%
rural	100%	60.6%

Table 5.5 Share of grid assets that need to be replaced until 2050.

Figures 5.4 and 5.5 show that the impact of the SEV and the BEV in terms of peak loads (kW) on the grid differs slightly. The peak loads for the BEV scenario are higher than the peak loads for the SEV scenario. This is a consequence of the difference in the technical characteristics of the EVs: the SEV has a lower energy consumption and generates electricity by its solar panel. From the analysis in section 5.1, it was already explained that the SEV needs to charge ~3 times less during rush hours compared to the BEV in winter. The reason that the difference is only small, is explained by the 69% effective smart charging strategy. The 69% effective smart charging strategy incentivizes EV users to charge their EV during off-peak hours. Therefore, most EVs charge during the night. The assumption that not all EV users adhere to the smart charging strategy despite its financial benefits, causes part of the EV users to charge during peak hours. Hence, the charging behaviour plays a role in determining the peak loads. Because the charging need for the SEV is lower than the charging need for the BEV, a small difference in peak loads is found. The presented difference in peak loads is therefore originating from the combination of the charging behaviour, the technical characteristics of EVs, and the smart charging strategy.

The residential load curve BEV

Note: *The results in Figures 5.4 and 5.5 average of the load curves of ten runs per experiment, derived from the ABM. Accordingly, the peak loads that are used for the system costs calculations lie higher than the peaks that are illustrated in the graphs in Figures 5.4 and 5.5.*

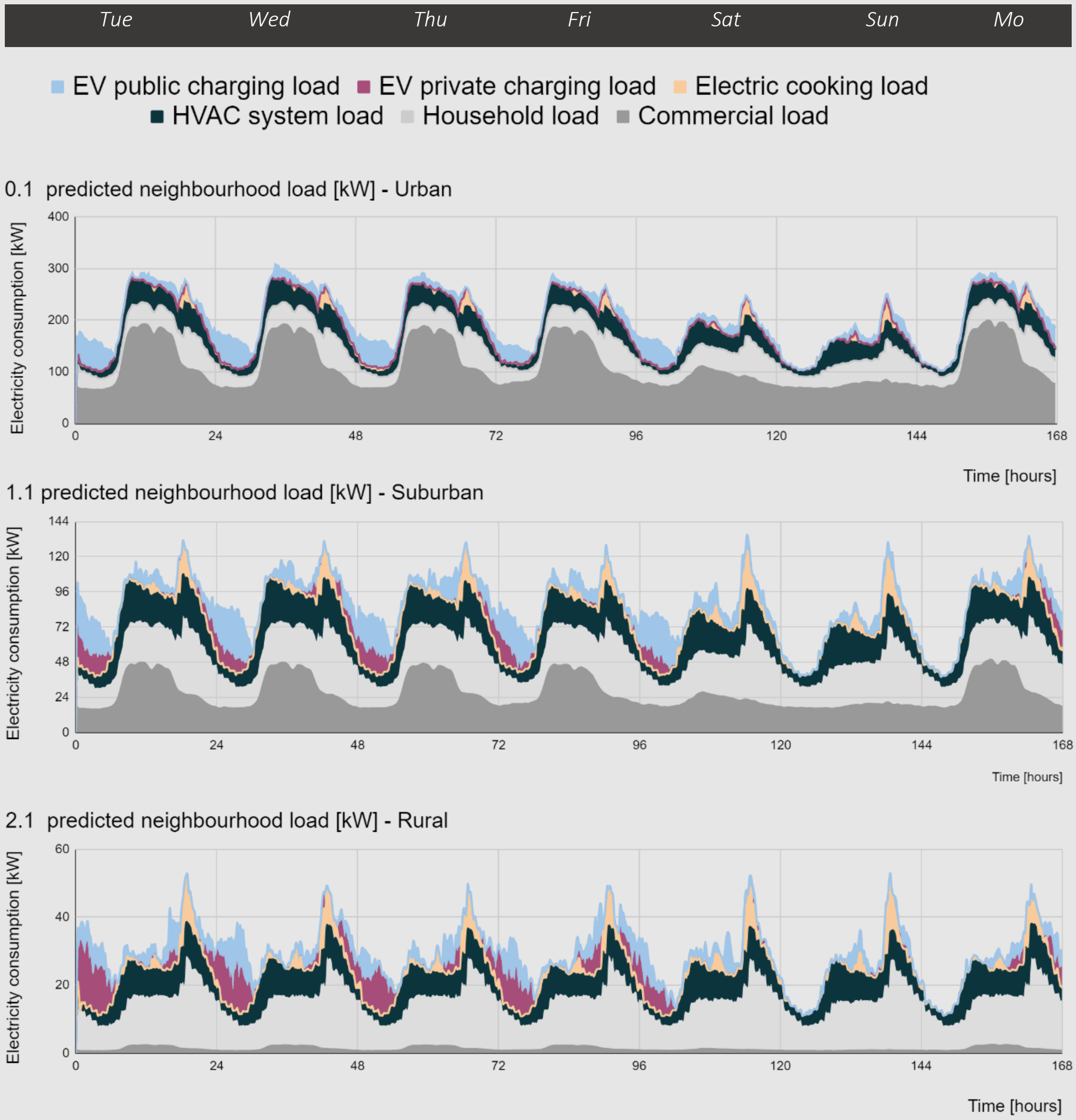


Figure 5.4 Local load curve at 100% BEV penetration in urban, suburban, and rural neighbourhoods.

The residential load curve SEV

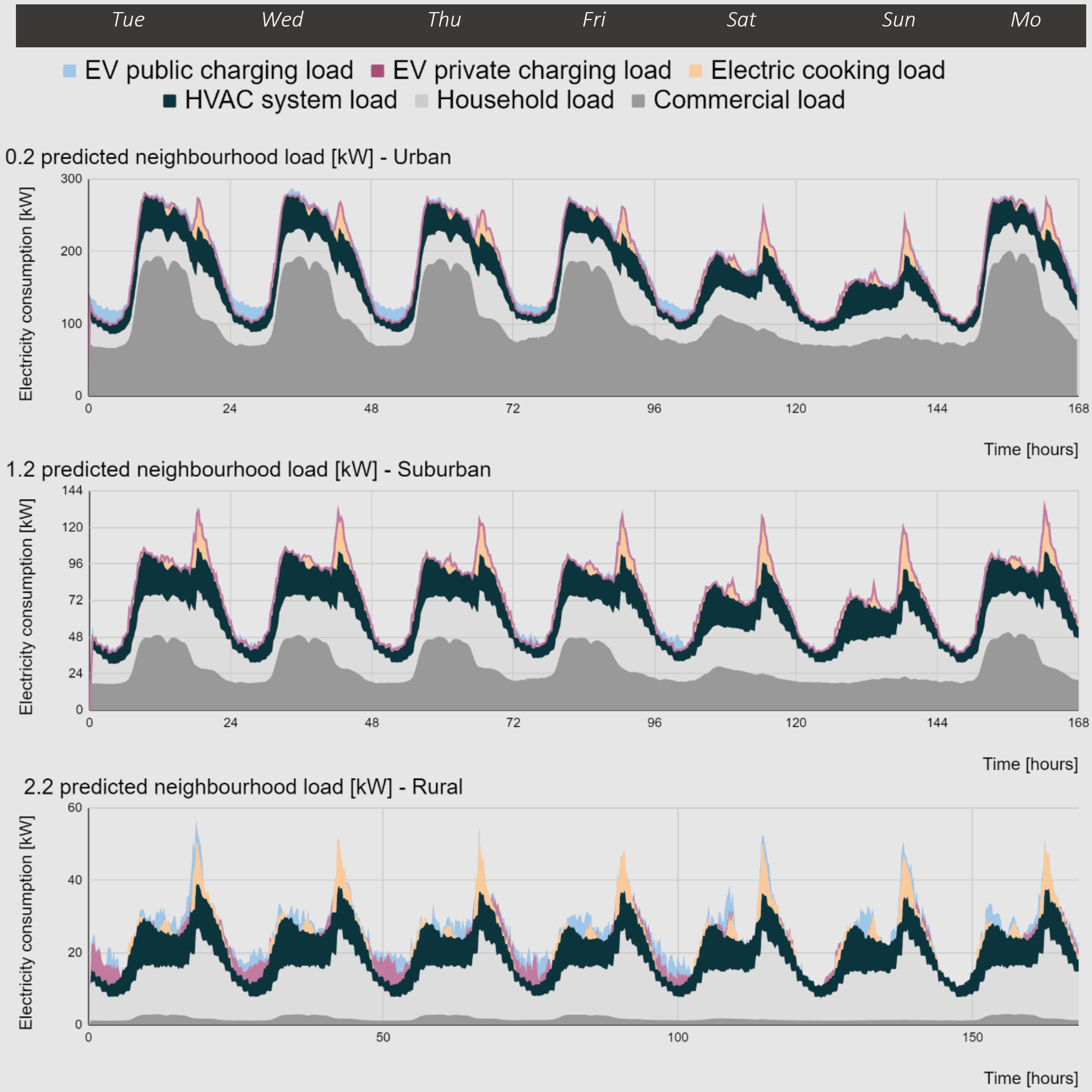


Figure 5.5 Local load curve at 100% SEV penetration in urban, suburban, and rural neighbourhoods.

5.1.3 Impact factors

The general results that are explained, are greatly dependent on how the future energy system will emerge. Many factors influence the system costs of electric mobility. In the upcoming section, more details are given about the three aspects that are found to have a large influence on the shape of the load curve, and therefore the system costs. Accordingly, the analysis focuses here on the impact of smart charging, the integrated solar panel, and the energy consumption on the system costs. Note that these results are only expressed in terms of maximum simultaneity rate and the peak loads and therefore indirectly tell something about the system costs. Moreover, the results have only been acquired for the urban areas.

5.1.3.1 The impact of smart charging

As already followed from the results, the impact of smart charging influenced the system costs estimations for the SEV and the BEV. Where in the main model results presented earlier in this chapter, 69% of the EV owners are incentivized to charge their car during off-peak hours, no specific charging strategy is incorporated in this scenario. Looking at the results for the charging infrastructure the maximum simultaneity rate at 100% BEV and SEV penetration increases by 28% and 48% respectively. This is a logical consequence of uncontrolled charging. People have no incentive to charge their EV at planned times, during off-peak hours. EV users do not apply their planning of charging to the already planned charging sessions of other cars and charge their car when it suits them best. Compared to the load curve including a smart charging strategy, the load is shifted from midnight to the late evening. Moreover, the peaks are 27% and 12.5% higher than with a smart charging strategy for the BEV and the SEV, respectively. Accordingly, it is expected that the smart charging strategy plays a big role in reducing the system costs, especially for the BEV.

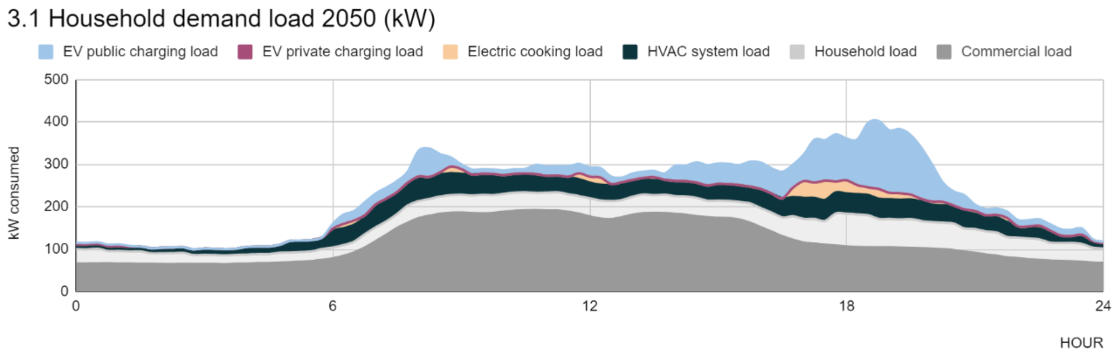


Figure 5.6 Neighbourhood demand at 100% BEV penetration in an urban neighbourhood in winter without applying a charging strategy.

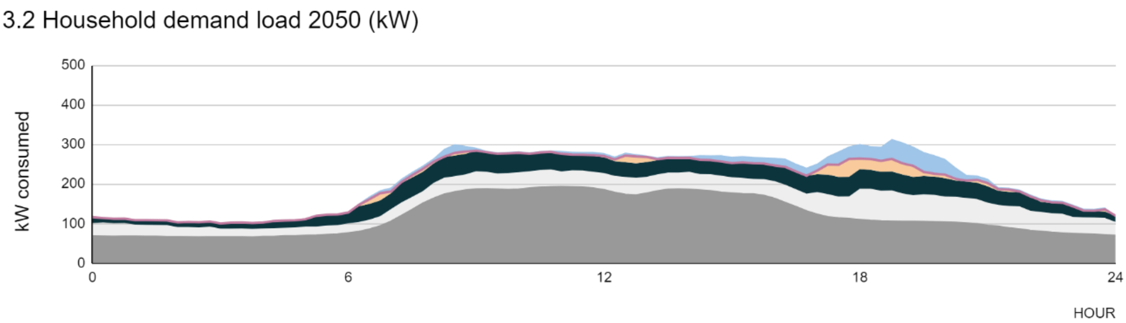


Figure 5.7 Neighbourhood demand at 100% SEV penetration in an urban neighbourhood in winter without applying a charging strategy.

Experiment 3	*BEV*	*SEV*
Max peak load (kW)	405 kW	315 kW
Max simultaneity (public)	12.6%	3.6%
Base scenario peak loads:	318 kW	280 kW
Base scenario max simultaneity (public)	8.5%	2.8%

Table 5.6 Experiment results for an urban neighbourhood without a charging strategy.

The results imply that the smart charging strategy is more effective for the BEV than for the SEV as the maximum peak load in the case of the 100% BEV-fleet increased respectively more than the maximum peak load of the 100% SEV-fleet. Moreover, they imply that for optimal use of the charging infrastructure, it is favourable to apply a smart charging strategy in the case of both the SEV and the BEV.

5.1.3.2 The impact of the sun

The impact of the SEV on the system costs of electric mobility is presented for the coldest winter week. In this winter week, ~35 km extra solar range could be generated by the electricity generation of the solar panel. To find out what happens when the solar irradiance is higher an extra experiment in the week with the highest solar irradiation has been executed; the week of May 25 till June 1 in 2017. In this week extra solar power is generated equivalent to a range of ~318 km for a SEV. This is on average ~45 km per day, overwriting the distance that is on average driven by the Dutch average driver (18 km).

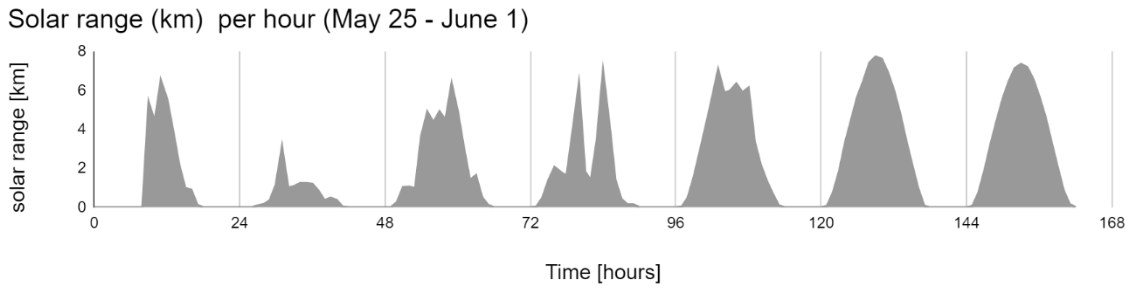


Figure 5.8 The solar irradiation in the week with the highest solar irradiance from May 25 – June 1, 2018.

The results in Table 5.7 show that the maximum simultaneity rate for the SEV decreases compared to the results presented before. Where the impact on the charging infrastructure in the base scenario first was 3 times less for the SEV compared to the BEV, the SEV could decrease the impact on the charging infrastructure with a factor of ~8 compared to the BEV in a week with high solar irradiation. This is a logical consequence of the higher solar electricity generation of the SEV, making the electricity consumption of the SEV users minimal. The peaks in the load curve decrease by 6% due to the decentralized solar power generation; less electricity from the grid is required to satisfy the power demand. These results show that the electricity consumption for the SEV user differs per season. They show that the SEV can almost become grid-independent in weeks of high solar irradiation.

Experiment 4	BEV	SEV
Max peak load (kW)	305 kW	270 kW
Max simultaneity (public)	8.5%	1.1%
Base scenario peak loads:	318 kW	280 kW
Base scenario max simultaneity (public)	8.5%	2.8%

Table 5.7 Experiment results in the week with the highest solar irradiation.

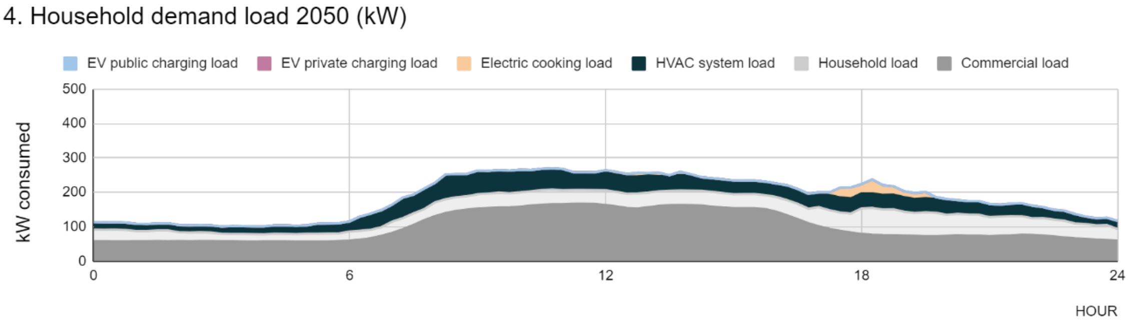


Figure 5.9 Neighbourhood demand at 100% SEV penetration in an urban neighbourhood in the week with the highest solar irradiation.

5.1.3.3 *The impact of the EVs efficiency*

Another analysis has been performed to explore what happens if the SEV would not have a solar roof, and is solely a high-efficient electric vehicle. The results in Table 5.8 show that the SEV without a solar roof has ~44% less impact on the required charging infrastructure than the BEV. This is solely caused by the lower energy consumption of the SEV; the WLTP energy consumption is ~45% lower than the WLTP consumption of the BEV. The results show that the solar roof influences the system's impact on the charging infrastructure considerably. Subsequently, the size of the effect of the solar electricity generation and the electricity consumption on decreasing the maximum electricity consumption of EVs was derived and is illustrated in figure 5.10. Concerning the impact of the SEV without a solar roof on the grid, the peak loads grow by 3%.

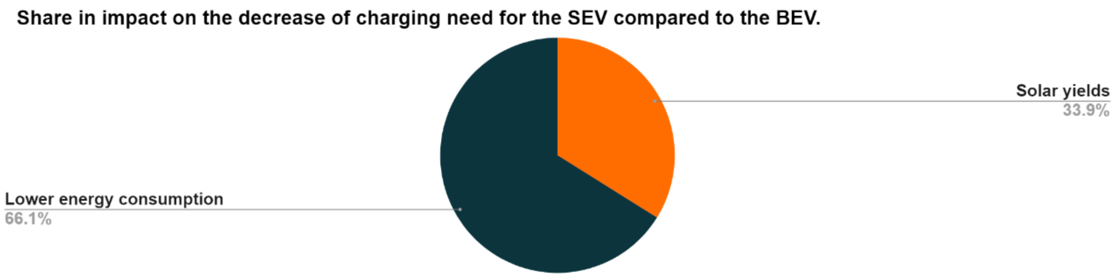


Figure 5.10 Share in impact on the decrease of the charging need for the SEV compared to the BEV.

Experiment 5	*BEV*	*SEV*
Max peak load (kW)	318 kW	295 kW
Max simultaneity (public)	8.5%	4.5%
Base scenario peak loads:	318 kW	280 kW
Base scenario: Max simultaneity (public)	8.5%	2.8%

Table 5.8 Experiment results in the week including SEV without the solar roof.

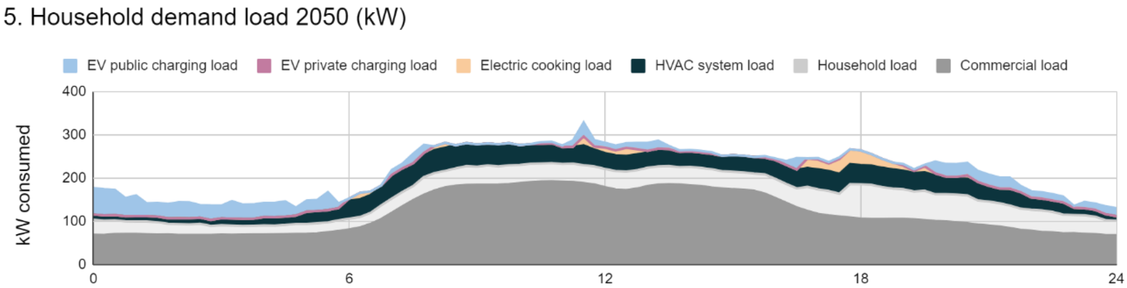


Figure 5.11 Neighbourhood demand at 100% penetration of SEVs without a solar roof in an urban neighbourhood in winter.

5.2 The estimated system costs of electric mobility

Based on the national capacity requirements and the costs for grid assets and charging stations the system costs could be determined. The system costs that were already presented in figure 5.1 show the results of an average estimated system capacity requirement. The national capacity requirement was derived from the local capacity requirement, which is based on the maximum simultaneity rate and the peak loads retrieved from the approximated local load curve. For determining the maximum simultaneity rate and the peak loads the average of these values of ten runs per experiment in the ABM was considered in the average cost calculations (Appendix G). However, a more nuanced oversight is given here on the system costs of electric mobility; the extreme outcomes of the experiments were analysed in the CBA following the steps in chapter 4. The best-case model outcomes are the outcomes with the lowest maximum simultaneity rate and the lowest peak loads, causing the lowest system costs. The worst-case model outcomes are the outcomes with the highest maximum simultaneity rates and the highest peak loads. The specific model outcomes are presented in Appendix I. Following the system cost calculations, the cost difference between the SEV and the BEV is ranging between €7.4 billion and €8.5 billion in the best- and worst-case scenarios, respectively.

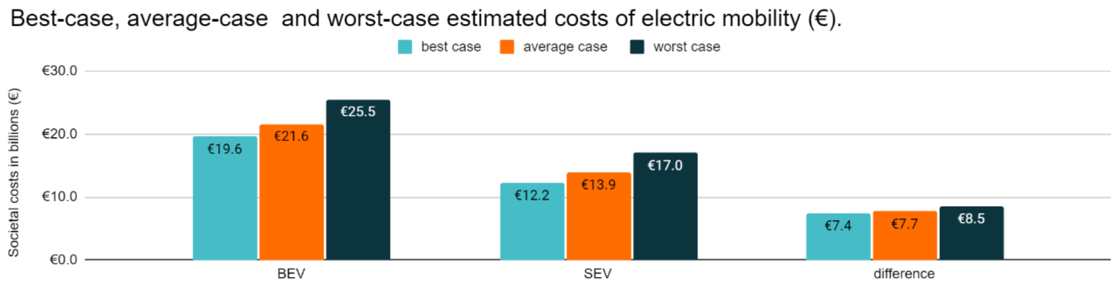


Figure 5.12 Best case, the average case, and worst-case estimated costs of electric mobility until 2050.

For the analysed scenario in 2050, the exact cost-difference, given the assumptions, will be somewhere in between the worst-case and best-case system costs outcomes. It could be argued that all the ten outcomes could fit ten different neighbourhoods. In that case, the costs are expected to be within the range that is given in figure 5.12. The worst-case and best-case model outcomes are explained below while looking into the results for the grid and the charging infrastructure separately.

5.2.1 The charging infrastructure

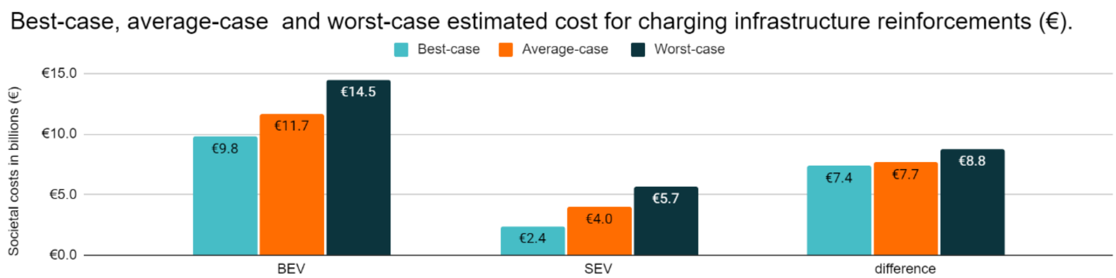


Figure 5.13 Best case, the average case, and worst-case estimated costs of electric mobility until 2050 (charging infrastructure).

The system costs for the charging infrastructure on average are estimated to be up to €11.7 billion for the BEV and €4 billion for the SEV. These are solely the costs for the public charging infrastructure in neighbourhoods when considering all assumptions that were made beforehand. Subsequently, the costs difference between the SEV and the BEV until 2050 ranges between €7.4 billion and €8.8 billion.

5.2.2 The grid

Equally, the worst- and best-case outcomes of the model outcomes are implemented in the system cost calculations. Whereas the average model outcomes do not result in a difference in costs between the SEV and the BEV a cost difference of €0.3 billion was measured for the worst-case model outcomes. This cost difference is caused by the overloaded 400 KVA transformer in urban areas in case of 100% BEV penetration. In the case of 100% SEV penetration, the peak load does not exceed the capacity limit of this transformer. Hence, a difference in costs is measured in the case of the worst-case scenario. For the best-case scenario, the system cost difference does not change.

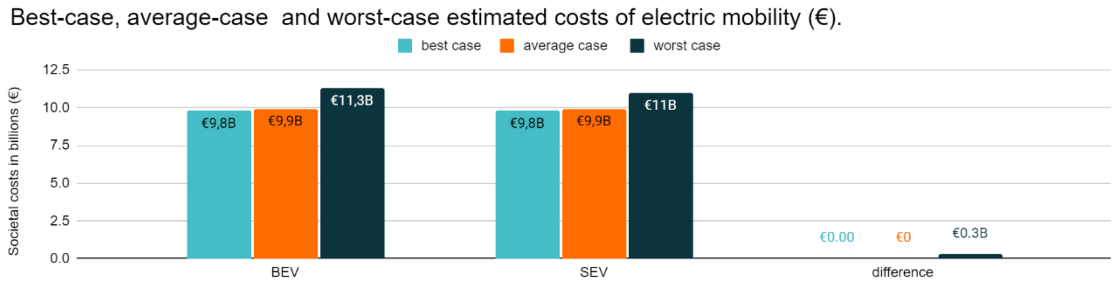


Figure 5.14 Best case, the average case, and worst-case estimated costs of electric mobility until 2050 (grid).

5.3 A sensitivity analysis

Whereas the verification of the research concerns the question: did we build the thing right, the validation answers the question, did we build the right thing; are the outcomes convincing? This vital step in academic knowledge enrichment has been a continuous process during this research. It must be emphasized that no model is 100% valid. As such research validity must be considered in the light of its goal [37]. Did we answer our main research question?

'***What are the system costs of SEVs compared to BEVs?***'

Research validation can be executed in different ways. For research that is comparable to a real-life situation, a historic replay can be applied. In this case, a scenario is applied to the same research from the past until now [67]. However, as the energy system is subject to change, historic replay is not considered as a 'valid' method to validate this research. Another way is expert validation, which is the most used validation approach in agent-based modelling. In this method, experts discuss the behaviour of the system and the application of the research. However, experts have a good understanding of the past and the present but might not have a systematic understanding of what may happen in the future. A specific validation for an ABM could replication the model designed for the research, with a different system composition or a different modelling technique, such as system dynamics [67]. However, this is a very labour-intensive validation and is therefore not considered during this thesis. So, what validation approach is appropriate to validate the research?

"You should perform a sensitivity analysis anytime you create a model, write a set of requirements, design a system, make a decision, do a trade-off study, originate a risk analysis or want to discover cost drivers [64]". Indeed, a sensitivity analysis is used to validate the ABM. One of the major challenges in ABM is to determine the system parameters that control the agent behaviour and interactions [103]. In a sensitivity analysis parameter values are changed, to see the effect of the change. A sensitivity analysis is a powerful technique to understand systems and to see what parameters have a big impact on the model outcomes. It gives perspective to the model results in the first instance and shows the main uncertainties in the research. Values of critical parameters can be refined while parameters that have a little effect can stay the same.

5.3.1 Configuration

The analytical framework in chapter 2 shows that the system costs are indirectly derived from the load curve. The costs were based on the capacity requirements for the charging infrastructure and the grid, which were based on the maximum simultaneity rate and the peak loads. The maximum simultaneity rate (see equation 4.1) is derived from the charging speed, the occupancy ratio, and the maximum EV load. The peak loads are derived from the total load curve in which the maximum EV load is included. The sensitivity analysis is only performed over the maximum EV load over time because the other factors influencing the results, such as the charging speed, the occupancy ratio, and the factors that are considered in the total load curve are not the focus of the analysis and therefore held constant in the sensitivity analysis. Focusing on the maximum charging load enables an unambiguous insight into the effects that take place when a parameter changes. The EV load reflects the blue area in figure 5.16 and leaves out the other loads that are incorporated in the load curve, such as the household load and the heat pump load as these are mostly based on historical data and therefore show little variation. Accordingly, the focus is on measuring the impact of a parameter change on the maximum electricity consumption in kW of EVs, which is now referred to as the maximum charging load.

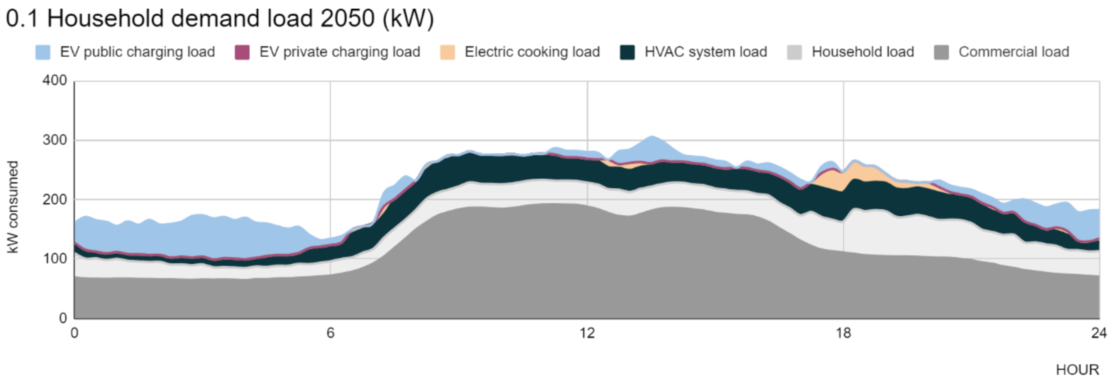


Figure 5.16 The Load curve on a weekday in an urban area in winter. The blue area reflects the maximum charging load.

Max. charging load [kW]	*100% BEV*	*100% SEV*
	77.5 kW	25.7 kW

Table 5.9 The maximum electricity consumption (kW) of EVs measured in an urban neighbourhood.

To measure the sensitivity the parameters' values of the expected fundamental parameters are changed. In this research, it is chosen to perform a sensitivity analysis with the parameters that influence the emerging charging behaviour in a neighbourhood. The results showed that smart charging and the EV technical characteristics had a big impact on the charging behaviour. Therefore, the section 5.1.3 elaborated on the impact of smart charging and the efficiency of EVs. The other factors that influence the emerging charging behaviour are the driving behaviour, the number of EVs, and the charging speed (see section 2.4). Hence, these factors are considered in the sensitivity analysis below. The rule of thumb in sensitivity analysis is as follows: the higher the sensitivity and/or the rougher the assumption, the more the research validity must be questioned. The sensitivity experiments are only executed for the urban neighbourhood. The results are presented in figure 5.17.

5.3.1 The outcomes explained

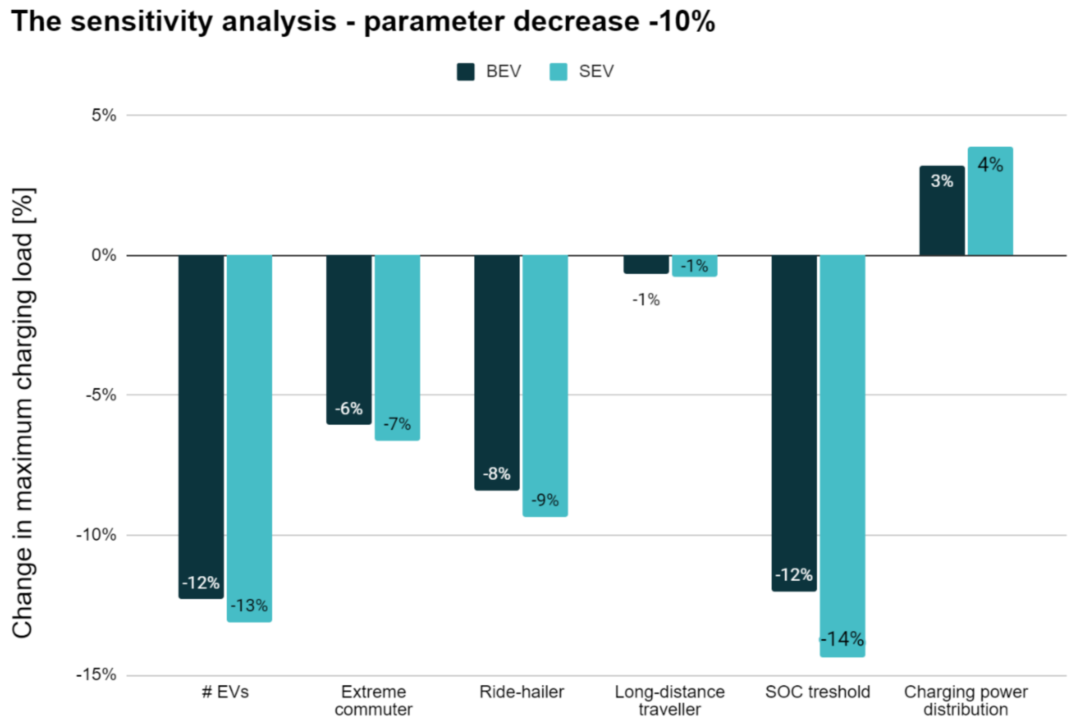


Figure 5.17 Sensitivity analysis on the impact on the maximum charging load measured with a parameter decrease -10%.

As figure 5.17 presents the values of the parameters are all reduced by 10%. The change in maximum charging load shows the sensitiveness of the parameters. Generally, it is found that the maximum charging load does not show a linear reaction to the parameter change. While this sounds striking, this is normal for the use of an ABM. Due to the behaviour that is considered in the model, no linear reaction takes place. Besides the non-linearity, it is observed that the sensitivity for the 100% SEV scenario is generally higher than for the 100% BEV scenario. This is logically caused by the lower absolute values that are reported for the charging load of the SEV. A change of 1 kW in charging load has a bigger impact on the SEV scenario than the BEV scenario. Despite the non-linear sensitivity and the small difference for the sensitivities of the SEV and the BEV are found logical, it shows that the uncertainties in the assumptions in the model and the behaviour of the agents are significant for the results. Therefore, the results of this research are only valid for the set of assumptions that are made in chapter 3. The measured sensitivities are explained in order below.

In the first experiment, the number of EVs that are adopted in a neighbourhood is reduced. A decrease in maximum charging need of 12% and 13% are presented for the BEV and the SEV respectively. The maximum charging load logically decreases; when there are fewer EVs in the neighbourhood fewer EVs need to be charged. The change of the maximum charging load value is not linear. This is caused by the lower probability that the reduced number of EVs need to charge at the same time. Accordingly, a higher sensitivity to the parameter change is measured. In the following three experiments the sensitivity of the persona parameter value is reduced by 10%. Compared to the other personas the maximum charging load in the case of the ride-hailer decreases the most; the sensitivity is the highest. This is a logical consequence of the higher number of trips the ride-hailer and the longer distances it travels (~135 km). The longer travel distances also are applicable for the extreme commuters (~125 km) and the long-distance travellers (~367 km). The impact of the long-distance traveller is smaller than the impact of the commuter while it drives greater distances. This is caused by the low frequency the extreme traveller travels (3 times per year). The measured sensitivities for the personas are found logical as the maximum charging load changes to the extent of the impact the personas have on the ~average driving behaviour. In experiment 4 the SOC threshold parameter value is reduced by 10%. It stands out that both the sensitivity for the BEV and the SEV is relatively high. This is logically caused by the fact that the moment of charging is delayed because the moment people decide to charge is delayed. On average it lasts longer before a user decides to charge. Hence, the number of charging moments decreases, causing fewer people to charge simultaneously. The relation is not linear due to the driver's behaviour modelled. The SEV has a higher sensitivity on the SOC threshold than the BEV. This means that the maximum charging load gap between the SEV and the BEV becomes bigger when the SOC threshold is reduced. This is likely to be caused by the solar panel that is generating more energy from the sun until the next charging moment, therefore the next charging moment could be delayed even more. In the last experiment, the average charging power was reduced by 10%. Due to a decreased charging power, the charging sessions are likely to last longer. This results in a higher maximum charging load.

Next to a validity measurement, the results of the sensitivity analysis could be used to show what parameters potentially have a big impact on the system costs of electric mobility.
It is found that the SOC threshold and the number of EVs show relatively high sensitivities. The results imply that when we can reduce the SOC threshold and the number of EVs in the future energy system, the system costs could be reduced. This applies to a lesser extent to the change in driving behaviour, by reducing the number of people with driving profiles of the defined personas in society. On the other hand, the maximum charging load is measured to become bigger when the average charging power is reduced. The system costs are therefore likely to increase. However, it must be noted that charging points with lower charging powers are less expensive than charging points with a higher rated power. Subsequently, it is found that the implications of the sensitivity analysis give a direction of what the impact of the parameters on the system costs could be. However, before concluding on these topics, further research is necessary.

Chapter 6: Discussion

This chapter provides a discussion of the results and methods in this thesis. First, a critical review is provided on the main results of the thesis. Afterward, the implications of the results for the academic world and society are discussed.

6.1 Discussion of the main results

Making a prognosis for future electricity consumption involves uncertainties. This is inherent in a transition. Ongoing developments in technology, politics, the market, and user groups lead to a complex interplay that can change the electricity system in the future. One of the main limitations of this research is that methods and assumptions that are used to predict the required number of charging stations and the required capacity of the grid in 2050 contain uncertainties. The important points of discussion are described below.

In this thesis, two imaginary scenarios have been sketched: (1) a 100% BEV fleet and (2) a 100% SEV fleet. Only the "average BEV" and the SEV are considered in the future mobility fleet of passenger vehicles. None of the scenarios is expected to be fully realistic and consequently has several limitations. The electricity demand for mobility logically changes when the mobility fleet composition is different. This might result in other electricity peaks and maximum charging rates than the current ones influencing the system costs that are presented in this thesis. Firstly, the assumption that corresponds to the ambition to have all cars in The Netherlands to be electrically powered by 2050, is uncertain. In case that the market development of the BEV in The Netherlands is slower than expected, the passenger vehicle fleet would look different than initially sketched in this thesis. EV alternatives, for example, hydrogen-powered vehicles and methane-powered vehicles, could enter the mobility fleet [12]. The number of EVs would then obviously be lower than assumed, resulting in lower estimated system costs. Secondly, developments such as Mobility as a Service (MaaS)[5], shared driving platforms and autonomous driving could influence the number of EVs that are needed within a neighbourhood. Possibly fewer electric cars will be adopted in the future when the (rapid) developments would continue. In addition, due to the rapidly developing EV industry, it is uncertain how the technical characteristics regarding the WLTP energy consumption and the solar electricity generation of the SEV and the BEV will develop. Therefore, the difference between the SEV and the BEV in system costs would be different than sketched in the results of this thesis. Even though future scenarios of a 100% SEV and BEV fleet are hardly realistic, the main goal was to compare the SEV with the BEV. To be able to make a good comparison within the time scope it was chosen to focus on one reference EV and to investigate the unambiguous scenarios of 100% BEVs and 100% SEVs. Accordingly, the chosen assumptions are here justified for the research goal that was pursued in the research.

One major aspect that was found valuable to explore when defining the system costs of electric mobility is charging and driving behaviour. While driving and charging were fundamental for the research outcomes, little data was found about the EV driving behaviour in The Netherlands. First, no straightforward data was found about the driving behaviour of EV drivers specifically. Subsequently, only the driving behaviour of ICE vehicles was used. This was a rough assumption as it is expected that the driving behaviour of EV users is different compared to the behaviour of ICE users. However, the data about the EV user behaviour that was found, showed contradictory results. Besides, in the absence of data about Dutch driving behaviour, some rough assumptions were made based on research of the UK and the US. For example, the state of charge (SOC) threshold, the moment that people decide to charge, was derived from a study

[5] MaaS is a development of transport services that are available on-demand instead of a personally owned transport means.

that was held in the UK [93]. The sensitivity analysis showed that the SOC threshold has a high sensitivity, meaning that it has a relatively big impact on the results of the research. It is also questionable if the SOC threshold for Dutch drivers is comparable with the SOC threshold for BEV drivers. No differentiation was made for the SEV and BEV driving behaviour as no data was available about that yet. However, it is questionable if the SEV and the BEV users would indeed demonstrate comparable behaviour. The SOC threshold for the SEV user could be for example lower when the user knows the future solar irradiation prediction. In addition, only a few personas could be defined based on real data. Accordingly, there is relatively little variation between EV driver characteristics in the model. As the ABM attempts to counterfeit reality, it is favourable to implement a bigger differentiation between different user groups defined in the ABM. Finally, the impact of future developments such as autonomous driving shared driving, and MaaS could influence the driving behaviour of EV users. These developments were left out of the scope in this research as the focus was on comparing the SEV with the BEV.

In assessing the system costs of electric mobility on the grid the research left out interventions such as storage, V2G, and S2V technology. These interventions could influence the impact of integrating the EV in the electricity system, by unburdening the grid. However, the extent to which they will be applicable in the future energy system is uncertain too. Moreover, the main goal of this thesis was to compare the SEV and the BEV. The target may be jeopardized when considering different system interventions. The intervention that was considered is the smart charging strategy as the future governmental plans already aim to make smart charging an integral part of the mobility system. However, smart charging is a broad notion, and the exact concept of smart charging is still vague and ambiguous. In this thesis, the time of charging solely was optimized within the smart charging strategy. The charging speed, for example, that is sometimes considered in the design of a smart charging strategy was not considered in the ABM [11]. Moreover, the smart charging strategy that was applied in the model is not 100% effective. It is questionable how smart charging will take shape and to what extent smart charging will be adopted by society in the future mobility system. Assuming a 69% effective smart charging strategy is a rough assumption that has a large influence on the results of the research. However, it gives a direction of what the system costs could be under the defined assumptions.

The capacity requirements for the grid were based on the load curve of 2050. Many assumptions were made to approximate the future load curve. However, as 2050 is still far away, many uncertainties are hidden in the assumptions that were made. Available plans made by Dutch governmental instances, TSOs, and DSOs appear to be different. Despite the difference that was found between the plans, assumptions were made regarding the future load curve. Heat pump loading of the grid played a relatively big role in the prediction of the future load curve considering that 42% of the households in 2050 are planned to be heated by heat pumps. As earlier discussed, other developments such as district heating nets are alternatives for electric heating, without necessarily using gas or coal. However, the share of electric heat supply is very uncertain in any future energy system but should not be ignored on the other hand. Besides [10], the PV panels that were considered in the load curve can only generate power for the concerned households. In chapter 2 of this thesis the concept of PV panels feeding energy back into the grid has been explained. This concept was not considered within the time scope of the research but could still have a very significant impact on future grid reinforcements. Another rough assumption was made about the number of households that have solar panels on their roof providing them with electricity. It is assumed that 57% of the households will have solar panels on their roofs in 2050, which could provide electricity to the concerned households. Despite the rough assumptions that were made about the future demand load curve, it is still considered more valuable to make a rough assumption about the future development of heat pumps and solar PV than leaving the developments out.

Due to a lack of data, the current level of the grid has been estimated in this research. An approximation, that was based on the historical loads and a yearly growth rate of electricity demand has been used to estimate the current level of the grid. This approximation was made based on a former method of an existing DSO in determining the capacity of the grid. While this was a rough assumption, no better method was found yet to investigate the current level of the distribution grid in The Netherlands. However, the method has been recently verified by two (senior) asset managers of the above-mentioned DSO. The assumption is nonetheless expected to have a great impact on the absolute and to a lesser extent the relative estimation of the system costs of the grid.

Although in this thesis, the charging capacity requirement has generally been based on the maximum simultaneity rate, the occupancy ratio[6], and the charging speed in neighbourhoods, literature does not show consensus on the way how to determine the capacity requirements of the charging infrastructure. The chosen metrics have the disadvantage that for example the spatial distribution of the charging infrastructure, the compatibility of sockets and EVs, and the existence of semi-public charging points are not considered. Other limitations of the factors that were included in the method are discussed below. Firstly, only one distribution of the charging speeds for the charging infrastructure was considered [13]. However, there are different thoughts about the future of the charging infrastructure. Some think that it will be dominated by fast-chargers [13], while others discourage this by stating that the grid cannot handle the peak loads [19]. Accordingly, it is uncertain how the power distribution of the future will look like. This assumption is important as the sensitivity analysis showed that the average charging power has an impact on the outcomes of the research. Secondly, the charging capacity requirement has been multiplied by the occupancy ratio that amounts to five. The occupancy ratio has a high influence on the absolute system costs of the charging infrastructure. Favourably, the behaviour of EV users regarding the occupancy of charging stations was also modelled in the ABM. However, this was not considered to be feasible within the time scope. The assumption that when a charging station is occupied the charging point is not accessible for other EV drivers, is considered to be a logical assumption. Therefore, it was important to include the occupancy ratio in estimating the system costs of future electric mobility. Thirdly, the research assumes that EV users always need to be able to charge their EV at any time. It is questionable if this is economically and politically favourable.

Finally, the system impact is measured in national system costs. In this research, the costs are roughly extrapolated from one rural, one suburban, and one urban neighbourhood to national costs. The assumption here is that specific reinforcement costs per different neighbourhoods are representative of the rest of The Netherlands. While this is a strong assumption, it gives the first estimation of the system costs that are needed to support the mass deployment of BEVs and SEVs in The Netherlands. In reality, neighbourhoods are different and therefore the system impact is expected to be different for different neighbourhoods. Moreover, there are other areas than neighbourhoods that also need charging points and might need to reinforce the grid for this reason, such as spots along the highway and industrial areas. These areas were not considered during this research within the time scope. Another limitation in the system costs measurements is that the costs are only measured in terms of CapEx. Naturally, the OpEx such as maintenance costs and service costs must be considered to conclude the total system costs. However, it was not expected that the OpEx for the SEV would differ compared to the BEV. For simplicity reasons, these costs were not considered. In future systems, the OpEx of the charging infrastructure and or the grid might become of significant value with the introduction of smart services such as smart charging.

[6] The occupancy ratio is the ratio of the average time that an EV user is occupying a charging point to the effective time the EV is charging.

The determination of the costs for the charging infrastructure has several limitations. Firstly, the costs for the SEV are expected to be up to 3 times lower. However, the learning effects and financial benefits of placing multiple charging stations in one place are not considered during the calculations. The costs per charging station may be reduced if more charging stations are installed, for example, due to relatively lower installation costs. When considering this the difference between the costs for the charging infrastructure of the BEV and the SEV would be lower. Besides, when determining the charging capacity requirement, the lifetime of the charging points is not considered. The lifetime of charging points currently is 10-15 years. When considering system costs, the lifetime of the charging points was not considered yet. A charging need that is three times less than the current average BEV, could therefore potentially decrease the costs for the charging infrastructure even more in the long-term than in the short term. Accordingly, the costs for the charging infrastructure are expected to be higher over the decades. While the absolute numbers are expected to be different in 2050 the relative cost-difference is expected to give a good estimation for the indication of the SEV and the BEV.

Next to a questionable method for determining the current capacity level of the grid, the limits of the grid are found to be highly volatile. The capacity of a cable or transformer is either exceeded or not. This polarity influences the difference in system costs that were presented. If a grid asset has been critically overloaded it needs to be replaced, bringing extra system costs for neighbourhoods. To somewhat tackle these problems, insight was given into different model outcomes and their impact on the system costs of the grid. A system costs range has been presented looking into the worst and best model outcomes. Where the *absolute* numbers of the system cost estimations are quite uncertain, the results of the *relative* difference between the grid reinforcement investment needed for the BEV and the SEV appear to have better reliability.

The system costs were determined based on the capacity requirements of the system when an EV is integrated into the system. However, more aspects are relevant when estimating the societal costs of electric mobility. For example, the external costs could rise by an increase in CO_2 emission right prices. Higher CO_2 intensity takes place when the central electricity demand rises. This is a consequence of the merit order that prioritizes renewable energy sources above CO_2–emitting sources. When there are peaks in the load curve, gas and coal plants are turned on, the higher the peak load, the higher the emissions due to electricity generation. The impact of the BEV or the SEV on CO_2 emissions is largely dependent on the energy mix composition. The CO_2 emissions are left out of scope during this research as the Dutch future energy mix is planned to be more based on vRES [5]. The CO_2 emissions are expected to have a less system impact than the system integration of the BEV and the SEV in The Netherlands. Another source of societal costs that is not considered is the TCO. The TCO calculates the total cost for EV owners and the costs of using a car for the duration of this ownership [19]. TCOs were not considered in this thesis, as earlier research already gave a corner of the veil about the future TCO of both the SEV and the BEV. In addition, no system interventions other than smart charging were considered during the system impact and cost calculations in the research. However, they could influence the system costs by on the one hand unburdening the grid and the charging infrastructure and on the other hand incur costs. For example, storage could have a high impact on the load curve, but also entails system costs. The interventions are not considered within the time scope of the research as they deviated slightly from the main target. Another factor that is not considered in the system costs estimations is the rise of central electricity generation by vRES. Peak loads caused by excessive and simultaneous charging behaviour, ask for more flexibility of electricity supply to adapt to the changing load curve. Due to the rise of vRES electricity supply contrarily tends to become less flexible because of the rise of variable renewable energy sources (vRES) in the future energy mix [17]. The so-called flexibility challenge is likely to bring about a significant system impact. It is not included in this research as the flexibility challenge is considered to be not primarily caused by the rise of EVs. However, the challenge must be considered when making a final decision about the 'optimal' design of the future energy system.

With all restrictions mentioned the main outcome of the research is those cost savings that the SEV could make, which might range up to between €7.4 billion and €8.5 billion, regarding the impact on the grid and the charging infrastructure in neighbourhoods until 2050.

6.2 Scientific contribution

This research has several scientific contributions: (1) it provides the first estimated difference in system costs for the SEV compared to the BEV until 2050, (2) a method is introduced to determine the future charging infrastructure capacity requirement, (3) the impact of the SEV compared to the BEV on the simultaneity rate of charging in different neighbourhoods is calculated, and (4), the impact of the SEV and the BEV on the local electricity load curve is explored. Each contribution is briefly discussed below.

From the literature review that was performed in chapter 2, it was concluded that no specific details about the system costs of SEVs were explored yet. For the charging infrastructure, only short-term (2035) cost estimations had been executed under different scenarios by for example NAL [42] and Ecofys [104]. However, no long-term (2050) system cost estimations were performed for The Netherlands yet. Different sources showed that the long-term roll-out strategy had not been determined yet [105] [31]. This research adds for both the SEV and the BEV a first estimation of the charging infrastructure costs in 2050 under the presented assumptions and roll-out strategy. For the grid, literature already showed various results on the system costs due to the rise of the BEV. Recently, Netbeheer Nederland [9] for example estimated the distribution grid reinforcement to be ~ €15 billion by 2050. In this research, the costs for the BEV are presented to be ~€9.9 billion for both the SEV and the BEV. The cost difference is possibly caused by the information asymmetry about the state of the grid. The main scientific contribution is therefore not the absolute cost estimation for the grid. The current scientific contribution lies in the comparison between the SEV's and the BEV's impact on system costs.

This research provides a roll-out strategy determining the future charging capacity based on the factors that are derived from the literature and considered in figure 2.5. For the charging infrastructure, different authors state that the costs are dependent on the roll-out strategy that is applied. However, the authors that are addressed in the literature review give a different view on how this roll-out strategy must look like. At the end of 2019, the Ministry of Infrastructure and Water Management had no standards, target values, or indicators to determine whether the growth of electric transport is sufficient to keep pace with the growing number of EVs [106] [105]. Therefore, it is also not known if the current number of charging stations in The Netherlands is sufficient. It makes it even harder to estimate the number of charging stations that are required in the future. As the roll-out strategy has not been set for the future in The Netherlands, the literature still focuses on the different factors that are important when planning the future dimensions of the charging infrastructure. Based on the different factors found in the literature, this research provides a method to determine the future distribution grid capacity needed of The Netherlands. The capacity requirement of the charging infrastructure that is described in this thesis is not just based on the number of EVs in the future energy system but also the occupancy rate and the maximum simultaneity rate. The maximum simultaneity rate is determined by other factors such as driving behaviour, the technical characteristics of cars, the composition of the mobility fleet, and the charging speed. Based on this method, the results in this research present a goal of ~3.7 BEVs and ~11.6 SEVs per charging point in the future charging infrastructure. The results for the BEV are higher than the current Dutch ratio of the number of EVs to the number of public charging points equalling 2.5 EVs per charging point. RVO [42], states that a public charging capacity of 1.6 EVs per charging point is required. The European Commission contrarily set a goal of maximally 9,5 EVs per charging point [13].

The maximum simultaneity rate for the BEV and the SEV in different neighbourhoods was one of the outcomes of this research and therewith added to the current body of literature. Earlier research already showed some results about the maximum simultaneity rate for the BEV. Brouns [34] found that under different charging behaviour scenarios the maximum simultaneity rate ranged between 0% and 30%. Ullfers [39] also looked into the maximum simultaneity rate and found that if there are 100 cars stationed in a neighbourhood, the maximum simultaneity rate is around 10%. The results for the BEV in this research are in line with the findings of Ulffers and Brouns. In this research distinction between urban, suburban, and rural areas has been made, where other (earlier) research did not distinguish between neighbourhoods with different urbanization degrees. Moreover, it adds the maximum simultaneity rate of the SEV for different neighbourhoods to the existing body of literature.

For the determination of the grid reinforcement costs, the literature presented multiple results on how the future peak loads could take shape, under the defined conditions. Lousberg [35] for example shows a comparable research method but does not include charging behaviour based on real data and smart charging. Therefore, different results on the peak loads are presented. In contrast, this thesis describes an overview of the peak loads while considering charging behaviour that is based on real data including a smart charging strategy. It shows that the peak load values for the SEV and the BEV barely differ under these circumstances, resulting in no cost difference between the different EVs. These results correspond to the promising perspective the body of literature gave about the potential of smart charging and give a first estimation on the impact of the SEV on the costs for the grid.

6.3 Societal contribution

Within the master's program Complex System Engineering and Management students are challenged to design solutions for complex socio-technical problems. The presented framework and the results, therefore, do not only have a scientific but also a societal contribution.

The analysed concept in this thesis, the SEV, constitutes a solution that would potentially accelerate the development of sustainable mobility, by limiting societal costs. Electric mobility is nowadays still very much dependent on the electricity supply system, including the grid and the charging infrastructure. When no intervention takes place, expensive grid and charging infrastructure reinforcements are necessary soon. The lower dependency of the SEV on the charging infrastructure leads to a solution for three major societal challenges. First, when mass adoption of SEVs takes place, the required number of charging stations in The Netherlands could be reduced considerably, saving societal costs. Second, a lower charging infrastructure dependency means that customers need to charge less. This is a positive perspective for EV users, who often still suffer from so-called 'range anxiety'. The SEV would overcome this barrier and might therefore have the potential to accelerate the adoption of cleaner electric mobility in The Netherlands. Third, the lower dependency of the SEV on the charging infrastructure could potentially decrease the daily costs for EV users. When EV users need to charge less, they need to pay less. However, before concluding on these societal contributions in detail, further research needs to be executed on this specific topic.

Chapter 7: Conclusion & recommendations

This chapter provides an answer to the main research question and explores possibilities for further improving and extending the research. Moreover, policy and company recommendations are done.

7.1 Conclusion

The conclusion provides an answer to the research question that was stated in the introduction of the report.

'What are the system costs of SEVs compared to BEVs?'

The research objective in this thesis was to uncover the differences between the SEV and the BEV to explore to what extent SEVs could reduce the system costs of BEVs in the future energy system. This research has been performed by assessing the system costs of a 100% SEV fleet compared to a 100% BEV fleet considering large-scale penetration of smart charging. The results are based on the existing ABM that was extended in this research.

The results show that the charging infrastructure is the main factor responsible for the system costs when the SEV and the BEV are compared. In the coldest winter week, the SEVs maximum number of cars charging at the same time was estimated up to 3 times lower compared to the BEV. Subsequently, the charging infrastructure costs for the SEV were estimated to be up to three times lower than for the BEV; €4 billion and €12 billion. This difference is caused by the charging behaviour of EV drivers, which is influenced by the smart charging strategy, the energy generation, and the higher efficiency of the SEV. Where the charging infrastructure reinforcements represent different investment needs for the SEV and the BEV, the estimated costs for the distribution grid are €10 billion for both the BEV and the SEV scenario. A relatively small difference between the peak loads of the SEV scenario and the BEV scenario has appeared. Therefore, no extra grid asset investments are necessary to avoid overloading in the case of mass adoption of the SEV. The slightly lower peak load values at the SEV scenario and the BEV scenario appear to be primarily caused by the charging behaviour of EV drivers, which is influenced by the smart charging strategy, the energy generation, and the higher efficiency of the SEV.

The smart charging strategy has a large impact on the results for both the charging infrastructure and the grid. The results imply that this strategy is more effective for decreasing the impact on the system for the BEV than for the SEV. The peak loads of the BEV scenario grew faster than the peak loads for the SEV scenario when an uncontrolled charging strategy was implemented. In addition, the system impact of the SEV and the BEV in a summer week was assessed with the ABM, the required capacity of charging stations for the SEV appeared to be ~8 times lower compared to the BEV, the cause being the higher electricity generation of the solar panel in this season. Another analysis showed what happens if the SEV would not have an integrated solar roof and solely represented a high-efficient electric vehicle. The results showed that under the modelled behaviour and the smart charging strategy, the solar panel, and the low energy consumption of the SEV are responsible for respectively roughly one-third and two-third of the decrease in system costs.

Finally, the system costs were estimated. The estimated cost savings that the SEV could make if it would be fully (100%) adopted in society, range between €7.4 billion and €8.5 billion until 2050. These cost savings are primarily caused by the bigger charging infrastructure roll-out that needs to be planned to pace with the rise of BEVs compared to SEVs in society. The cost savings for the grid were presented to be at most €0.3 billion when the SEV dominates the system.

7.2 Recommendations

In this section scientific, policy, and company recommendations are given.

7.2.1 Recommendations for further research

This study provides an overview of the impact of the SEV compared to the BEV on the charging infrastructure and the distribution grid costs. The research gives input for further research. The recommendations for further research are listed below. As there is almost no literature dedicated to the SEV yet, there are many research challenges to be tackled in this specific field. Only the most relevant recommendations that apply to this research are considered here.

Recommendations for further research	
1	***Further specify the future Dutch driving and charging behaviour.***
	It is recommended to further specify the future Dutch driving and charging behaviour by researching the behaviour of a higher variation of personas considering the SEV and BEV users separately. As presented in the analytical framework of the research, behaviour is fundamental to the outcomes of the research. Where now relatively little information is found about Dutch driving behaviour, more detailed information is expected shortly [13]. Where for example this research used a SOC threshold that was based on research in the UK, favourably different Dutch SOC thresholds for different personas are considered.
2	***Explore a wider variety of mobility products and services within the mobility fleet.***
	It is recommended to explore other compositions of the mobility fleet in 2050 to find out how this influences the system costs. It could be considered to for example consider autonomous driving, shared driving, and MaaS in the future mobility system. Moreover, other types of cars such as ICE vehicles and Fuel cell electric vehicles (FCEVs) could be considered.
3	***Apply more future scenarios to compare the system costs of the BEV and the SEV.***
	Favourably, more scenarios are explored regarding the system costs of the SEV compared to the BEV. It could be for example interesting to consider the combination of central vRES generation, V2G, and the SEV in the electricity system. Other factors that could be considered in these scenarios are different types of smart charging, storage options, and the decentral unidirectional supply of vRES. Moreover, different adoption rates of the heat pump and residential solar PV supply could be considered, as the future of the heat pump is still very uncertain.

4	***Explore what long-term roll-out strategy is socio-technically favourable.***
	At the end of 2019, the Ministry of Infrastructure and Water Management had no standards, target values, or indicators to determine whether the growth of electric transport is enough to keep pace with the number of EVs [106] [105]. Therefore, it is recommended to explore what metrics and target values are favourable from a socio-technical point of view. This could help to ensure an effective method of dimensioning the charging infrastructure in the future.
5	***Explore different distributions of charging speeds.***
	Where this thesis explored one charging speed distribution, the future of the share of adopted charging stations with a specific charging speed is still very uncertain. It would be good to see what a socio-economically favourable charging speed distribution would be, in which the costs for the system could stay limited. It could be for example interesting to explore the possibility of charging via the household socket, where no significant extra costs for a charging point are included; or to exploit a scenario with a high share of fast chargers; or to consider technological developments such as the possibility of wireless charging
6	***Perform an analysis on the status of the distribution grid.***
	It is recommended to perform a more thorough analysis on the status of the distribution grid in The Netherlands. This could be executed by for example clustering different types of neighbourhoods and their belonging grid asset capacity. By doing this a better system cost estimation could be performed based on these standardized neighbourhoods.
7	***Explore the impact of the SEV and the BEV on the total societal costs of electric mobility.***
	This thesis only provides an overview of the system costs. However, to determine the difference in societal impact, it is favourable to also investigate the product-level and external costs of different EVs.
8	***Explore the system costs of the SEV and the BEV in different countries.***
	It is recommended to explore what the system costs are of the BEV compared to the SEV in other countries than The Netherlands. This research showed that in the week with the highest solar irradiance, the impact of the SEV compared to the BEV on the charging infrastructure is 8 times less. When assessing a country with a higher solar irradiance, it is expected that the difference in system costs will be bigger. Moreover, the parameters that are used in the research, regarding for example the number of EVs, the driving behaviour, and the charging strategy might differ and therefore give different insights into the potential of the SEV reducing the system costs.
9	***Explore the system costs of the SEV and the BEV on a national level.***
	This thesis considers the capacity requirements of the grid and the charging infrastructure bottom-up, from an agent level. It would be interesting to extend this research by looking into the system costs of EVs on a national scale. For the grid, this means that the impact of the residential behaviour on the HV and MV grid is assessed. For the charging infrastructure, this means that the total road network is considered including the spatial distribution of charging points.

7.2.2 Policy recommendations

When doing policy recommendations, it is very important to note that the advice only is relevant in the light of its goal. Especially in the complex electricity system, an intervention always has its positives and negatives. In this section, different policy recommendations are given. Since the electricity system is very complex, it is recommended for public and private actors to collaborate and create win-win strategies, test them in pilots and enable large-scale improvements for the future mobility/electricity system.

This thesis presented that the maximum electricity consumption for the highly efficient solar electric vehicles (SEV) is up to 3 times lower than for the average conventional battery electric vehicle (BEV). This difference is associated with a decrease in the capacity requirement for the deployment of public charging points in the future mobility system. The lower electricity consumption is explained by (1) a low energy consumption and (2) the solar electricity that is generated by the integrated solar panels combined with Dutch driving behaviour and the smart charging strategy. To reduce the number of charging points required over the years it is therefore recommended to support the arrival of the highly efficient solar electric vehicle, by for example running campaigns or provide financial incentives to support the adoption of highly efficient mobility.

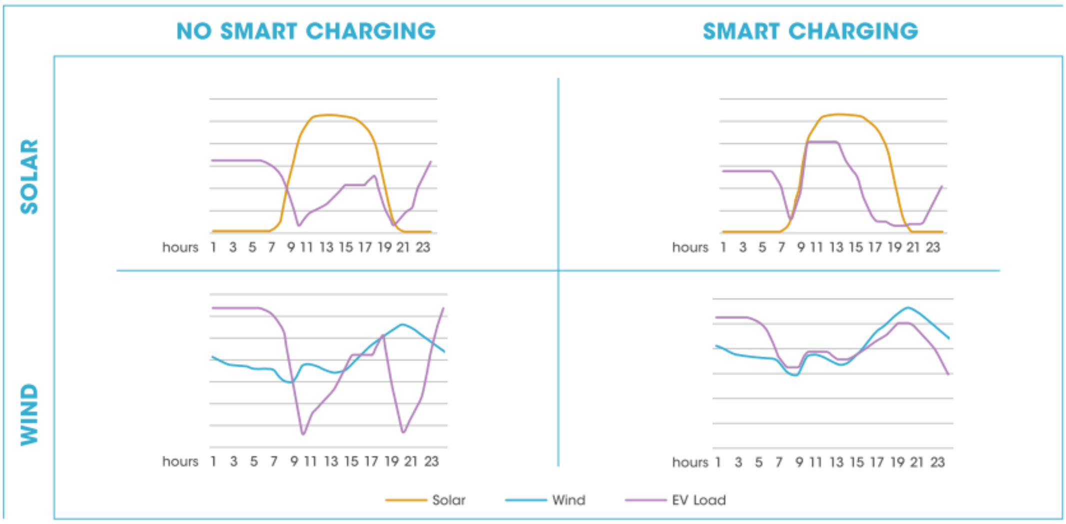


Figure 7.1 Smart charging for solar and wind generation profiles, when considering BEVs.
Source: Adapted from [58].

Based on the results of the thesis it is recommended to promote smart charging under the Dutch population. This research assumes a 69% effective smart charging strategy. However, currently, only 20% of EV users implement smart charging regularly, and 40% are not even familiar with the concept of smart charging [107]. This research showed that smart charging could (1) limit the peak loads of both BEVs and SEVs and (2) limit the maximum simultaneity rate of charging and therefore reduce the required charging infrastructure and grid assets that are needed. A more effective smart charging strategy, moreover, helps to stabilize the peak power supply of the electricity generation of vRES as illustrated in figure 7.1. Therefore, it is recommended to create efficient price signals or other load management schemes to incite smart charging. To do so it is important to understand driving behaviour and on the other side create awareness on this topic.

It is recommended to draw up standards, target values, and/or indicators and to collect targeted information about the development of the charging infrastructure. These targets must also be designed for determining the long-term charging roll-out strategy which is not developed yet. When developing the targets and the long-term roll-out strategy, it is recommended to consider different technical characteristics of EVs; the composition of the mobility fleet; the occupancy rate; the spatial distribution; different speeds of charging stations; and the charging strategy that is applied.

From the sensitivity analysis, it appeared that the number of EVs that are adopted in a neighbourhood has a high impact on the charging infrastructure capacity requirement. When there are 10% fewer electric vehicles operational in a neighbourhood the impact on the grid and the charging infrastructure reduces by 12%. It is therefore recommended to investigate future options in which the need for electric passenger vehicles could be reduced. This could be done by for example promoting shared driving, public transport, and/or MaaS. The sensitivity analysis also brought to light that the state of charge (SOC) threshold, the moment that people decide to charge, has a relatively high sensitivity. When the SOC threshold is reduced, the maximum electricity demand of EVs, and especially SEVs, decreases stronger than the SOC threshold. This implies that reducing the SOC threshold could be favourable for decreasing the impact of electric mobility. Accordingly, a policy recommendation is given, to create awareness about the positive effects of reducing the SOC threshold.

7.2.3 Recommendations for Lightyear

In this section, the research concludes with the final recommendations for Lightyear. Hence, the recommendations below are only applicable to SEVs.

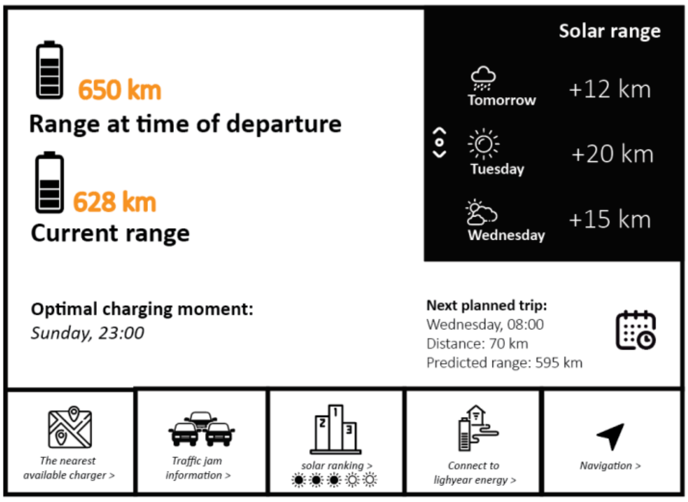


Figure 7.2 An idea of a dashboard giving insight into future power generation of the integrated solar roof.

It is recommended to develop a system in which customers can see when their optimal moment of charging is depending on their driving behaviour and the solar irradiation of the upcoming days. The longer a SEV user waits until the next charging moment, the higher the solar electricity that is generated between the charging sessions. The theoretical optimum is when the cumulative electricity consumption of the SEV is equal or lower to the cumulative income of the solar panel. Besides, it is also recommended for Lightyear to investigate the opportunity of a market in countries with high solar irradiance. As the results showed, the charging need was presented to be 8 times lower in the week with the highest solar irradiance in The Netherlands. A limited dependency on the grid will be favourable for both customers and the system.

References

[1] V. Gray, "Climate change 2007: The physical science basis summary for policymakers," *Energy Environ.*, vol. 18, no. 3–4, pp. 433–440, 2007.
[2] United Nations, "Paris agreement," Paris, 2015.
[3] A. Hoekstra, M. Steinbuch, and G. Verbong, "Creating agent-based energy transition management models that can uncover profitable pathways to climate change mitigation," *Complexity*, vol. 2017, 2017.
[4] Rijksoverheid, "Hoe lang kan ik nog koken en stoken op gas?," 2021. [Online]. Available: https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/vraag-en-antwoord/hoe-lang-kan-ik-nog-koken-op-gas. [Accessed: 29-Jun-2021].
[5] Netbeheer Nederland, "Samenvatting Het Energiesysteem van de Toekomst," no. April, 2021.
[6] K. Beckman and J. van den Beukel, "The great Dutch gas transition," *Oxford Energy Insight*, vol. 54, no. July, pp. 1–24, 2019.
[7] R. Gupta *et al.*, "Spatial analysis of distribution grid capacity and costs to enable massive deployment of PV, electric mobility and electric heating," *Appl. Energy*, vol. 287, no. January 2021, p. 116504, 2021.
[8] J. Sijm, P. Gockel, A. Van der Welle, W. Van Westering, ECN, and Alliander, "Demand and supply of flexibility in the power system of the Netherlands, 2015-2050 - Key messages of the FLEXNET project," *Ecn-E-17-063*, no. November, pp. 1–69, 2017.
[9] Netbeheer Nederland, "Basisinformatie over energie-infrastructuur," 2019.
[10] H. Fennema and M. van Beek, "Infrastructure Outlook 2050," *Gasunie & TenneT*, pp. 1–62, 2019.
[11] A. Hoekstra and N. Refa, "Characteristics of Dutch EV drivers," *EVS 2017 - 30th Int. Electr. Veh. Symp. Exhib.*, no. October, 2017.
[12] R. Torensma, "The future of public charging infrastructure in the Netherlands," 2017.
[13] L. Mathieu, "Transport & Environment Further information," 2020.
[14] "Eindrapport van de werkgroep IBO Toekomstig Internationaal Klimaatbeleid," no. 1, 2006.
[15] D. B. Layzell and B. Straatman, "The Potential Impact of Electric Vehicles on Alberta's Energy Systems," *McKinsey Co.*, vol. 1, no. Exhibit 1, p. 32, 2016.
[16] P. Jochem, T. Kaschub, A. G. Paetz, and W. Fichtner, "Integrating electric vehicles into the german electricity grid - An interdisciplinary analysis," *World Electr. Veh. J.*, vol. 5, no. 3, pp. 763–770, 2012.
[17] L. J. de Vries, A. F. Correljé, and H. P. A. Knops, "Electricity. Market design and policy choices," p. 137, 2015.
[18] E. Veldman, *Power play : impacts of flexibility in future residential electricity demand on distribution network utilisation Power Play*. Eindhoven: Technische Universiteit, 2013.
[19] RVO (Government of the Netherlands), "Vision on the charging infrastructure for electric transport.," *Policy agenda Look. ahead to 2020*, p. 36, 2017.
[20] J. Liu, C. Hu, A. Kimber, and Z. Wang, "Uses, Cost-Benefit Analysis, and Markets of Energy Storage Systems for Electric Grid Applications," *J. Energy Storage*, vol. 32, no. August, p. 101731, 2020.
[21] N. Organisatie *et al.*, "Final report PV in Mobility (PViM) Project information," vol. 2020, no. December 2020, pp. 1–22, 2021.
[22] O. Kanz, A. Reinders, J. May, and K. Ding, "Environmental impacts of integrated photovoltaic modules in light utility electric vehicles," *Energies*, vol. 13, no. 19, pp. 1–13, 2020.
[23] J. Yang, L. He, and S. Fu, "An improved PSO-based charging strategy of electric vehicles in electrical distribution grid," *Appl. Energy*, vol. 128, pp. 82–92, 2014.
[24] S. Tamura, "Teijin's advanced carbon fiber technology used to build a car for the World

Solar Challenge," *Reinf. Plast.*, vol. 60, no. 3, pp. 160–163, 2016.
[25] D. B. Richardson, "Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 247–254, 2013.
[26] E. V. Database, "Electric Vehicle Database," 2021. [Online]. Available: https://ev-database.nl/#sort:path~type~order=.rank~number~desc%7Crange-slider-range:prev~next=10~1000%7Crange-slider-bijtelling:prev~next=25~1400%7Crange-slider-acceleration:prev~next=2~23%7Crange-slider-fastcharge:prev~next=0~1500%7Crange-slider-lease:pr. [Accessed: 02-May-2021].
[27] A. P. Mock, J. Kühlwein, U. Tietge, V. Franco, A. Bandivadekar, and J. German, "The WLTP : How a new test procedure for cars will affect fuel consumption values in the EU," no. October 2014, 2021.
[28] T. Selten, "Stella Lux: The energy-positive family car," *Europhys. News*, vol. 48, no. 3, pp. 13–16, 2017.
[29] S. Samadi, "The social costs of electricity generation-categorising different types of costs and evaluating their respective relevance," *Energies*, vol. 10, no. 3, 2017.
[30] Q. De Clerck *et al.*, "How Total is a Total Cost of Ownership ?," vol. 8, pp. 742–753, 2016.
[31] R. van den Hoed, J. Helmus, and S. Maase, "E-mobility getting smart with data," *Creat. Tomorrow*, 2019.
[32] J. Vervoordeldonk, "The feasibility of fast charging in Dutch cities: The technological, economical, social and political factors explained," 2018.
[33] R. Wolbertus and R. Van Den Hoed, "De 'laadpaalklever' : de cijfers," pp. 1–4, 2017.
[34] G. Brouns, "Rapport Mobile Smart Grid Business Case," 2010.
[35] T. A. H. T. Lousberg, "How Smart Electric Vehicle Charging Strategies Solve Future Grid Congestion at Residential Area Level in the Netherlands How Smart Electric Vehicle Charging Strategies Solve Future Grid Congestion at Residential Area Level in the Netherlands," 2020.
[36] B. Nijenhuis, "Electric vehicle charging in the Dutch low-voltage grid," Enschede, The Netherlands, 2020.
[37] B. Visser and B. Daniels, "Modelling Future Investments in the Dutch Electricity Infrastructure," 2020.
[38] PhaseToPhase, "Netten voor distributie van elektriciteit," 2020. [Online]. Available: https://www.phasetophase.nl/boek/. [Accessed: 07-May-2021].
[39] J. Ulffers and A. Scheidler, "Grid Integration Studies for eMobility Scenarios with Comparison of Probabilistic Charging Models to Simultaneity Factors," no. October, 2018.
[40] R. A. Verzijlbergh, M. O. W. Grond, Z. Lukszo, J. G. Slootweg, and M. D. Ilic, "Network impacts and cost savings of controlled EV charging," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1203–1212, 2012.
[41] S. W. Hadley, *Impact of Plug-in Hybrid Vehicles on the October 2006 Prepared by*, no. October 2006. 2014.
[42] RVO, "Nationale Agenda Laadinfrastructuur," p. 47, 2019.
[43] A. Mora, "Interoperability of electric vehicle charging infrastructure," *EVS 2017 - 30th Int. Electr. Veh. Symp. Exhib.*, 2017.
[44] W. J. Luthander R, Shepero M, Munkhammar J, "Photovoltaics and opportunistic electric vehicle charging in the power system- A case study on a Swedish distribution grid," *IET Renew. Power Gener.*, 2019.
[45] A. Klettke and A. Mose, "Effect of electromobility on the power system and the integration of RES," no. June, pp. 1–54, 2018.
[46] M. Li and M. Lenzen, "How many electric vehicles can the current Australian electricity grid support?," *Int. J. Electr. Power Energy Syst.*, vol. 117, no. October 2019, p. 105586, 2020.

[47] Tennet TSO B.V., “Investeringsplan Net op land 2020 - 2029,” p. 109, 2020.

[48] X. Lin, J. Sun, S. Ai, X. Xiong, Y. Wan, and D. Yang, “Distribution network planning integrating charging stations of electric vehicle with V2G,” *Int. J. Electr. Power Energy Syst.*, vol. 63, pp. 507–512, 2014.

[49] J. García-Villalobos, I. Zamora, J. I. San Martín, F. J. Asensio, and V. Aperribay, “Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches,” *Renew. Sustain. Energy Rev.*, vol. 38, pp. 717–731, 2014.

[50] R. Jarvis and P. Moses, “Smart grid congestion caused by plug-in electric vehicle charging,” *Texas power energy Conf.*, pp. 1–5, 2019.

[51] J. Pillai, P. Thgersen, J. Møller, and B. Bak-Jensen, “Integration of Electric Vehicles in low voltage Danish distribution grids,” *IEEE power energy Soc. Gen. Meet.*, pp. 1–8, 2012.

[52] Intergovernmental Panel on Climate Change (IPCC), “Climate Change 2014 Synthesis Report Summary for Policymakers,” 2014.

[53] A. Hoekstra and P. Hogeveen, “Agent-based model for the adoption and impact of electric vehicles in real neighbourhoods,” *EVS 2017 - 30th Int. Electr. Veh. Symp. Exhib.*, pp. 1–16, 2017.

[54] G. R. Bharati and S. Paudyal, “Coordinated control of distribution grid and electric vehicle loads,” *Electr. Power Syst. Res.*, vol. 140, pp. 761–768, 2016.

[55] W. van Westering and H. Hellendoorn, “Low voltage power grid congestion reduction using a community battery: Design principles, control and experimental validation,” *Int. J. Electr. Power Energy Syst.*, vol. 114, no. June 2019, p. 105349, 2020.

[56] “Rijksbijdrage laadinfrastructuur voor elektrische auto’s.” [Online]. Available: https://https//www.rvo.nl/subsidies-regelingen/rijksbijdrage-laadinfrastructuur-voor-elektrische-autos. [Accessed: 19-Feb-2021].

[57] N. Refa and N. Hubbers, “Impact of Smart Charging on EVs Charging Behaviour Assessed from Real Charging Events,” *32nd Electr. Veh. Symp. (EVS32)*, no. May, pp. 1–10, 2019.

[58] International Renewable Energy Agency (IRENA), “Electric-Vehicle Smart Charging Innovation Landscape Brief,” 2019.

[59] T. Verschueren, K. Mets, B. Meersman, M. Strobbe, C. Develder, and L. Vandevelde, “Assessment and mitigation of voltage violations by solar panels in a residential distribution grid,” *2011 IEEE Int. Conf. Smart Grid Commun. SmartGridComm 2011*, no. October, pp. 540–545, 2011.

[60] M. Bilton, N. Ebeanu, M. Woolf, P. Djapic, M. Wilcox, and G. Strbac, “Impact of Low Voltage - Connected low carbon technologies on network utilisation.,” p. 55, 2014.

[61] A. M. M. Nour, A. Y. Hatata, A. A. Helal, and M. M. El-Saadawi, “Review on voltage-violation mitigation techniques of distribution networks with distributed rooftop PV systems,” *IET Gener. Transm. Distrib.*, vol. 14, no. 3, pp. 349–361, 2020.

[62] International Energy Agency (IEA), “Technology Roadmap – Energy- efficient buildings: Heating and cooling equipment,” 2011. [Online]. Available: http://www.iea.org/publications/freepublications/publication/ buildings roadmap.pdf. Last accessed: Jan. 2013. [Accessed: 02-May-2021].

[63] M. Rüdisüli, S. L. Teske, and U. Elber, “Impacts of an increased substitution of fossil energy carriers with electricity-based technologies on the Swiss electricity system,” *Energies*, vol. 12, no. 12, 2019.

[64] E. D. Smith, F. Szidarovszky, W. J. Karnavas, and A. T. Bahill, “Sensitivity Analysis , a Powerful System Validation Technique,” pp. 39–56, 2008.

[65] N. Loomans, “Sustainable Energy in Noord Brabanat,” 2019.

[66] I. Nikolic, “Introduction to ABM Modeling in general,” 2020.

[67] H. Deguchi, *Agent-Based Modelling of Socio-Technical Systems*. 2013.

[68] CBS (Centraal Bureau voor Statistiek), “The Netherland on the European scale 2019 Car ownership,” 2019. [Online]. Available: https://longreads.cbs.nl/european-scale-2019/car-ownership/. [Accessed: 07-May-2021].

[69] geobasisregistraties, “Basisregistratie adressen en gebouwen,” 2018. .

[70] Nedu, “Verbruiksprofielen,” 2021. [Online]. Available: https://www.nedu.nl/documenten/verbruiksprofielen/. [Accessed: 05-May-2021].
[71] KNMI (Koninklijk Nederlands Meteorologisch Instituut), “Archief maand/seizoen/jaaroverzichten,” 2018. [Online]. Available: https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/. [Accessed: 02-May-2021].
[72] CBS (Centraal Bureau voor Statistiek), “Elektriciteit in Nederland,” pp. 1–28, 2015.
[73] CBS (Centraal Bureau voor Statistiek), “Energieverbruik van particuliere huishoudens,” 2018. [Online]. Available: https://www.cbs.nl/nl-nl/achtergrond/2018/14/energieverbruik-van-particuliere-huishoudens.
[74] Energievergelijken.nl, “Energieverbruik winkel,” 2021. [Online]. Available: https://www.energievergelijken.nl/zakelijke-energie/energieverbruik-winkel#:~:text=Gemiddeld verbruikt een kleine winkel in de non-foodsector 81,het elektriciteitsverbruik is veel hoger.
[75] Rijksoverheid-Combendium voor de Leefomgeving, “Ruimtegebruik openbare watervoorziening,” 2002. [Online]. Available: https://www.clo.nl/indicatoren/nl006503-ruimtegebruik-openbare-watervoorziening. [Accessed: 05-May-2021].
[76] Greenmatch, “Comparing Air to Water and Water to Water Heat Pumps,” 2021. [Online]. Available: https://www.greenmatch.co.uk/blog/2015/10/comparing-air-to-water-and-water-to-water-heat-pumps. [Accessed: 02-May-2021].
[77] P. Fahlén, “Capacity control of heat pumps,” vol. 1, no. October, pp. 1–15, 2012.
[78] Daikin, “Domestic hot water heat pumps,” 2021. [Online]. Available: https://www.daikin.eu/en_us/product-group/domestic-hot-water-heat-pump.html. [Accessed: 02-May-2021].
[79] CBS (Centraal Bureau voor Statistiek), “Energieverbruik particuliere woningen; wonintype en regio’s.,” 2019. .
[80] When2HeatHeatingProfiles, “Data Platform: When2Heat Heating Profiles,” 2019. [Online]. Available: https://data.open-power-system-data.org/when2heat/. [Accessed: 07-May-2021].
[81] Direct Energy, “How Much Energy Does an Electric Oven and Stove Use?” [Online]. Available: https://www.directenergy.com/learning-center/how-much-energy-does-oven-and-electric-stove-use#:~:text=Most electric ovens draw between,per hour at high heat. [Accessed: 05-May-2021].
[82] International Renewable Energy Agency (IRENA), “FUTURE OF Deployment , investment , technology , grid integration and socio-economic aspects,” International Renewable Energy Agency, Abu Dhabi, 2019.
[83] International Renewable Energy Agency (IRENA), “Global energy transformation: A roadmap to 2050 (2019 edition),” 2019. [Online]. Available: https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition. [Accessed: 02-May-2021].
[84] Netherlands Enterprise Agency, “Electric vehicle charging definitions and explanation,” no. October, 2018.
[85] R. Cobbenhagen, “Performance analysis of solar cars for everyday use,” no. December, 2020.
[86] Worldometer, “World population: Netherlands,” 2020. [Online]. Available: https://www.worldometers.info/world-population/netherlands-population/#:~:text=The population density in the,1%2C316 people per mi2. [Accessed: 02-Jun-2021].
[87] E. Geographics, “USA Population Density Map,” 2013. [Online]. Available: https://www.arcgis.com/apps/View/index.html?appid=49471c66463e486c880ca8ff43b2ecbd. [Accessed: 02-Jun-2021].
[88] B. Pals, “Gemiddelde omzet straattaxi in grote steden is 21,87 per uur,” 2013. [Online]. Available: https://www.taxipro.nl/straattaxi/2013/04/04/gemiddelde-omzet-straattaxi-

in-grote-steden-is-e-2187-per-uur/. [Accessed: 02-Jun-2021].
[89] CBS (Centraal Bureau voor Statistiek), "Onderzoek Verplaatsingen in Nederland 2017 - Plausibiliteitsrapportage," no. july, p. 39, 2018.
[90] MARKETandMarkets, "Ride Sharing Market," 2021. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/mobility-on-demand-market-198699113.html. [Accessed: 02-Jun-2021].
[91] CBS (Centraal Bureau voor Statistiek), "Vakanties," 2019. [Online]. Available: https://longreads.cbs.nl/europese-meetlat-2019/vakanties/#:~:text=Ruim 85 procent van de,procent gaat met de auto. [Accessed: 02-Jun-2021].
[92] P. Denholm, E. Ela, B. Kirby, and M. Milligan, "The role of energy storage with renewable electricity generation," *Energy Storage Issues Appl.*, no. January, pp. 1–58, 2011.
[93] J. Quirós-tortós and B. Lees, "Accepted Paper A Statistical Analysis of EV Charging Behavior in the UK Accepted Paper," no. October, 2015.
[94] CBS (Centraal Bureau voor Statistiek), "In 2019 helft van volwassenen 50-plusser," 2014. [Online]. Available: https://www.cbs.nl/nl-nl/nieuws/2014/38/in-2019-helft-van-volwassenen-50-plusser#:~:text=Nederland telde op 1 januari,de laatste decennia gestaag toegenomen. [Accessed: 02-Jun-2021].
[95] M. Jonathan, "Resources, Environment, and Economic Development."
[96] W. Donker, V. Loenen, D. Version, W. Donker, V. Loenen, and L. Harrie, "Societal costs and benefits of high-value open government data : a case study in the Netherlands," 2018.
[97] Ș M. Gavrila, G. Ș Gh, M. Cazacu, C. O. Carp, and I. Andrei, "Reducing Active Energy Losses in Low Voltage Distribution Grids," vol. 8, no. 3, pp. 113–120, 2017.
[98] M. Nijhuis, *Long-term Planning of Low Voltage Networks*. Technische Universiteit Eindhoven, 2017.
[99] B. Kruizinga, *Low Voltage Underground Power Cable Systems: Degradation Mechanisms and the Path to Diagnostic*. Haarlem: Eindhoven University of Technology library., 2017.
[100] CBS (Centraal Bureau voor Statistiek), "CBS statista [a]," 2017. [Online]. Available: https://www.cbs.nl/nl-nl/onze-diensten/methoden/onderzoeksomschrijvingen/korte-onderzoeksbeschrijvingen/onderzoek-verplaatsingen-in-nederland--ovin--. [Accessed: 02-May-2021].
[101] Statista, "Total number of households in the Netherlands in 2020, by type," 2020. [Online]. Available: https://www.statista.com/statistics/519863/total-number-of-households-in-the-netherlands/. [Accessed: 04-Jun-2021].
[102] S. Crolius, A. Wiederer, R. P. Mpp, S. Leaders, P. Hermann, and D. J. Haigh, "Policy options for electric vehicle charging infrastructure in C40 cities For," 2010.
[103] A. Niida, T. Hasegawa, and S. Miyano, "Sensitivity analysis of agent-based simulation utilizing massively parallel computation and interactive data visualization," *PLoS One*, vol. 14, no. 3, pp. 1–10, 2019.
[104] C. Maarten, W. Bakker, M. Staats, and A. Hoekstra, "Eindrapport Toekomstverkenning elektrisch vervoer."
[105] J. R. Helmus, J. C. Spoelstra, N. Refa, M. Lees, and R. van den Hoed, "Assessment of public charging infrastructure push and pull rollout strategies: The case of the Netherlands," *Energy Policy*, vol. 121, no. February, pp. 35–47, 2018.
[106] Rijksoverheid, "Resultaten verantwoordingsonderzoek 2019. inisterie van Infrastructuur en Waterstaat," no. 260, pp. 1–7, 2019.
[107] Nationaal Laadonderzoek, "Laden van EV's in Nederland," 2020.
[108] H. Turton and F. Moura, "Vehicle-to-grid systems for sustainable development: An integrated energy analysis," *Technol. Forecast. Soc. Change*, vol. 75, no. 8, pp. 1091–1108, 2008.
[109] T. L. Gibson and N. A. Kelly, "Solar photovoltaic charging of lithium-ion batteries," vol. 195, pp. 3928–3932, 2010.

[110] G. Rizzo, “Automotive applications of solar energy,” *IFAC Proc. Vol.*, vol. 43, no. 7, pp. 174–185, 2010.

[111] W. Kempton and J. Tomi, “Vehicle-to-grid power implementation : From stabilizing the grid to supporting large-scale renewable energy,” vol. 144, pp. 280–294, 2005.

[112] H. Neumann, D. Schär, and F. Baumgartner, “The potential of photovoltaic carports to cover the energy demand of road passenger transport,” no. November 2011, pp. 639–649, 2012.

[113] A. Hoekstra, “The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions,” *Joule*, vol. 3, no. 6, pp. 1412–1414, 2019.

[114] Lumen, “Applications of Thermodynamics: Heat Pumps and Refrigerators,” 2021. [Online]. Available: https://courses.lumenlearning.com/physics/chapter/15-5-applications-of-thermodynamics-heat-pumps-and-refrigerators/#:~:text=Second%2C it means that heat,%3D 1 E f f). [Accessed: 02-May-2021].

[115] CBS (Centraal Bureau voor Statistiek), “Car ownership,” 2019. [Online]. Available: https://longreads.cbs.nl/european-scale-2019/car-ownership/. [Accessed: 02-Jun-2021].

[116] P-Direct (Ministerie van Binnenlandse Zaken en Koninkrijkrelaties), “Arbeidsduur en werktijden,” 2020. [Online]. Available: https://www.p-direkt.nl/informatie-rijkspersoneel/mijn-werk/huidig-dienstverband/arbeidsduur-en-werktijden. [Accessed: 02-Jun-2021].

APPENDICES

The system costs of future electric mobility

Comparing battery electric vehicles with solar electric vehicles

List of APPENDICES

Appendix A EV database

EV database	Availability NL	Price NL	Battery capacity (kWh)	range	WLTP energy consumption [Wh/km]
Lightyear HVS	June 2024	€30,000 - €35,000	60.4	725	83
Lightyear ES	March 2021	€149,990	60.0	725	83
Battery Electric vehicles were released in The Netherlands in 2017.					
Volkswagen ID.3 Pro S	September 2020	€43,987	82.0	550	149
Skoda Enyaq iV 80	February 2021	€40,000	82.0	537	153
Volkswagen ID.3 Pro	August 2020	€35,000	62.0	420	148
Renault Zoe ZE50 R110	November 2019	€33,590	55.0	395	139
Hyundai Kona 64 kWh	November 2019	€41,595	67.1	484	139
SEAT el-Born	June 2021	€37,500	62.0	418	148
Opel Ampera-e	September 2017	€34,149	60.0	380	158
Volkswagen ID.4	March 2021	€45,000	82.0	400	205
Volkswagen ID.3 Pure	September 2020	€30,000	49.0	330	148
Renault Zoe ZE50 R135	November 2019	€35,190	55.0	385	143
Opel Corsa-e	March 2020	€30,999	50.0	330	152
Kia e-Soul 64 kWh	January 2020	€42,985	67.1	452	148
Ford Mustang Mach-E ER RWD	November 2020	€58,075	98.8	600	165
Skoda Enyaq iV 60	February 2021	€37,500	62.0	390	159
Kia e-Niro 64 kWh	January 2020	€44,995	67.1	455	147
Skoda Enyaq iV 50	February 2021	€35,000	55.0	350	157
Peugeot e-208	February 2020	€36,250	50.0	340	147
Tesla Model 3 Long Range Dual Motor	February 2019	€59,995	75.0	560	134
Mercedes EQA	March 2021	€45,000	60.0	420	143
BMW i4	March 2021	€65,000	80.0	600	133
Hyundai IONIQ Electric	October 2019	€37,000	38.3	311	123
Nissan Leaf e+	June 2019	€45,850	62.0	385	161
Hyundai Kona Electric 39 kWh	May 2020	€36,795	42.0	305	138
Fiat 500e Cabrio	October 2020	€38,900	42.0	320	131
Tesla Model 3 Standard Range Plus	April 2019	€39,990	50.0	409	122
Tesla Model 3 Long Range Performance	February 2019	€65,595	75.0	560	134
Lucid Air	January 2022	€69,660	113.0	649.6	174
Tesla Model Y Long Range Dual Motor	March 2021	€65,018	75.0	505	149
Peugeot e-2008 SUV	March 2020	€40,930	50.0	310	161
DS 3 Crossback E-Tense	January 2020	€43,190	50.0	320	156
BMW i3 120 Ah	October 2018	€42,411	42.2	310	136
Tesla Model Y Long Range Performance	March 2021	€71,018	75.0	480	156

Table A-1 EV database, cars available from 2017 in The Netherlands.
Source: Adapted from [26].

EVs filtered	*Availability NL*	*Price NL*	*Battery capacity (kWh)*	*rang e*	*WLTP energy consumption [Wh/km]*
Skoda Enyaq iV 80	February 2021	€40,000	82.0	537	153
SEAT el-Born	June 2021	€37,500	62.0	418	148
Skoda Enyaq iV 60	February 2021	€37,500	62.0	390	159
Skoda Enyaq iV 50	February 2021	€35,000	55.0	350	157
Mercedes EQA	March 2021	€45,000	60.0	420	143
average EV	April 2020	€44,630	64.2	423	152
Reference BEV	-	-	60	395	152

Table A-2 EV database, cars available from 2021 in The Netherlands within a price range of €25.000 – €40.000.

Source: Adapted from [26]

Appendix B *Out of scope: interventions and societal cost sources*

In this Appendix, the interventions and societal costs sources that are left out of scope are explained.

Other interventions

In this research, only the smart charging intervention is considered. However, other interventions are left out of scope such as V2G technology, battery storage systems, and solar-to-vehicle (S2V) technology, which also could unburden the grid or the charging infrastructure.

A special form of smart charging is enabled by vehicle-to-grid (V2G) technology. An EV with V2G technology stores electrical power during off-peak hours and returns it to the grid during peak hours. It makes use of the EV battery to feed power back to the grid using a bidirectional EV charger. EVs with V2G technology serve as a storage facility to ensure constant load curves [25]. Research by Turton & Moura [108] states that the installed renewable energy capacity could increase by 30 – 75% with V2G capable EVs due to their ability to store intermittent energy. Richardson [25] states that V2G could contribute to the balancing of demand and supply, provide a spinning reserve, and enable peak power provision. The potential of V2G is often criticized due to its technical complexity and its high costs caused by excessive battery degradation [25]. Some argue that it is better to use a smart charging strategy than to have expensive V2G chargers [35]. The little consensus about the potential of V2G technology in literature leaves the question of whether this technology is yet available in 2050. Due to this uncertainty, V2G technology is not considered in this thesis.

Battery storage systems are becoming very attractive improving asset utilization and potentially preventing grid reinforcements [7]. Accordingly, energy storage systems are increasingly installed in both the distribution and transmission grid. Storage technologies enable peak shaving of the load curve by storing energy during off-peak hours and returning energy to the grid during peak hours. Research on storage technologies is in rapid progress. Storage technologies such as lithium-ion and flow batteries can provide high energy capacities showing high potential for unburdening the grid during peak hours. By peak shaving, storage technology could defer investment for additional transformer and cable capacity. However, storage technology is also expensive. A former cost-benefit analysis on existing storage practices reveals that a battery of 4 MWh costs €4.25 Million [20]. Currently, these storage systems are 15% more cost-effective than grid reinforcements. However, Gupta [7] also found that, as the total residential load curve increases, grid reinforcements become cheaper.

Finally, S2V is a method where solar cells are placed on a roof, powering EVs during the day. The results of S2V technology so far show interesting results in the mission of unburdening the grid. Solar technologies make direct battery charging possible without any transmission losses [109]. When using solar energy as an off-grid energy source, the residual demand and the corresponding peak loads are likely to decrease [110]. However, the peak of solar power will be mostly around noon, while the peaks due to increasing EV loading of the grid are at the end of the working day [111]. One example is shown by a study on S2V technology where solar cells were placed over all available large parking lots in a medium sized-Swiss city. The author finds that 14 – 50% of the city's passenger transportation energy demand could be provided [112].

The concept of S2V technology partly overlaps with the concept of the SEV. Accordingly, it is chosen to just focus on the SEV to ensure that the effect of the SEV is measured correctly and not influenced by S2V technology. Hence, S2V technology is just like the battery storage systems and V2G technology left out of scope in this thesis but is recognized as a potential development in the future that could help unburdening the grid.

Other societal costs sources

The system costs of electric mobility are highlighted in chapter 2. Now the other sources of societal costs are shortly described. In figure 2.3 the external costs and the TCO were already presented to be left out of scope. As they are still important, it is here explained what they contain, and why they are not considered during the analysis of the research.

The costs of negative externalities

As indicated in chapter 2.2 the external costs form a category in the calculation of societal costs. External costs often associated with transport are accidents, congestion, infrastructure, and noise. It is assumed here that the BEV and the SEV do not significantly differ on these aspects and therefore are not considered either during this research. Another category of external costs is the costs of GHG emissions. GHG emissions affect the climate and have a high societal impact. GHG emission costs are barely internalized in the costs of energy nowadays. Indirect GHG emissions of BEVs are expected to have an impact on societal costs in the coming years. BEVs are often seen as a sustainable zero-carbon transport form. Looking from a system point of view this notion of “zero-carbon” driving is currently untenable; BEVs are charged by electricity from the grid. This makes the GHG emissions of BEVs inherently dependent on the Dutch electricity mix. The dirtier the mix, the more GHG emissions, and vice versa. GHG emitting sources entail a high risk of future costs in the form of costly emission taxes or in the form of implementing abatement measures [17]. Hoekstra [113] concluded that current European BEVs and Diesel cars emit respectively 95 and 244 gram GHG per km accounting for driving, manufacturing, and battery production emissions. However, the GHG emissions are left out of scope during this research as the Dutch future energy mix is planned to be more based on vRES [5]. Accordingly, the GHG emissions are expected to have a less significant societal impact than the integration of the BEV and the SEV on the future societal costs.

Total costs of ownership

Another form of societal impact is the price of EVs. Consumers mostly consider the substantial initial costs of EVs above the costs involved in car ownership. Some aspects of the costs of ownership, such as fuel and car efficiency, can however be quite significant for the TCO [30]. The TCO calculates the total cost for EV owners and the costs of using a car for the duration of this ownership [19]. Clerck [30] states that the TCO exists of the initial purchase, operational, non-operational, maintenance, and taxation costs. The initial purchase costs of a car exist of: The depreciation costs, the registration tax, and the costs for private charging infrastructure. The operational costs exist of the fuel costs and the non-operational costs are road taxes, insurances, and the replacement of the battery pack. The TCO of the SEV and BEV are estimated at around €48.000, - and €49.000, - respectively. These amounts are derived from an internal study of Lightyear, calculating the TCO of the SEV and a Nissan Leaf, having comparable characteristics with the reference BEV used in this research. Because the TCO was already explored earlier and does not appear to differ significantly, they are not included in the analysis during this research.

Appendix C The DDZ model in detail

This Appendix explains all the level 2 assumptions made in the DDZ model. It gives more detailed background information on the model.

Historical household and commercial load

Model assumptions	*Data*	*Level*
• *Baseload profile buildings 2017.*	[70]	1
• *Baseload households 2017.*	[73]	1
• *No growth rate is considered for the commercial and residential load curve in 2050.*	[72]	1
• *The future developments from 2017 until 2050 impacting the load curve contain the use of HVAC systems, heat pumps, electric stoves, and electric transport.*	DDZ	1
• *The data of the profile factor in a year is gathered via NEDU. From the different load profiles, an average load profile of a company with less than 2000 working hours is chosen for the non-food sector (E3A). For the food sector, an average load profile of a company with more than 5000 working hours is chosen (E3D).*	[70]	2
• *Buildings in the food and non-food sector consume respectively 467 kWh and 81 kWh per square meter per year.*	[74]	2
• *Power consumption of households.*	[73]	2
• *The load variation is incorporated to let the household demand profile vary per household, and is uniform distributed between 0.6 and 1.4*	DDZ	2

Table C-1 Model assumptions made to calculate household and commercial load.

Commercial load

The total commercial load is the sum of the load of the different commercial buildings. The load of a commercial building is dependent on the commercial demand profile, the average power consumption, and the surface area of a building. The equation for calculating the load per commercial building is given below.

$$Commercial\ load\ building\ non-food\ (h) = Commercial\ demand\ profile\ (h) * 81 * surface\ area\ [m_2] \tag{C.1}$$

$$Commercial\ load\ building\ food\ (h) = Commercial\ demand\ profile\ (h) * 467 * surface\ area\ [m_2] \tag{C2}$$

The commercial demand profile is a factor that indicates the load variation during a day. The data of the profile factor in a year is gathered via NEDU. From the different load profiles, an average load profile of a company with less than 2000 working hours is chosen for the non-food sector (E3A). For the food sector, an average load profile of a company with more than 5000 working hours is chosen (E3D). Here it is considered that companies in the food sector have a relatively higher electricity need, as food must be cooled during the night. Buildings in the food and non-food sector consume respectively 467 kWh and 81 kWh per square meter per year [74]. The function and the size of a building are based on real data of the different neighbourhoods.

Household load

All households have a load that is aggregated as the total household load. The load of a household is dependent on the energy profile factor, the load variation, and the demand profile. The household demand profile gives a distribution of a load of households during the day. The load variation is incorporated to let the household demand profile vary per household and is uniformly distributed between 0.6 and 1.4.

$$Household\ load = household\ demand\ profile(h) * energy\ profile\ factor * uniform\ (load\ variation\ low, load\ variation\ high) \quad \textit{(C.3)}$$

The energy profile factor is the ratio between the energy consumption per day per household dependent on the number of people occupying the household and the sum of the household demand profile over a year. It is calculated via the following formula:

$$Energy\ profile\ factor = \frac{household\ electricity\ consumption\ per\ inhabitant(x)}{4297.875\ (=sum\ of\ household\ demand\ profile*365)} \quad \textit{(C.4)}$$

In the formula above x represents the number of inhabitants a household contains. Below the different number of occupants and the belonging energy consumption per household is shown.

nb of occupants per household	*kWh per year*
1	1925
2	3005
3	3605
4	4155
5	4375
6	4385

Table C-2 The energy consumption per household per year is modelled in DDZ.

HVAC system load

Model assumptions	*Data*	*Level*
• *Data for projecting the electricity demand for space/water heating and cooling in 2050 is derived from historical data of the gas consumption in 2019.*	[73]	1
• *Fully electric heat pumps are situated in 43% of the households by 2050.*	[5]	1
• *AW heat pumps account for all the different heat pumps in a neighbourhood.*	[75]	1
• *All heat pumps are variable-stage heat pumps operating at a thermal energy level of 4kW. For the heat pump, this is the same for cooling and heating and varies between 2.3- and 6-kW thermal energy depending on the type of household and its belonging gas consumption.*	[77]	1
• *Coefficient of performance (COP) WW and AW heat pump derived from historical data.*	[80]	2
• *Ambient temperature based on historical data of 2018.*	[71]	2

Table C-3 Model assumptions made to calculate the load of HVAC systems.

While the gas consumption gradually stops until 2050, the current gas consumption is considered as an indicator for the electricity demand for the use of heating and cooling of space in 2050. Hence, in DDZ historical data of the gas supply from 2019 is used to project the future electricity demand for heating and cooling in households [79]. The gas consumption of the different apartments is shown below.

Type of household	*mean Gas consumption [m_3]*	*Power factor*	*Max power heat pump [kW]*
Apartment	850	0.57	0. 57 * 4 kW = 2.3 kW
Corner house	1330	0.97	0.97 * 4 kW = 3.9 kW
Semi-detached house	1680	1.14	1.14 * 4 kW = 4.7 kW
Detached house	2200	1.5	1.5 * 4kW = 6 kW
Terraced house	1190	0.81	0.81 * 4 kW =3.24 kW

Table C-4 Thermal power per household type.

The heat demand in kWh is calculated via equation C5.

$$Heat\ demand\ [kW](\mathrm{h}) = 35.17\ \left[\frac{MJ}{m_3}\right] * 0.28 * mean\ gas\ consumption\ * gas\ demand\ fraction \qquad \textbf{(C.5)}$$

In this equation, 35.17 stands for the energy density of natural gas, and 0.28 is the conversion factor from MJ to kWh. The mean gas consumption is given C4 and the gas demand fraction, reflecting the distribution of the annual consumption, is derived from historical data of NEDU [70]. When the ambient temperature is lower or higher than the heat demand in a specific hour, the heat pump starts producing heat. The ambient temperature is derived from historical data of 2018 of the KNMI [71]. If the heat demand is bigger than the capacity of the heat pump, the maximum power of the heat pump is being used. The maximum power of the heat pump is expected to differ per type of household. As such the maximum power of the heat pump is assumed to have a proportional ratio (power factor) with the gas consumption in C5.

As the power of the variable stage heat pump can adapt to the amount of energy demanded, the heat pump can consume less power than the maximum power of the heat pump. This happens when the heat demand is lower than the maximum power and higher than the ambient temperature. The heat demand or the Thermal power in kW is given in equation C6.

$$Electricity\ consumption\ [kW]\ = COP * electricCapacity\ HP \qquad \textbf{(C.6)}$$

The coefficient of performance (COP) is a heat pump’s efficiency when heating and is dependent on the ambient temperature. The COP shows how much heat transfer occurs into the warm space compared with how much electricity is required [114]. The COP is derived from historical data [80].

PV load

Model assumptions	Data	Level
• *57% of the households have solar panels installed on their roof by 2050.*	[10]	1
• *The mean PV efficiency on household roofs in 2050 is 22%.*	[82]	1
• *The PV irradiance per hour is originating from the historical data of KNMI.*	[71]	2
• *The installed area of PV is dependent on the size of the roofs of households. The area of the roof is different per building and derived from GIS data of The Netherlands.*	[31]	2

Table C-5 Model assumptions made to calculate the PV load.

PV production in the model is calculated via the following formula:

$$PV\ production\ [kW] = Installed\ area\ PV * PV_{irradiance} * PV\ efficiency * performance\ ratio \quad (C.7)$$

Here the installed area PV is dependent on the size of the roofs of the households. The PV irradiance per hour is originating from the KNMI data from 2018 [71]. The International Renewable Energy Agency (IRENA) [82] predicts that solar cell efficiency will grow in the future. It, however, does not predict the efficiency of solar cells. The PV efficiency is set to 22% in the 2050 scenario, where it is now 18% on average

Appendix D *Dutch driving behaviour*

The average Dutch driver characteristics that account for 53% of the adults in the model are revealed in this Appendix. The driver characteristics mentioned before differ per type of trip. The DDZ model distinguishes between, weekend, day, evening, and work trips. The distributions and the driver characteristics that are different depending on the trip type are presented in Table D1. The assumptions and reasoning done for this distribution are described here.

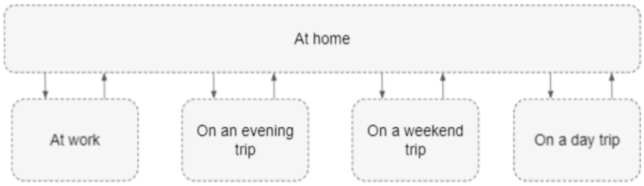


Figure D-1 Different types of trips defined in the DDZ model.

	Chance distribution of going on a trip	*Trip duration distribution [hours]*	*An average distance [km]*
Work	37%	Uniform (6 – 8)	24 [24]
Evening	31%	Uniform (0.25 – 1.5)	16.3 [24]
Weekend	31%	Uniform (0.25, 3)	13.5 [24]
Day	31%	Uniform (0.25, 3)	16.3 [24]

Table D-1 Driver characteristics differing per type of trip in the DDZ model.

Trip chance

The chance of going on either a work, evening, weekend, or day trip by car depends on the first instance if an adult posits a car. In The Netherlands ~54% of the adults possess a car, hence this percentage is used for the DDZ model [115]. From the Dutch inhabitants, 68,7% go to work of which 50% go by car [94]. For simplification of the model, it is assumed that every adult having a car and a job, goes to work by car. Hence, ~37% of the adult population is assumed to go by car to work. For simplification reasons, people with part-time jobs are not considered here. In DDZ it is modelled that when a person does not have a job but possesses a car, it can go on a day trip (Mo-Fri). Following the CBS 57% of the trips consists of trips other than going to work, such as shopping or sporting [24]. Accordingly, it is here assumed that 57% of the adults possessing an EV go on a day trip. Therefore ~31% of the population goes on a day trip by car if not going to work. During the weekend, the population does not go to work but can go on a weekend trip. As the chance is 57% to go on a trip other than work, this percentage is also used for the chance of people in the population going on a weekend trip. Again, only the people possessing a car can go on a weekend trip by car. Hence, the percentage of going on a weekend trip is 31% for both Saturday and Sunday. Just like going on a weekend trip, a person can always go on an evening trip from Monday till Friday, when it possesses a car. The chance of going on an evening trip is the same as for the weekend days following the same way of reasoning.

Departure times

When an adult goes on a trip, the departure time is decided by the model using the distribution in figure D2. Onderzoek verplaatsing Nederland (OVIN) gave specific insights into the hourly trip distribution by the departure in hours [89]. The departure times are set the same for all the different types of trips.

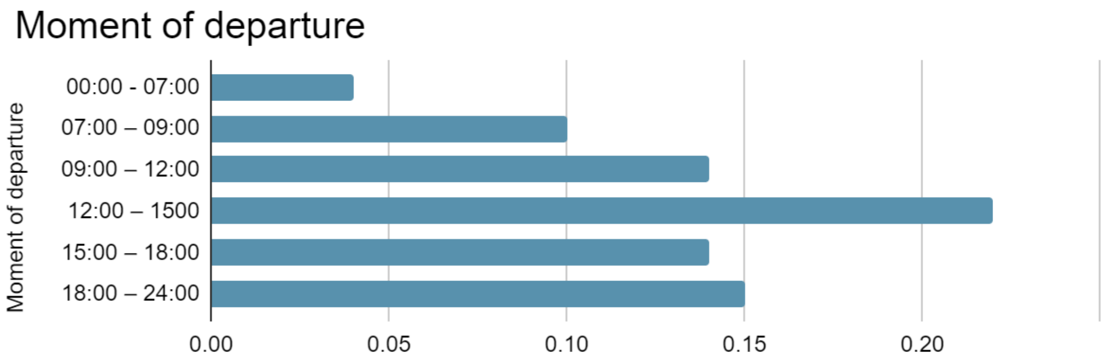


Figure D-2 Departure times.
Source: adapted from [89][92].

Trip duration

After departure, a driver drives to its destination, stays there for an undetermined time, and goes back home, the sum of the time needed for this is being referred to when trip duration is mentioned in this thesis. The average time spent working is 7.2 hours. Hence, the trip duration of going to work is set on a uniform distribution between 6 and 8 hours including the driving time [116]. Where the working times in The Netherlands are clearly defined, the driving times of going on an evening, day, or weekend trip are hard to define. Most trips here have different purposes; when a person goes shopping the trip duration is likely to be shorter than when a person goes visiting family 200 km away. Hence, for the evening, day, and weekend trips a top-down approach is used to define the trip duration distribution. Via sensitive data of charging station operators in the UK, it is found that almost 50% of the people come home between 16:00 and 20:00 as they start charging their car then. Also, the NREL found that more than two-thirds of the hours away from home find a place between 10:00 till 20:00. Knowing this the trip duration is adapted to fit these empirical data results.

Driving distance

The amount of km driven by a driver is defined in the characteristic driver distance. This characteristic influences the SOC and influences the amount of charging and the moment of charging. The average Dutch driver drives on average 18 km per day [89]. Onderzoek Verplaatsingen in Nederland" (OViN) [89] shows that the distances vary per activity type; about 24 km for commuting to work, 21 km for school, 7 km for shopping trips, and 19 km for other activities. In the model, the average work distance is set to 24 km copying the data of the CBS. The day trips and the evening trips are set to 16.3 km, which is a weighted average of the 'other' and 'shopping' trips that account for 7% and 40% of the activities. For the weekend trips a distinction is made. Having a closer look on the data of CBS, the average weekend and week driver distances differ. Accordingly, a difference is made between the weekend distance and the week distance with an average of 15.5 km for the weekend and an average of 19 km for the week. In conclusion the average driving distance in the model is set 24, 16.3, 16.3 and 15.5 km for work trips, day and evening trips and weekend trips respectively.

SOC threshold

One of the driver behaviour characteristics mentioned in the SOC threshold, representing the minimal SOC that a user's car can have before the user starts charging. The SOC threshold is fixed to the same distribution for all types of users in this research. Quiros-Tortos [93], found in a statistical analysis of EV charging behaviour that 70% of the people decide to charge when the

SOC is between 25% and 75%. The resting 30% charges already when the SOC is above this threshold. Hence, this distribution is applied to the EV users in the model.

Appendix E *Model verification*

The verification has been done continuously and step-by-step for every change in the model; steps of the methodology of Deguchi are presented below [67]. In this Appendix, we zoom in to some of the high-level verification calculations that have been made to verify the ABM. The verification is reported for an uncontrolled charging strategy, the urban neighbourhood, and the BEV only.

1. **Agent behaviour tracking:** Selecting relevant output variables to be monitored. These outputs in the DDZ model were in the first instance all the variables represented in the residential load curve and the maximum number of cars charging. The relevant output variables that are discussed here, are the high-level output variables that were monitored continuously. These are the *maximum number of cars charging and the maximum peak load.* Besides, the timing of the peak load was used for the high-level verification of the model.
2. **Single-agent testing:** Here the behaviour of single agents is explored. When for example setting a slider to 100% SEVs in the model, did the value of the SEV indeed equal: ''true''? As such, all model output variables added to the model have been tested. Moreover, graphs were used to verify the values of the agent behaviour, for example showing the solar range of the solar car at any moment during the simulation run. Normal calculations, next to the model calculations have been done to verify if the right values were calculated by the ABM.
3. **Multi-agent testing:** Once the single-agent testing was done, the entire model outcome with all agents present has been tested. The emergent behaviour shown in the total load curve was verified and compared to literature predictions for the charging and the behavioural load.

Maximum simultaneity rate

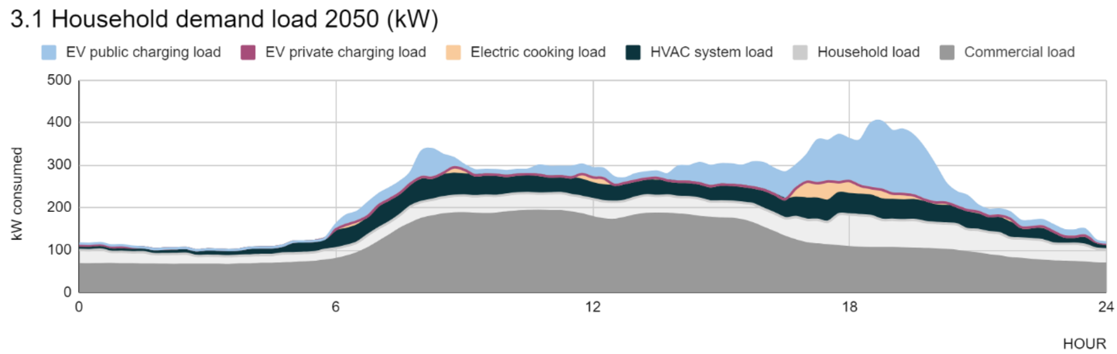


Figure E-1 Household demand load 2050 with an uncontrolled charging strategy in an urban neighbourhood.

Multi-agent testing is done with the neighbourhood demand in an urban setting, without smart charging applied (figure E1). First, the timing of the EV charging load is evaluated. Via sensitive data of charging station operators in the UK, it is found that almost 50% of the people come home between 16:00 and 20:00. They start charging their car in this timeslot. The peak of the UK research data is around 20:00 this corresponds to the peak load around 19:00-20:00 that is found in the research results. Moreover, in figure E1 it is found that there is also a smaller peak around 08:00/09:00. This corresponds to the data of the research of the UK in which the peak is between 09:00 and 10:00. The maximum simultaneity rate in the same research in the UK is 10%. This corresponds to the presented results in this thesis: an average Dutch maximum simultaneity rate of 10.4%. Moreover, Ulffers [39] found that the maximum simultaneity rate is 9% in an urban neighbourhood with 100 EVs in it.

The peak load [kW]

Household peak loads

On average a household has an actual peak power demand of about 0.8 kW [4]. The peak power of the 100 households in the neighbourhood is therefore estimated at 103 kW. The peak power of the households in this research is measured to be 85 kW. This is caused by the on average 20% lower electricity consumption (compared to average) of the apartments that were included in urban neighbourhoods in the model. Accordingly, the household peak load was verified.

Commercial peak load

Buildings in the food and non-food sector consume respectively 467 kWh and 81 kWh per square meter per year [74]. In the ABM there is a scenario with 13 commercial buildings of which there is one operational in the food sector. Table E1 shows the average kWh consumed per hour over all the commercial buildings is 105 kWh. In the DDZ model, this is 102 kWh. This is different due to different energy profile factors. Accordingly, the commercial load curve is found correct for the assumptions that were made in this research.

building	food sector	area [m2]	kWh per year
other	no	150	8505
other	no	175	9922.5
other	no	7500	425250
other	no	155	8788.5
other	no	110	6237
shop	no	1484	84142.8
industry	no	1171	66395.7
other	no	1186	67246.2
office	no	200	11340
meeting	no	100	5670
office	no	150	8505
meeting	no	662	37535.4
shop	yes	550	183260
		Total	922798.1
		Average per hour	105.3

Table E-1 The kWh per year consumed per commercial building in the urban area modelled in DDZ.

HVAC system load

Most of the households are apartments in the urban area in DDZ. Apartments are assumed to have a gas consumption of 850 m_3 per year. This is equal to 8967 kWh electricity consumption per year. As there are 100 EVs modelled in the urban neighbourhood the HVAC system electricity consumption is expected to be 24 kWh per household per day and 1.02 kWh per hour. As it is assumed that 42% of the households have electrified their heat demand by 2050. The aggregated consumption of the HVAC system is expected to be 43 kWh. In the model, the aggregated average consumption per hour of the urban neighbourhood is 49 kWh. This is measured in winter. Therefore, a higher average heat consumption in the winter is found logical.

Electric cooking load

On average 2.1 electric stoves are used with a power of 1 kW. The probability that someone starts cooking during peak hours is 16%. Accordingly, the peak of electric cooking, when all households cook on an electric stove is 31.5 kW. In the model, the peak is 33.9 kW.

Private charging load

The private charging load is almost zero in the model for the urban scenario. This is the consequence of the apartments that are modelled to not have access to private charging places. Subsequently, the private charging load for the modelled situation is verified. In suburban and rural areas, the private charging load accounts for 58% of the total charging load and in a suburban area, the charging load accounts for 36% of the charging load. A weighted average brings that to a national private charging share of 24.3%. This corresponds to the assumption that 25% of households in 2050 will have access to a private charging point.

Public charging load

The aggregated charging peak of the BEVs in the model is 135 kW uncontrolled charging. The average charging power is 11 kW and the number of cars charging simultaneously is 12.5 kW. Together this gives the expectation that the charging peak load amounts to 138.5 kW. In the model, this is 135 kW. The peak load is 1.35 kW per average BEV. This is within the range of earlier research that found that the average peak demand of charging lies between 1 – 2.8 kW depending on the EV type [5].

Appendix F *Experiments*

This Appendix gives an oversight of the different experiments that were executed.

		Experiment 0
	BEV	SEV
Number of EVs	100	100
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
		Experiment 1
	BEV	SEV
Number of EVs	65	65
Suburban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
		Experiment 3
	BEV	SEV
Number of EVs	*33*	*33*
Rural	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27

Table F-1 Main experiments.

	Experiment 3	
	BEV	SEV
Number of EVs	100	100
urban	TRUE	TRUE
smart charging	FALSE	FALSE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
	Experiment 4	
	BEV	SEV
Number of EVs	100	100
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Summer week	June 25 – May 1	June 25 – May 1
	Experiment 5	
	SEV	SEV without a solar roof
Number of EVs	100	100
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27

Table F-2 Additional experiments.

	SA1	
	BEV	SEV
Number of EVs	90 (-10%)	90 (-10%)
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
	SA 2	
	BEV	SEV
Number of EVs	100	100
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	0%	0%
persona 2	3.5%	3.5%

persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
		SA 3
	BEV	SEV
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	*13.5%*	*13.5%*
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
		SA 4
	BEV	SEV
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	*24%*	*24%*
Charging power (3.6/11/22/50)	12%/60%/17%/1%	12%/60%/17%/1%
SOC	~61%	~61%
Winter week	January 20 - 27	January 20 - 27
		SA 5
	BEV	SEV
urban	TRUE	TRUE
smart charging	TRUE	TRUE
persona 1	10%	10%
persona 2	3.5%	3.5%
persona 3	34%	34%
Charging power (3.6/11/22/50)	13%/67%/19%/1%	13%/67%/19%/1%
SOC	*~51%*	*~51%*
Winter week	January 20 - 27	January 20 - 27

Table F-3 Sensitivity analysis experiments.

Appendix G *The system cost calculations*

The local capacity requirements are determined via the method described in chapter four. The calculations are described below.

The charging infrastructure

$$The\ maximum\ simultaneity\ rate\ per\ charger\ type\ (S(x)) = \frac{E}{P(x)} * T(x) \quad \textbf{(G.1)}$$

$$Local\ charging\ capacity\ requirement\ per\ neighbourhood = \sum_{x=1}^{4} S(x) * N * O \quad \textbf{(G.2)}$$

Parameter definition
S (x) = The maximum simultaneity rate per charger type (x)
x= 1….4 for charging points 3.7 kW, 11 kW, 22 kW and 50 kW
E = The maximum electricity consumption of the EVs.
P(x) = The speed of charger type (x)
T(x) = The share of available chargers of type (x)
x= 1….4 for charging points 3.7 kW, 11 kW, 22 kW and 50 kW
N = number of EVs
O = Occupancy ratio

The local capacity requirement calculations for different neighbourhoods are given in equation G.1 where x stands for the different types of chargers and S stands for the absolute number of EVs charging per neighbourhood. The maximum simultaneity rate and capacity requirements of charging are illustrated in Tables G1 and G2. The occupancy ratio that reflects the ratio of time an EV on average occupies a charging station to the effective time it is charging, is assumed to be 5, based on Wolbertus [33]

Maximum simultaneity	100% BEV	100% SEV	Number of EVs
Urban	8.5%	2.8%	100
Sub-urban	11.7%	4%	65
Rural	12.7%	4.85%	33

Table G-1 The maximum simultaneity rate for the different neighbourhoods.

Local capacity requirement BEV				
public charging power 3.7; 11; 22; 50	19%	67%	13%	1%
Urban	8.075	28.475	5.525	0.425
Suburban	7.22	127.3	24.7	1.9
Rural	3.99	14.07	2.73	0.21
Local capacity requirement SEV				
Urban	2.66	9.38	1.82	0.14
Suburban	2.47	8.71	1.69	0.13
Rural	1.52	5.36	1.04	0.08

Table G-2 The local capacity requirements for the different neighbourhoods.

The national charging stations needed in 2050, proportionally multiplied with the number of neighbourhoods per type of neighbourhood (urban, suburban, and rural) needed are presented in Table G3. Subsequently, the number of charging points needed in the case of a BEV/SEV fleet is presented in Table G4.

$$Charging\ investment\ need = \sum_{n=1}^{3}\sum_{x=1}^{5} S\,(x)\ *\ Nev * C(x) * N(n) \qquad \textbf{(G.3)}$$

Parameter definitions
S (x) = The maximum simultaneity rate per charger type (x)
Nev = The number of EVs that are available in a neighbourhood
C (x) = Costs in € per charger type (X).
x= 1….5 for charging points 3.7 kW, 11 kW, 22 kW and 50 kW
N (n) = The number of type n of neighbourhood on national scale
N = 1, 2, 3 for urban, suburban, and rural neighbourhoods

y	*Number of neighbourhoods per urbanization category*	
1	Number of neighbourhoods urban (47%)	39.232
2	Number of neighbourhoods suburban (29%)	24.207
3	Number of neighbourhoods rural (24%)	20.033

Table G-3 Number of neighbourhoods per urbanization degree.

National charging points needed (100% BEV)

public charging power distribution	19%	67%	13%	1%	
Public	3.7 kW	11 kW	22 kW	50 kW	Total
urban	316799	1117133	216757	16674	1667362
sub-urban	174775	616311	119583	9199	919866
rural	79933	281870	54691	4207	420701

National charging points needed (100% SEV)

Public	3.7 kW	11 kW	22 kW	50 kW	Total
urban	104357	367997	71402	5492	549249
sub-urban	59791	210843	40910	3147	314691
rural	30451	107379	20835	1603	160267

Table G-4 Number of charging points needed nationally.

The costs at 100% BEV and SEV penetration rate per charger and neighbourhood are given in Table G5. Now the total costs are summed up. The NPV is calculated with the current Dutch rent rate of 1.65%. The population growth is estimated at 19%. These results are presented in G6.

National costs charging infrastructure at 100% BEV penetration.

Charging speed	3.7 kW	11 kW	22 kW	50 kW	
Costs per charging point	€3,400	€3950	€4500	€31.000	TOTAL
Urban	€1,077,116,027	€4,412,674,249	€975,406,928	€516,882,304	€6,982,079,508
Sub-urban	€594,233,723	€2,434,426,544	€538,121,870	€285,158,598	€3,851,940,735
Rural	€271,772,955	€1,113,385,643	€246,110,184	€130,417,362	€1,761,686,144
National costs charging infrastructure at 100% SEV penetration.					
Urban	€354,814,691	€1,453,586,811	€321,310,518	€170,267,112	€2,299,979,132
Sub-urban	€203,290,484	€832,830,134	€184,094,324	€97,554,257	€1,317,769,199
Rural	€103,532,554	€424,146,912	€93,756,260	€49,682,805	€671,118,531

Table G-5 Costs for the charging infrastructure at 100% BEV and SEV penetration in 2050.

Charging infrastructure cost calculations	*BEV*	*SEV*	*difference*
Sum of costs for charging infrastructure.	€12,595,706,386	€4,288,866,861	€8,306,839,524
Mean NPV (r = 1.65)	€9,824,650,981	€3,345,316,152	€6,479,334,829
NPV with 19% population growth	€11,691,334,667	€3,980,926,221	€7,710,408,446

Table G-6 Charging infrastructure cost calculations 2050.

The grid

A grid asset needs to be replaced when the peak load of the grid is higher than the rated capacity of the asset itself. The grid CBA calculations, therefore, consists of two steps: (1) determine the current status of the grid and (2) determine the capacity requirements for the grid in 2050. Two types of assets are considered: (1) transformers and (2) cables. When the capacity requirement is higher than the current level of the grid, the grid asset needs to be replaced.

The status of the grid: the transformers

The grid assets that are replaced with grid reinforcements are cables and transformers separately. Before presenting the results of the local capacity requirements of transformers and cables the pre-research that is executed to determine the status of the grid is presented. This experiment used equation G.4. The historical peak load was just as for the other experiments derived from the ABM.

$$Current\ transformer\ capacity = f(x) = H(x) * 1.01^{l} * (1 + s) \tag{G.4}$$

Parameter definition
H (x)= The historical peak load of neighbourhood x.
x = 1, 2, 3 for urban, suburban, and rural neighbourhoods.
S = Safety margin
L = Lifetime transformer

Equation 4.2 is applied to the historical peak load H, measured in apparent power (kVA), in urban, suburban, and rural areas. The historical peak load is taken in the year 2010 and the lifetime l is set to 40 years [40]. The planned capacity of the transformer that was placed in 2010 is assumed in this research to be representative of all transformers in The Netherlands.

	Peak load grid 2017 [kW]	Peak load grid 2010 [kW]	Peak load grid 2050 [kW]	safety margin	Capacity requirement estimated kW	Capacity estimated [kVA]	*Current transformer capacity*
urban	235.7	219.8	327.3	0.1	360.0	400.0	*400/630*
sub-urban	79.3	74.1	110.4	0.1	121.4	134.9	*160/250*
rural	28.4	26.5	39.4	0.1	43.3	48.2	*100*

Table G-7 The outcomes of experiment -1: status grid.

In Table G8 the status of the grid was matched to the current distribution of transformers that were presented in figure G1.

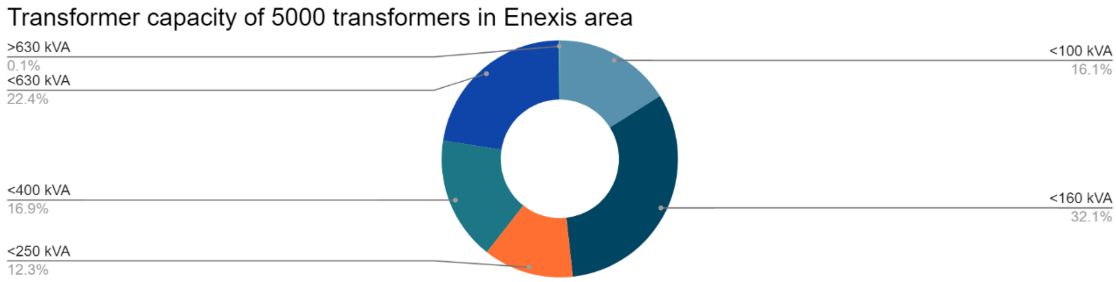


Figure G-1 Transformer capacity distribution of 5000 transformers in the Enexis area.
[Information obtained via internal data Enexis (2007).]

The status of transformers	100 kVA	160 kVA	250 kVA	400 kVA	630 kVA
Share of transformers	16.1	32.1	12.3	16.9	22.4
Urban	-	-	-	43.00%	57.00%
sub-urban	-	72.30%	27.70%		-
rural	100.00%		-	- -	-

Table G-8 The current status of transformers.

The status of the grid: cables

Next to the transformers, the cables in the grid are considered. This research uses former Ph.D. research [98] of Nijhuis that clustered 88.000 cables in the network of a Dutch DSO into 26 common clusters accounting for 71.3 % of the total LV network of this specific DSO. The top 5 of the clusters accounting for 35% of the Dutch distribution network are used to sketch the different cables in the distribution network. The distribution of cable types in figure G2 shows the distribution used for the system cost calculations in The Netherlands in this research. Table G-11 shows the status of the cables that were used for the cost calculations.

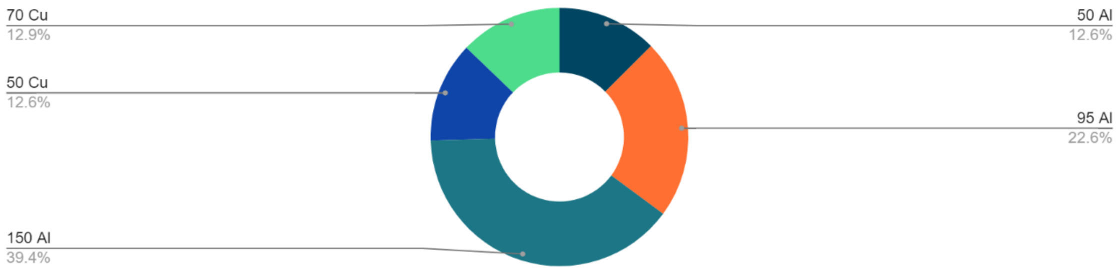


Figure G-2 Cable capacity distribution of 88.000 cables.

Status cable: Capacity distribution

Type	Capacity [A]	Capacity [kw]	Share [%]
50 Al	115	26.4	12.6
95 Al	175	40.25	22.6
150 Al	230	52.9	39.4
50 Cu	125	28.7	12.6
70 Cu	155	35.65	12.9

Source: Adapted from [36].

Table G-9 Current cable capacity distribution in The Netherlands.

The capacity of the cables in neighbourhoods is the length of the cables times the amount of the cables that are presented in Table G-10. In Table G-11 the final current level of the cables was determined.

Cable dimensions	number of households	Number of cables per neighbourhood	meter cable per household (m)	meter cable needed in the neighbourhood (m)
Urban	129	5.6	25	3870
sub-urban	85	3.7	37.5	3187.5
rural	43	1.9	50	1935

Table G-10 Cable dimensions per type of neighbourhood.
Source: Adapted from [98].

Status of cables	*50AL*	*95AL*	*150AL*	*50CU*	*70CU*
Share of cables	12.6%	22.6%	39.4%	12.6%	12.9%
Urban	148.1 kW	225.8 kW	296.7 kW	161.0 kW	200.0 kW
sub-urban	97.6 kW	148.8 kW	195.5 kW	106.1 kW	131.8 kW
rural	49.4 kW	75.3 kW	98.9 kW	53.7 kW	66.7 kW

Table G-11 The current status of the cables in The Netherlands.

The local capacity requirements of the grid

The grid infrastructure is dimensioned such that the rated capacity of the grid assets is equal to the energy demand they are subject to. After determining the current capacity of the transformer and cables in the pre-research, the needed capacity for the future transformers in the three different neighbourhoods was determined. The capacity is based on the future load curve modelled in the DDZ model described in chapter 3. The estimated local capacity requirements in 2050 for transformers are given in kVA and based on the peak loads per neighbourhood in the ABM in Table G-12. A safety margin of 10% is included in the calculations. The local capacity requirements for the cables are calculated similarly and given in Table G-13 in kW.

Local capacity requirements Transformers	Capacity requirement at 100% BEV [kVA]	Capacity requirement at 100% SEV [kVA]
Urban	388.7	342.0
sub-urban	201.7	183.2
rural	103.7	100.6

Table G-12 Local capacity requirements for transformers.

Local capacity requirements cables	*Capacity requirement at 100% BEV [kW]*	*Capacity requirement at 100% SEV [kW]*
Urban	350	308
Suburban	182	165
Rural	93	91

Table G-13 Local capacity requirements for cables.

The national capacity requirements of the grid

A grid asset needs to be replaced when the peak load of the grid is higher than the rated capacity of the asset itself. Based on the status of the grid (Table G8 and Table G11) and the *local* capacity requirements (Table G12 and G13) from the DDZ model the *national* capacity requirements could be derived. When the capacity requirement is higher than the current level of the grid, the grid asset needs to be replaced.

Transformer capacity requirement	100 kVA	160 kVA	250 kVA	400 kVA	630 kVA	% Of transformers replaced at 100% BEV penetration	% Of transformers replaced at 100% SEV penetration
Urban	-	-	-	43.00%	57.00%	0%	0%
sub-urban	-	72.30%	27.70%		-	72.30%	72.30%
Rural	100%	-	-	-	-	100.00%	100%

Table G-14 National transformer capacity requirements.

Cable capacity requirement	*50AL*	*95AL*	*150AL*	*50CU*	*70CU*	***BEV replaced cables***	***SEV replaced cables***
Share	12.6%	22.6%	39.4%	12.6%	12.9%		
Urban	148.1 kW	225.8 kW	296.7 kW	161.0 kW	200.0 kW	100.00%	100.00%
sub-urban	97.6 kW	148.8 kW	195.5 kW	106.1 kW	131.8 kW	60.60%	60.60%
rural	49.4 kW	75.3 kW	98.9 kW	53.7 kW	66.7 kW	60.60%	60.60%

Table G-15 National cable capacity requirements.

The costs for the grid

The type of transformer replacing the old one is always the first transformer available in a higher capacity than the replaced transformer. The type of cable replacing the old one is always the standard 150 AL cable unless this capacity is also exceeded. Then a 240 AL cable is used for the replacement bringing higher costs. The costs per neighbourhood are proportionally extrapolated to national costs by multiplying the capacity needed with the costs and the number of neighbourhoods (Table G3) within the belonging urbanization category.

$$Grid\ investment\ need = \sum_{n=1}^{3}(C_{trans} + l_{cable}\ C_{cable})\ * N(n) \qquad \textbf{(G.5)}$$

Parameter definitions
C_{trans} = The material and installation costs of a transformer. [€]
C_{cable} = The material and installation costs for one kilometre of cable [€]
L_{cable} = Length of a cable [km]
N (n) = The number of type n of neighbourhood on national scale
N = 1, 2, 3 for urban, suburban, and rural neighbourhoods

Costs transformer [€]

Trafo category	Material & installation material	Installation costs	Total (excl.)	Taxes (10%)	Total (incl.)
100 kVA	€ 4,000	€ 1,000	€ 5,000	€ 500	€ 5,500
160 kVA	€ 6,000	€ 1,000	€ 7,000	€ 700	€ 7,700
250 kVA	€ 7,000	€ 1,000	€ 8,000	€ 800	€ 8,800
400 kVA	€ 11,000	€ 1,000	€ 12,000	€ 1,200	€ 13,200
630 kVA	€ 16,000	€ 1,000	€ 17,000	€ 1,700	€ 18,700

Table G-16 Costs of transformer reinforcements.
[information obtained via internal information of Enexis.]

Costs cable [€]	Costs per meter material (AL 150)	Extra costs (AL 240)	installation costs per meter	extra costs per meter	total costs per meter (50AL)
Urban	€12	€12	€20	€15	€47
sub-urban	€12	€12	€15	€15	€42
rural	€12	€12	€10	€15	€37

Table G-17 Cost breakdown cables.

National transformer costs [€]	Total costs at 100% BEV penetration	Total costs at 100% SEV penetration
	€0	0
sub-urban	€154,014,617	€154,014,617
rural	€154,257,095	€154,257,095

Table G-18 National transformer costs per neighbourhood.

National cable cost [€]	Total costs at 100% BEV penetration	Total costs at 100% SEV penetration
	€7,464,878,965	€7,464,878,965
sub-urban	€1,963,872,496	€1,963,872,496
rural	€965,755,593	€965,755,593

Table G-19 National cable costs per neighbourhood.

The results of the calculations of equation G.5 are shown in Tables G18 and G19. In the equation, G.6 t is 2050 and t0 is 2017 as the simulated scenario is 2050 and the data for calculating the load curve has been derived from data of 2017. The NPV has been calculated for both the SEV and the BEV. Consequently, the TSC_{system} is calculated for the SEV and the BEV. Finally, the growing population is considered in the analysis. A report of Netbeheer Nederland [9] states the number of connections is expected to rise by around 19% until 2050. Hence the TSC is calculated with a population growth factor (P_{growth}) of 1.19. The result that considers the NPV and the population growth is illustrated in Table G20.

$$TSC_{system} = \frac{TSC}{(1+r)^{t-t_0}} * P_{growth} \qquad \textbf{\textit{(G.6)}}$$

Parameter definitions
TSC = Total system costs. [€]
R = Dutch interest rate [%]
P_{growth} = growth of the population [%]

Grid cost calculations	BEV	SEV	difference
Sum of costs for grid	€10,702,778,765	€10,702,778,765	€0
Mean NPV (r = 1.65)	€8,348,167,437	€8,348,167,437	€0
NPV with 19% population growth	€9,934,319,250	€9,934,319,250	€0

Table G-20 National grid reinforcement costs predicted until 2050.

Total costs

The steps above describe how the costs are established. Here the total costs per neighbourhood and system asset are broken down.

National system costs	100% BEV	100% SEV	difference
Grid reinforcements costs	€9,934,319,250	€9,934,319,250	€0
Charging reinforcement costs	€11,691,334,667	€3,980,926,221	€7,710,408,446
TOTAL	€21,625,653,917	€13,915,245,471	€7,710,408,446

Table G-22 National system reinforcement costs predicted until 2050.

Cost-breakdown per neighbourhood

Experiment 0: urban				
Grid reinforcements		100% BEV	100% SEV	difference
	Transformer	€0	€0	€0
	Cables	€6,928,900,655	€6,928,900,655	€0
Charging infrastructure reinforcements	Charging points	€6,480,766,199	€2,134,840,630	€4,345,925,569
TOTAL		€13,409,666,854	€9,063,741,285	€4,345,925,569
Experiment 1: suburban				
Grid reinforcements		100% BEV	100% SEV	difference
	Transformer	€142,956,367	€142,956,367	€0
	Cables	€1,822,866,451	€1,822,866,451	€0
Charging infrastructure reinforcements	Charging points	€3,575,371,390	€1,223,153,370	€2,352,218,020
TOTAL		€5,541,194,208	€3,188,976,188	€2,352,218,020
Experiment 2: rural				
Grid reinforcements		100% BEV	100% SEV	difference
	Transformer	€143,181,436	€143,181,436	€0
	Cables	€896,414,341	€896,414,341	€0
Charging infrastructure reinforcements	Charging points	€1,635,197,078	€622,932,220	€1,012,264,858
TOTAL		€2,674,792,855	€1,662,527,997	€1,012,264,858

Table G-23 National system reinforcement costs predicted until 2050 per type of neighbourhood.

Appendix H *Observations results*

In contrast to the mentioned differences between the BEV and the SEV, the similarities of the model results are explained here below. The neighbourhood demand including the electricity consumption of EVs for a winter day is given in figure H1. A general finding is that the rush hour of car charging for both the SEV and the BEV is during midnight. This is caused by the smart charging strategy that is effective for 69%, giving the car users the incentive to charge their car during off-peak hours.

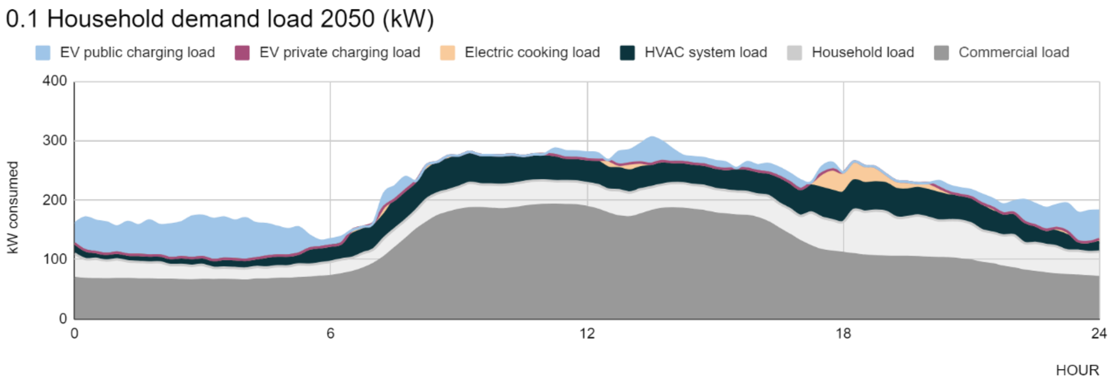


Figure H-1 Load curve on a weekday in an urban area in winter.

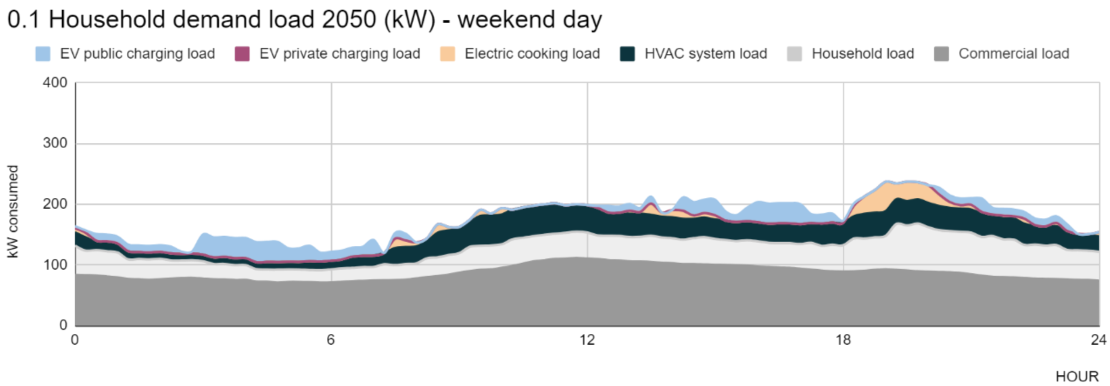


Figure H-2 Load curve on a weekend day in an urban area in winter.

In the figures above the residential demand is given for a weekday and a weekend day. On the weekend the charging need for both the SEV, and the BEV is visibly less. This is a consequence of the smaller distances driven and the lower frequency of driving on the weekend. Moreover, the load is more distributed over the day; fewer EVs are charging during the night. This is a consequence of the smart charging strategy. On weekends the peak loads are less present due to fewer fluctuations in electricity demand. Accordingly, the incentive to charge during the night decreases. For the SEV the same pattern is found. Looking at the relative numbers in Table 5.3 the maximum simultaneity rate increases when the urbanization degree decreases. This is a consequence of the smart charging strategy; the bigger the fluctuations in the load curve (see figure H1 and figure H3) the higher the incentive for car users to charge their car during off-peak hours. The fluctuations are higher in thinly populated areas as the household load and the commercial load, reflecting the constant loads in the load curve, are lower; there are fewer commercial buildings and households in lower populated areas. The impact of the introduction of unpredictable loads of the EV is therefore expected to be relatively higher for rural areas. The last finding that is applicable for both the SEV and the BEV is that public charging points are relatively more used in highly populated areas than private charging points. This is a logical consequence of the generally lower availability of private charging points in areas with a higher urbanization degree. There are more apartment buildings in urban areas that do generally have no access to private charging places. In rural areas, the number of private charging events generally is higher.

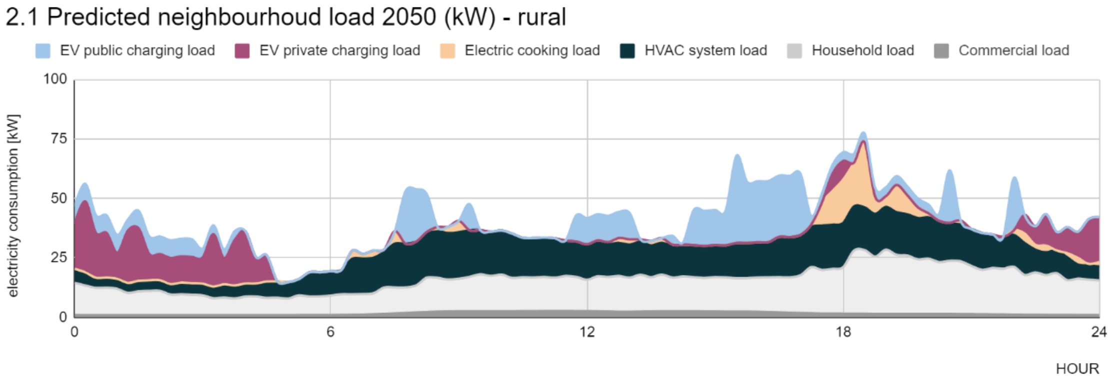


Figure H-3 The neighbourhood demand curve of the BEV in a rural neighbourhood during winter.

Appendix I *Different model outcomes*

Section 5.2 shows a range of the system costs for the different neighbourhoods and EVs. Here below the different model outcomes, regarding the maximum simultaneity rate and the peak loads are presented and explained.

The charging infrastructure

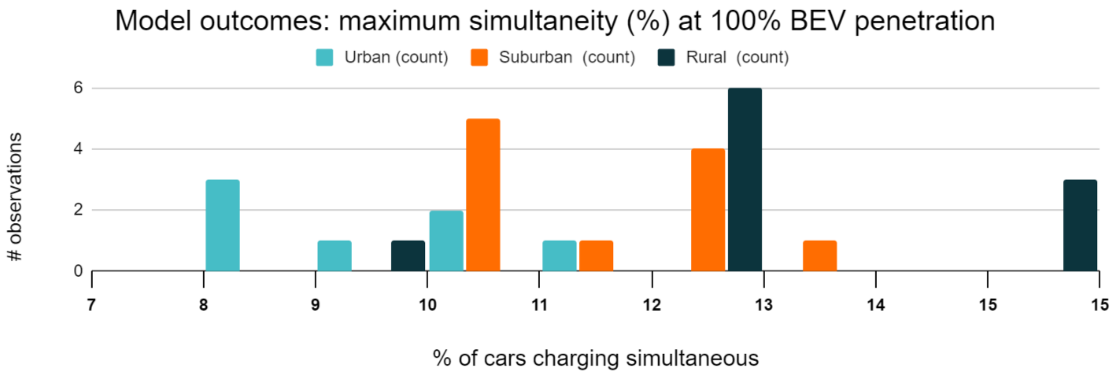


Figure I-1 The maximum simultaneity rate distribution at 100% BEV penetration.

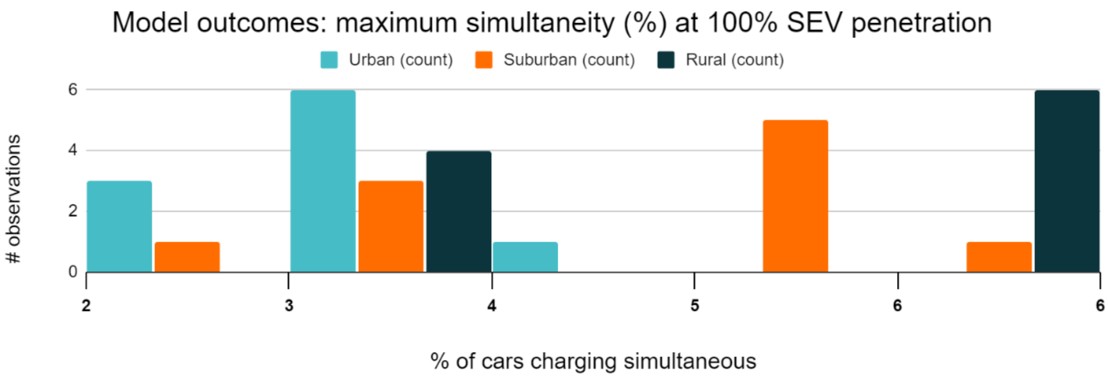


Figure I-2 The maximum simultaneity rate distribution at 100% BEV penetration.

It is observed that the maximum simultaneity rate shows bigger differences between the experiments in the rural scenario. This is caused by the fact that fewer EVs are incorporated in rural areas. Accordingly, the effect of for example one EV charging in a rural area is bigger than in an urban area. For the best and worst model outcomes in figures I1 and I2, the system cost calculations are executed. Looking into the results of these best and worst-case calculations the absolute cost-difference between the BEV and the SEV becomes logically bigger. The impact of the SEV on the charging infrastructure becomes relatively higher in the worst-case cost calculation. Instead of a 65% decrease in the maximum simultaneity rate, a 60% smaller impact is realized by ‘replacing’ the BEV with the SEV in the system. This is a consequence of the relatively higher simultaneity rate in the worst-case scenario for the SEV. On the other hand, in the best-case scenario, the maximum simultaneity rate of the SEV on system costs is even 4 times lower than the maximum simultaneity rate of the BEV.

The grid

The distribution of the model outcomes for the peak loads of ten runs is presented in figures I3 and I4. The variation of the peak loads is bigger for the areas with a lower urbanization degree as the average electricity consumption is lower in these areas. The impact of a change in energy demand of for example 1 kW is higher in rural areas compared to urban areas. This is caused by the fact that fewer EVs are incorporated in rural areas.

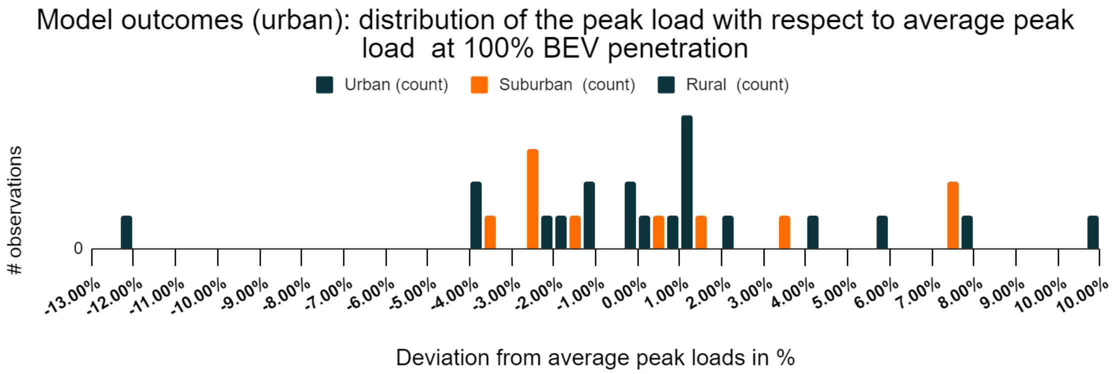


Figure I-3 Distribution of different peak loads deviating from the average peak load measured over the runs at 100% BEV penetration.

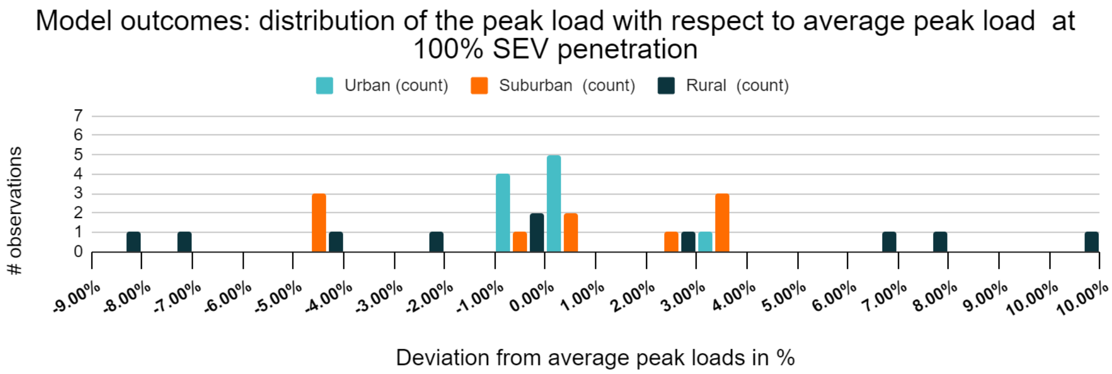


Figure I-4 Distribution of different peak loads deviating from the average peak load measured over the runs at 100% SEV penetration.