Designing future-proof electricity distribution network tariffs in the Netherlands

A comparative analysis of capacity based tariff structures

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Rik van Rossum

Executive summary

With the integration of renewable energy sources and the fast-growing electricity demand, challenges arise affecting the reliability and quality of the Dutch electricity distribution network. To cope with these challenges, the Distribution System Operators (DSOs) could expand the network capacity. Besides the fact that it is not sure if the network can be expanded fast enough, this would also result in high costs. Because the network is dimensioned for the peak load, incentivising demand response is another way to prevent these problems. Since demand response can be used to reduce the peak load of the electricity network.

Demand response can be incentivised by changing the current network tariff structure. The current network tariff structure for Dutch consumers is a fixed tariff based on the connection type. This tariff structure gives no incentives for efficient network usage. Additionally, the current tariff structure is not cost-reflective. In other words, consumers who incur more costs do not pay more. Changing the current tariff structure to a capacity based tariff, in which the amount of capacity used determines the height of the network charge, is currently discussed in the Netherlands.

It is uncertain which capacity based network tariff structure would be the most suitable in the Netherlands. The exact effects of different network tariff structures in the Netherlands remain unknown. Without knowing these exact effects, it is impossible to recommend one tariff structure over the other. This results in the following research question:

What are the effects of different capacity based distribution network tariff structures on electricity demand, expected network charges and network peak load in the service area of Stedin?

To answer this research question, a simulation model is used. This model simulates the expected electricity demand of consumers when subject to different capacity based network tariff structures. The primary constructor of the simulation model is Roman Hennig, a PhD candidate at the Faculty of Technology, Policy and Management at the TU Delft. The examined network structures are two different configurations of a capacity bandwidth tariff, one with bandwidths of 2, 4, 8 and 17 kW and one with bandwidths of 4, 8, 12 and 17 kW, and a personal peak charge model.

The model simulates the expected electricity demand of consumers by assuming that the electricity demand of consumers consists of an inflexible and a flexible part. The inflexible demand is assumed to be constant. The demand corresponding to the charging of an Electric Vehicle (EV) is used to simulate the flexible part. This is done under the assumption that consumers do not increase their network costs due to the charging of their EV.

Two different charging strategies are analysed. Consumers either charge upon arrival, in which they charge as soon as they get home. Or consumers individually optimise their charging behaviour based on the wholesale prices, in which they charge when the wholesale prices are lowest. The first charging strategy results in more electricity usage during peak hours, the second charging strategy results in a very high coincidence factor.

This thesis examines the effects on the electricity demand of consumers, the effects on the network peak demand and the expected network charge for consumers. The results are generated by simulating the model for four different neighbourhoods. In these neighbourhoods, the effect of an increasing number of consumers that charge their EV on the

maximum network peak load is investigated.

The four different neighbourhoods are recreated based on a data set of 378 consumers from the service area of Stedin. The four neighbourhoods are subsequently recreated from the data set, based on the housing type of consumers.

The results showed that all three examined capacity based network tariff structures significantly reduce the amount of network capacity that consumers use. The simulated network peak was significantly lower when consumers were subject to a capacity based network tariff structure. The results of the capacity bandwidth tariff with bandwidths of 4, 8, 12, and 17 kW and the results of the personal peak charge were very comparable. The capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW outperformed the other two tariff structures slightly.

The expected amount of network charges that consumers have to pay when a certain tariff structure is implemented depends highly on the assumptions made for the heights of each tariff. However, for all three examined tariff structures, active consumers are expected to pay more than passive consumers. Indicating that consumers who own an EV or produce electricity with the help of photovoltaics are expected to be paying more than consumers who do not.

The examined network tariff structures were also compared based on the five key regulatory principles to which they must adhere. These regulatory principles originate from European and Dutch law and regulation. The five key regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency. These regulatory principles were first defined to be able to compare different tariff structures based on these principles.

The results of the analysis showed that all examined capacity based network tariff structures adhere to the principles of non-discriminatory and transparency. Indicating that, for all examined network tariff structures, consumers with the same electricity demand were not charged differently and that the methodology to calculate the network charges is clear and unilateral interpretable.

For the regulatory principle of cost-recovery, which states that each DSO should be able to recover their efficient costs, no conclusions could be drawn because it is uncertain if the data set is an accurate representation of the service area of a Dutch DSO or the Netherlands.

Lastly, the cost-reflectiveness and the amount to which network tariff structures promote efficiency was computed. The analysis showed similar results as the analysis of the effects on the network peak load. It was shown that the capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW was the most cost-reflective in most cases.

In conclusion, the effects of the capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW are most significant. However, all three examined network tariff structures reduced the network peaks and incentivised efficient network usage.

Ideally, the cost-recovery problem of a DSO should be further investigated to see which tariff structure enables the DSOs to recoup their efficient costs. Thereafter, it is recommended to implement a capacity based network tariff structure in the Netherlands in the near future.

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List of abbreviations

AC	Air Conditioning
ACM	Netherlands Authority for Consumers and Markets
CEER	Council of European Energy Regulators
DSO	Distribution System Operator
EV	Electric Vehicle
HV	High-Voltage
LV	Low-Voltage
MV	Medium-Voltage
NEDU	Dutch Association for Energy Data Exchange
PV	Photovolaics
RES	Renewable Energy Sources
RME	Norwegian Energy Regulatory Authority
TSO	Transmission System Operator

1 Introduction

1.1 Context

More than 9 out of 10 EU citizens consider climate change to be a serious problem (European Commission, 2019). This problem is expected to get bigger over the next years and immediate and decisive action must be taken (European Commission, 2019). The Netherlands has its own climate policy to reduce emissions. Part of this policy is the goal to have 27 percent of energy production from renewable energy sources (RES) in 2030 (Ministerie van Economische Zaken, 2016). Energy production from RES accounted for 7,4 percent of the Dutch energy consumption in 2018 (Centraal Bureau voor de Statistiek, 2019). Based on both the trend from the last years and the 2030 goals, this percentage is expected to rise significantly in the next years. Furthermore, due to the large scale electrification of heating and transport, the electricity demand is also expected to grow significantly (Moraga-González & Mulder, 2018).

With the integration of RES and the fast-growing electricity demand, challenges arise affecting the reliability and the quality of the electricity distribution network (Mahmud & Zahedi, 2016). Voltage drops and thermal overloading are two of these problems and can be prevented in multiple ways (Etherden & Bollen, 2014; Mahmud & Zahedi, 2016). The Dutch Distribution System Operators (DSOs) could expand the network capacity. However, these additional network cost will subsequently be carried through to the consumers, resulting in higher total consumer costs (Ortega et al., 2008; Schittekatte et al., 2018). Moreover, it is assumed that the electricity demand will grow faster than network expansion can cope with. Since the network is dimensioned for the peak load, another way to prevent these problems is to try to incentivise demand response to reduce the peak load of the electricity network (Schittekatte et al., 2018). This can be done by changing the current network tariff structure.

1.2 Network tariff design

Since the electricity distribution system is a natural monopoly, the overall costs of the network are allocated from the DSOs to the consumers through network tariffs. There exist multiple different network tariff structures that allocate these costs differently. Network tariff design must make sure that these costs are allocated in an efficient, fair, and cost-reflective manner.

The Dutch and European legal framework includes so-called regulatory principles (Ortega et al., 2008). A network tariff structure must adhere to all these regulatory principles and therefore these principles can be seen as the different goals for network tariff design. A network tariff structure must adhere to the following principles: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency (CEER, 2017; Droste et al., 2018; European Commission, 2015). Because the network tariffs in most countries are not cost-reflective anymore, the current network tariff structure has become unfit (Strielkowski et al., 2017). This is caused by the increased penetration of RES and the differentiation of electricity demand. The regulatory principle of cost-reflectiveness states that costs are allocated to those who impose costs on the network (CEER, 2017). Next to the regulatory principles, also fairness plays a part in designing a network tariff structure. Access to the electricity network is seen as a basic-need, which may not be threatened under a different tariff structure (Neuteleers et al., 2017).

These regulatory principles are often quite vague and ill-defined. Additionally, trade-offs exist between the principles itself, for example between cost-reflectiveness and transparency (European Commission, 2015). Furthermore, because the costs of the electricity network are not available on the level of detail of individual users, and some costs are socialised, network tariffs can never be fully cost-reflective (Droste et al., 2018). From the standpoint of economic theory, maximising social welfare is done by making sure that prices are close to the marginal costs. However, since the electricity distribution system is a natural monopoly, the application of marginal costs may be inefficient. In such cases, costs must be allocated in a way that they reflect the marginal costs as closely as possible (Reneses & Ortega, 2014).

Fully cost-reflective tariffs would provide the most efficient signals in the short term. However, in the long term, DSOs must be able to recoup their investment costs. Vogelsang acknowledged that short-term pricing is important to avoid congestion. But at the same time, prices have to guide operating and investment decisions in the long term (2006). This suggests that a trade-off exists between short and long-term efficiency as well. Furthermore, in parts of the grid where congestion is not expected to be prevalent in the near future, a network tariff structure that incentivises consumers to minimise their peak load could be unnecessary and inefficient. Since this would not reduce the network costs and increase consumers costs, leading to higher total costs.

1.3 Network tariff design in the Netherlands

The current network tariff for residential consumers in the Netherlands is only based on the connection type (European Commission, 2015; Lu & Waddams Price, 2018). Since the tariff is not dependent on the electricity demand of consumers it can be classified as a fixed tariff. The three main categories of distribution network tariff structures are fixed, volumetric and capacity based tariffs (Ortega et al., 2008; Schittekatte et al., 2018). Within these categories, there are still many variants (Schittekatte et al., 2018).

Currently in the Netherlands, capacity based tariffs, on the contrary to volumetric tariffs, are discussed and examined as potential future network tariff options (D-Cision, 2019; Droste et al., 2018). Shifting to a capacity based tariff structure would be more efficient and cost-reflective (Nijhuis et al., 2017; Ren et al., 2016; Simshauser, 2016).

The most predominantly discussed option for a new network tariff structure is a capacity bandwidth tariff. Under a capacity bandwidth tariff, consumers contract a certain bandwidth in which they are free to use electricity (D-Cision, 2019; Droste et al., 2018). Another option is a tariff based on measured capacity, in the form of a personal peak charge, which will make its entry in 2020 in Flanders (Hylkema, 2020). Lastly, sticking with the current fixed tariff is also an option.

1.4 Problem Statement & Research Question

It is uncertain which network tariff structure would be the most suitable in the Netherlands. The exact effects of different network tariff structures in the Netherlands remain unknown. Furthermore, there are certain regulatory principles that network tariff design must adhere to (CEER, 2017; Droste et al., 2018; European Commission, 2015; Ortega et al., 2008;

Reneses & Ortega, 2014). The in literature examined network tariff structures are often not related to these regulatory principles.

Without knowing these exact effects and knowing how possible network tariff structures relate to these regulatory principles, it is impossible to recommend one tariff structure over the other.

This thesis aims to answer the uncertainty about the effects of possible network tariff structures in the Netherlands by answering the following question:

What are the effects of different capacity based distribution network tariff structures on electricity demand, expected network charges and network peak load in the service area of Stedin?

1.4.1 Scope

This thesis focuses on the effect of different capacity based distribution network tariff structures on small consumers (households) with a connection of 1x10 Ampere till 3x25 Ampere (1x10A - 3x25A) in the Netherlands. The current tariff structure in place for these consumers is a uniform capacitive tariff, where all consumers pay the same fixed amount.

Furthermore, it focuses primarily on the transport-dependent rate, which is a part of the network costs of the total electricity bill. With that, it is assumed that the other components of the electricity bill remain constant. The examined tariff structures are based on the electricity usage only because currently consumers are not charged for electricity that they feed back into the grid, which is made clear in Article 31c of the Dutch electricity law.

This thesis investigates the effects on electricity demand, the effects on the expected network charges that consumers are expected to be paying and the effects on the network peak load. Furthermore, the five key regulatory principles are quantified and used to compare the different tariff structures with each other.

The four tariff structures that are examined in this thesis are the current fixed tariff, two configurations of a capacity bandwidth tariff, and a personal peak charge.

1.5 Thesis outline

This thesis is structured as follows:

- A literature review that elaborates on the most important technological and institutional aspects that interact with network tariff design is performed in **Chapter 2**. This literature review sketches the framework that this research operates in.
- **Chapter 3** elaborates on the chosen research approach. In this chapter the main research question and the corresponding sub-questions are discussed, as well as the methods to answer these questions.
- The normative criteria which define the five key regulatory principles, on which the comparative analysis is based, are described in **Chapter 4**. This corresponds with answering the first sub-question. The five key regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency.

- To elaborate upon the electricity demand of dutch consumers, **Chapter 5** analyses the data set based on heating type, presence of Photovoltaics (PV) and Electric Vehicles (EVs). To elaborate upon the electricity demand of dutch consumers.
- Based on the conclusions of the data analysis, different Dutch residential neighbourhoods are be recreated in **Chapter 6**.
- **Chapter 7** explains the used simulation model, including the model inputs and outputs, which is used to simulate the electricity demand of consumers when subject to different network tariff structures. The results of the simulations enable us to answer the sub-questions. Different parts of this model are also validated in this chapter.
- In **Chapter 8** the effect of different network tariff structures on the electricity demand of consumers is investigated.
- In **Chapter 9** the effect of different network tariff structures on the maximum peak load of different neighbourhoods is elaborated upon.
- **Chapter 9** discusses the expected network charges for consumers and different consumer groups.
- In **Chapter 11** the different network tariff structures are compared with each other based on the five key regulatory principles.
- **Chapter 12** is used to discuss the main limitations and assumptions of the research. In this chapter the effects of these limitations and assumptions will be analysed and used to reflect upon the results. Furthermore, the results of this thesis are placed into broader context.
- In **Chapter 13** the answers to the five sub-questions are shortly summarized and the main research question is answered. Furthermore, recommendations are made for further research and a policy advice concerning a new network tariff structure in the Netherlands is given.
- **Chapter 14** is used to reflect upon the societal and academic relevance of this research.

2 Literature review

The literature review is performed to analyse the most important technological and institutional aspects that interact with network tariff design. By doing so, it sketches the framework that this thesis operates in.

First, the structure of the electricity bill of Dutch consumers is elaborated upon. Second, the Dutch electricity network is sketched briefly. Third, the legal framework, from which the regulatory principles that network tariff design must adhere to originate from, is analysed. Fourth, the regulatory principles are elucidated. Fifth, the notion of fairness in network tariffs is discussed. Sixth, network tariff design in other European countries is analysed. Last, an overview of the different options for network tariff structures that are currently discussed in the Netherlands is given.

2.1 Dutch electricity bill

The electricity bill for Dutch consumers is made up of multiple components. These components are delivery charges, network costs and taxes (Hage, 2019).

Delivery charges The delivery charges are the amount due for the used electricity. This amount is to be paid to the electricity supplier and consist of fixed costs and variable consumption costs. The consumption costs are the costs for the amount of used electricity. The total consumption costs are calculated by multiplying the electricity consumption with a fixed rate (Hage, 2019). The delivery costs are a fixed tariff that has to be paid regardless of the amount of electricity consumed.

The fixed rate per kWh of consumed electricity and the fixed delivery costs differ between electricity suppliers. Consumers are free to choose their preferred supplier. Consumers can influence the total delivery charges by consuming less electricity, for example through the installation of isolation (Hage, 2019).

Network costs The network costs are the amount due to the DSO for the transport of electricity. These costs are also paid to the electricity supplier, who subsequently pays the DSO (Hage, 2019). The network costs are made out of a standing charge, a capacity rate, a periodic connection fee and a measurement rate. The periodic connection fee is the amount due for the management of the connection. The capacity rate is the cost for the amount of contracted capacity and is dependent on the type of connection. The measurement rate is the costs for the use and management of the electricity meter. In Table 1 below, an overview of the height of the current network charges for small-scale consumers in the residential area of Stedin is given.

Tariff component	Tariff excl. VAT	Tariff incl. VAT
Standing charge	€18,00	€21,78
Capacity rate	€132,48	€160,30
Periodic connection fee	€19,90	€24,08
Measurement rate	€20,00	€24,20
Total per year	€190,38	€230,36

Table 1: Current network tariffs for households in Stedin area (Stedin, 2020)

Consumers currently cannot influence the number of network costs that have to be paid. However, this will be different with a different network tariff structure in place.

Taxes The last part that makes up the electricity bill of Dutch consumers are taxes. All Dutch consumers are paying energy tax. Additional to the regular taxes, 21 percent VAT has to be paid over all cost for the delivery, network charges and energy taxes (Hage, 2019).

2.2 Dutch electricity network

The Dutch electricity system is a very reliable multi-level system. It consists of multiple levels which can be distinguished based on the voltage level (Van Cappellen, 2019). In 2019, the average outage time per consumer was only 19,8 minutes per year (Dewkali & Bogaert, 2019). The three distinguishable levels in the Dutch electricity network are the high-voltage (HV) network, the medium-voltage (MV) network and the low-voltage (LV) network. This thesis focuses on the LV-network.

The high-voltage network The HV-network operates with a voltage level between 110 kV and 380 kV and its primary function is transporting electricity over long distances (Van Oirsouw, 2011). The HV-network is operated by TenneT, the Dutch Transmission System Operator (TSO). Most large electricity producers are connected to the HV-network.

The medium-voltage network The MV-network operates between 3 kV and 50 kV and is used to transport the electricity from the HV-network to the LV-network (Van Cappellen, 2019). The MV-network is operated by the DSOs. Together with the LV-network, the LV-network makes up the distribution network (Van Cappellen, 2019). Some smaller producers and some large-scale consumers are directly connected to the MV-network.

The low-voltage network The scope of this thesis is the LV-network. The LV-network connects the consumers with the rest of the electricity network. A transformer is used to transform the voltage of the MV-network and the LV-network. The voltage of the Dutch LV-network is 0,4 kV. A typical schematic of a Dutch LV-network is shown in Figure 1 on the next page.

In the schematic, the 400 kVA transformer consists of three LV feeders which feed to various customers. A typical LV feeder can serve between 40 and 50 household customers (Bhattacharyya et al., 2008).

Historically, large power plants injected electricity directly into the HV-network, and electricity was consumed in the distribution network. However, with the introduction of RES such as PV, electricity is also injected in the MV and LV-network (Van Cappellen, 2019).

The LV-network is dimensioned based on the expected demand profiles of the connected consumers and the expected coincidence factor. A coincidence factor of 1 means that all the individual peaks of all consumers in a neighbourhood are simultaneous. The needed capacity of the LV-network is computed by multiplying the number of consumers with a calculation value. The current calculation value for most residential consumers is 4 kW (Droste et al., 2018). However, older networks are still dimensioned based on a calculation value between 1 and 1,5 kW and therefore have lower capacity (Van Oirsouw, 2011).

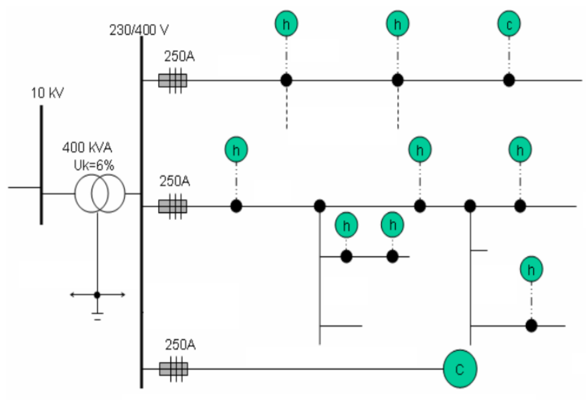


Figure 1: Typical schematic of a Dutch LV-network, adapted from (Bhattacharyya et al., 2008). Households are denoted with green circles with an "h", and the commercial loads are denoted with a "c".

2.3 Legal framework

This section analyses both European and Dutch regulation, to sketch the legal framework. The possible network tariff structures are constraint by the legal framework in place. The legal framework must be able to accommodate a different network tariff structure before that tariff structure is considered as a valid option to investigate.

2.3.1 Network tariffs in European Regulation 2019/943

The core principles of network tariff design are discussed in the most recent European Regulation 2019/943 about the internal electricity market. Article 18 of this regulation discusses the charges for access to networks, use of networks and reinforcements. The first paragraph of this article states the following:

"Charges applied by network operators for access to networks, including charges for connection to the networks, charges for use of networks, and, where applicable, charges for related network reinforcements, shall be cost-reflective, transparent, take into account the need for network security and flexibility and reflect actual costs incurred insofar as they correspond to those of an efficient and structurally comparable network operator and are applied in a non-discriminatory manner."

Multiple regulatory principles are recognised in this first paragraph of article 18. According to this paragraph, network charges must be cost-reflective, transparent, take into account the need for network security and flexibility, non-discriminatory and must reflect actual costs. It is important to note that these actual costs must correspond to those of an efficient and structurally comparable network operator.

This has two consequences: first, this means that network operators have an incentive to behave efficiently since they can only recoup the cost of an efficient and structurally comparable operator. Second, there must be an independent regulator that decides what the costs of an efficient and structurally comparable operator are. In The Netherlands, this is done by the Authority for Consumers and Markets (ACM). The ACM decides the maximum allowed income of each Dutch DSO and based on this and the expected electricity volumes, determines the height of the network tariffs (Autoriteit Consument & Markt, 2020).

The second part of this paragraph prohibits discrimination between production connected at different levels of the transmission system. Therefore, if large power plants do not pay transport-dependent rates, also prosumers that produce electricity with the use of PV do not have to. Furthermore, this paragraph also prohibits the discrimination of storage and aggregation. This means that when a certain network tariff is offered to an aggregator or a storage installation, the same tariff should be offered to any other aggregator or storage installation, even when they do not positively contribute to the network (Ackeby et al., 2013).

The eighth paragraph of this same article discusses the recovery of efficient costs through network charges, which was mentioned in the first paragraph. This paragraph also states the options that regulatory authorities have to achieve cost-efficient operation. It shows how regulatory authorities must incentivise DSOs to become more efficient, which is necessary since the distribution network is a natural monopoly (Reneses & Ortega, 2014).

2.3.2 Network tariffs in the Dutch electricity law

The in the previous section discussed paragraphs originate from European Regulation and therefore they are directly applicable in the Netherlands. However, also in the Dutch electricity law, *"Elektriciteitswet 1998"*, network tariffs are discussed. The first paragraph of article 36 states that:

"The ACM determines the tariff structure and conditions, taking into account: (...) the importance of promoting efficient trade and competition in the electricity market, the importance of promoting the efficient behaviour of consumers, the importance of a good quality of the service provided by network operators, the importance of an objective, transparent and non-discriminatory maintenance of the energy balance in a way that reflects costs."

In this paragraph, the Dutch electricity law specifies that the ACM is the regulator and that the ACM determines the network tariff structure and conditions. Furthermore, this paragraph states the importance of promoting efficiency, promoting efficient behaviour of consumers, good quality of service, and the importance of objective, transparent and non-discriminatory maintenance of the energy balance.

The goal of network tariff design is to be efficient and provide fair cost allocation (Droste et al., 2018). This is ought to be done by keeping certain regulatory principles in mind when designing network tariffs. These regulatory principles originate from European and Dutch law & regulation. In the aforementioned paragraphs, the regulatory principles of transparency, non-discriminatory, cost-recovery, cost-reflective and promoting efficiency are distinguished. These principles are also pointed out in other studies and together form the key principles of network tariff design (CEER, 2017; Droste et al., 2018; European Commission, 2015; Picciariello et al., 2015).

2.4 Regulatory principles

In the previous section, the five key regulatory principles of network tariff design were derived from European and Dutch law and regulation. The five key regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency. In this section, each of the regulatory principles is shortly explained and elaborated upon. Hereafter, trade-offs between these principles are pointed out.

2.4.1 Non-discriminatory

Non-discriminatory cost allocation means that seen from the perspective of the network, users of the network are handled equally in equal circumstances. It contributes to a fair cost allocation of the energy supply (Droste et al., 2018). This means that under the same circumstances the same use of the network should result in the same network charge, regardless of any features characterising the consumer or the purpose for which the electricity is used (CEER, 2017; Ortega et al., 2008; Reneses & Ortega, 2014).

2.4.2 Cost-recovery

Cost-recovery through network tariffs means that the total costs of the electricity distribution network are recouped through the network charges (Droste et al., 2018). The network tariffs must recover the costs to ensure the sustainable development of the electricity network and safeguard the needs of future customers at reasonable prices (CEER, 2017). This principle is directly related to the calculation of the allowed cost of a DSO (Reneses & Ortega, 2014). European legislation states that only the efficient costs, as determined by the regulator, should be recovered. This gives incentive to network operators to be more efficient.

This principle also states that the sum paid by all consumers for each type of connection should be equal to the total recognised cost of that type of connection (Ortega et al., 2008; Reneses & Ortega, 2014).

2.4.3 Cost-reflectiveness

Network tariffs must ensure that costs are allocated to those who impose costs on the network (CEER, 2017). Tariffs should give both DSOs and consumers the economic signals to behave in a way that maximises social welfare (Ortega et al., 2008). Cost-reflectiveness within network tariffs means that the network tariff gives incentives for efficient network usage, which contributes to an affordable energy supply (Droste et al., 2018). Maximising social welfare is not necessarily achieved by minimising network costs.

Because the costs of the network are not available on the level of detail of individual users and some costs are socialised, the principle of cost-reflectiveness does not hold perfectly (Droste et al., 2018). From the standpoint of economic theory, maximising social welfare is done by making sure that prices are close to the marginal costs. However, since the electricity distribution system is a natural monopoly, the application of marginal costs may be inefficient. In such cases, costs must be allocated in a way that they reflect the marginal costs as closely as possible (Reneses & Ortega, 2014).

2.4.4 Transparency

Transparent network tariff design includes that it should be clear to consumers what they are paying for (Droste et al., 2018). Furthermore, the network tariff design process should be transparent to facilitate acceptance and comprehension (CEER, 2017; Reneses & Ortega, 2014). More sophisticated and advanced societies demand more transparency in the process of tariff design (Ortega et al., 2008).

2.4.5 Promoting efficiency

Network tariffs should also promote efficiency. A network tariff structure should incentivise efficient network usage and promote efficient trade and competition. A network tariff structure that better reflects actual costs imposed on the network better promotes efficient network usage. This suggests that this principle is closely related to the principle of cost-reflectiveness.

Furthermore, efficient trade and competition should be promoted. Tariffs influence trade and competition significantly. For example, under the current network tariff structure, producers of electricity do not pay a transport-dependent rate (Droste et al., 2018). Currently, this gives competitive advantages when comparing an electricity production unit with a storage unit, since the storage unit pays when it charges. However, on the other hand, changing this may result in an uneven playing field in the (international) electricity market (Droste et al., 2018).

Vogelsang stated that there are different specific timing issues related to network tariff design (2006). These issues correspond with promoting efficiency on the long and the short term. It can be assumed that infrastructural investments can be postponed if a network tariff structure better incentivises demand response and a reduction in used network capacity in the long term. On the other hand, if there currently is no need to reduce the peak load, since the network capacity is large enough, incentivising demand response can lead to more consumer costs and therefore more overall system costs. This shows the difference between market efficiency in the short term and network efficiency in the long term.

2.4.6 Trade-offs

Even though the regulatory principles originate from the legal framework, they can be somewhat conflicting. In some cases, there are trade-offs to be made when designing network tariffs. For example, transparent tariffs might not be very cost-reflective. Cost-reflective tariffs might require the use of a complex methodology (European Commission, 2015), which results in the consumer not being able to tell what is being paid for and therefore results in a non-transparent tariff.

Second, the principle of cost-reflectiveness states that cost must be allocated to those who impose cost on the network. Next to the fact that this is not fully possible within network tariffs, this could be conflicting with the principle of non-discriminatory. If a consumer wants to be connected to the electricity network, the additional costs cannot be fully allocated to the single consumer, since the non-discriminatory principle states that consumers of the network should be handled equally based on their electricity demand.

Last, cost-reflectiveness could be conflicting with the principle of cost-recovery. In theory, cost-reflective tariffs could be achieved by setting the prices equal to the marginal costs. However, by doing so, the fixed costs of the electricity network are not recouped. One possible solution for this would be to recoup the fixed cost through taxes. However, the cost-recovery principle, originating from European Regulation 2019/943, specifies that all efficient costs must be recouped through the tariffs. This also shows the trade-off between short and long term efficiency. Short term efficiency can be achieved by real-time pricing and by costs that reflect the marginal costs. However, in the long term, also the fixed costs have to be recouped (Vogelsang, 2006).

The Council of European Energy Regulators (CEER) also recommends network tariff design to be simple, predictable and non-distortionary (CEER, 2017; Droste et al., 2018). Non-distortionary means that costs should be recovered in ways that avoid distorting decisions around access to and use of the network (CEER, 2017). Also with these additional principles clear trade-offs can be distinguished, for example between simplicity and cost-reflectiveness (European Commission, 2015; Picciariello et al., 2015).

The fact that trade-offs between the regulatory principles exist indicates that no single best network tariff design exists. Furthermore, the concept of fairness is intertwined with these regulatory principles. The principle of non-discriminatory contributes to a fair cost allocation (Droste et al., 2018). It could be perceived as unfair when the cost-recovery principle does not hold. Also, consumers perceive network tariffs as unfair when the tariffs are unpredictable (Neuteleers et al., 2017). Lastly, it could also be perceived as unfair when the competitive advantages between different consumers arise if the principle of promoting efficiency does not hold.

2.5 Fairness in network tariffs

The concept of fairness within distribution network tariff design can have different interpretations (Lu & Waddams Price, 2018). Often, fairness is directly linked to cost-reflectiveness. Cost-reflectiveness states that the network charges should reflect the costs imposed on the network. The fairness of a network tariff structure can be assessed from the extend to which it meets the principle of cost-reflectiveness (Lu & Waddams Price, 2018).

However, Schittekatte and Meeus argue the existence of a trade-off between cost-reflectiveness and fairness (2018b), implying that fairness and cost-reflectiveness in network tariffs are two different concepts. Cost-reflective tariffs sometimes yield more benefits for active consumers and therefore can be perceived as unfair from the perspective of passive consumers. Furthermore, passive consumers often do not have the financial opportunities to invest in DER and become an active consumer (Schittekatte & Meeus, 2018b). As a proxy for fairness in network tariffs, Schittekatte and Meeus use the difference in change in network charge between active and passive consumers (2018a). They assumed that the total network charges for all consumers stays equal, which implies that passive consumers are paying more if active consumers are paying less. They assumed this to be unfair, showing that fairness can be defined by inequality between consumers (Neuteleers et al., 2017).

Furthermore, Neutelers et al. showed that unpredictability of a network tariff is also perceived as unfair (2017). Lu and Price also conclude that unpredictable network tariffs are perceived as unfair. However, so is a difference in network charge that is not based on underlying costs (2018). Indicating that a relationship exists between fairness and cost-reflectiveness.

Fairness in network tariffs is defined differently in literature. Fairness is related to the predictability of the network tariff, the cost-reflectiveness and the way it interacts with different consumer groups. The previous sections showed how the different regulatory principles relate to fairness and that fairness is not a criterion that is stipulated in Dutch or European law and regulation.

Within the scope of this research, it is assumed that the concept of fairness in network tariffs is encapsulated within the different regulatory principles and that it is mainly represented through the principle of cost-reflectiveness. With this, it is assumed that it is fair that a certain consumer pays more if they impose more costs on the network.

2.6 Network tariff design in other European Countries

Since all European countries are subject to the same European legal framework, it is interesting to explore network tariff design in other European countries. To analyse the relevance of network tariff design in other European countries, three different topics are discussed.

First, the existing work surrounding the topic of network tariff design is analysed. Second, the recent publications of the CEER are examined. Third, the recent publications of two of the most prestigious European research centres, the Florence School of Regulation and the Vlerick Business School are analysed. Lastly, publications from European regulators on the topic of network tariff design are discussed.

Additionally, it is important to stress that the current network tariff structure differs between European countries. Only the Netherlands, Sweden, Italy and Spain have a network tariff structure in place that partly has capacity component. In all of these countries, the capacity component is a fixed (Nijhuis et al., 2017).

2.6.1 Analysis of existing literature

A literature review that analysed the most recent academic literature on the topic of distribution network tariff design is performed. The used methodology and search query can be found in Appendix A.1, the overview of the selected literature can be found in Appendix A.2.

The literature review shows that the current network tariff structure in most countries has become unfit as the network tariffs are not cost-reflective anymore (Strielkowski et al., 2017). Which is caused by the increased penetration of RES and the differentiation of electricity demand. Shifting to a capacity based tariff would be more efficient and cost-reflective (Nijhuis et al., 2017; Ren et al., 2016; Simshauser, 2016).

Consumers that produce electricity through PV significantly benefit from subsidies but only reduce peak load marginally, and even increase the feed-in peak (Simshauser, 2016). Introducing a different network tariff structure, which better reflects actual costs to the network, would result in a decrease of benefits for consumers with PV (Haapaniemi et al., 2017). Therefore, if a new network tariff structure would be introduced, investing in PV could become less beneficial.

Hoarau and Perez showed that network tariffs with a volume component stimulate RES such as PV, whereas capacity based tariffs stimulate the use of storage (2019). They even concluded that the more a tariff structure incentivises PV, the less it incentivises demand response through storage (Hoarau & Perez, 2019). Whereas storage can be used to lower the peak load and PV can be used to lower the total electricity use. Moreover, the potential network cost reduction capacity under capacity based network tariffs would be the highest with the use of demand response using storage (Ren et al., 2016; Steen et al., 2015; Young et al., 2019). This indicates that a capacity based tariff is more cost reductive but does not stimulate the use of PV.

It is difficult to directly adopt and apply these findings to the Netherlands. One of the reasons for this is that there are a lot of different options within capacitive or volumetric tariffs discussed in literature. To illustrate, a volumetric tariff is also referred to as a flat rate tariff (Young et al., 2019), a constant rate tariff (Ruppert et al., 2016), a time-of-use tariff (Young et al., 2019) or a wholesale based tariff (Ruppert et al., 2016). Also capacity based tariffs come in different forms (Narayanan et al., 2018; Simshauser, 2016; Young et al., 2019).

Multiple scientific articles covered network tariff design in Australia or with data from Australian consumers (Brown et al., 2015; Ren et al., 2016; Simshauser, 2016; Young et al., 2019). Even though this shows that network tariff design is currently relevant in Australia, the differences between the Australian and European legal framework makes it difficult to apply these results to European countries.

Other articles discussed network tariff design in Finland (Haapaniemi et al., 2017; Narayanan et al., 2018), the UK (Strielkowski et al., 2017), Austria (Brown et al., 2015) and also in the Netherlands (Nijhuis et al., 2017). An additional search showed the relevance of distribution tariff design in Germany (Hinz et al., 2018) and Belgium (Milis et al., 2019). A capacity based tariff is preferred in most analysed literature (Haapaniemi et al., 2017; Milis et al., 2019; Narayanan et al., 2018).

Although these articles are evidence that network tariff design is a relevant topic in other European countries, the research and their results are very general and do not investigate specific changes to the current network tariff structure. Furthermore, changing the current network tariff does not appear to be very relevant in the countries that are most similar to the Netherlands based on their current network tariff design, i.e. Sweden, Italy and Spain.

The literature review demonstrates that there are a lot of different possible tariff options that all slightly differ from each other and have their own specific benefits. Brown, Farqui and Grausz even concluded that there is no single best network tariff design (Brown et al., 2015). Although more recent literature prefers capacity based network tariffs over volumetric tariffs (Azarova et al., 2018; Nijhuis et al., 2017; Schittekatte et al., 2018; Simshauser, 2016). For these reasons, it is unknown which tariff structure would be most suitable for the Netherlands.

2.6.2 Analysis of CEER publications

The Council of European Energy Regulators published their guidelines of good practice for electricity distribution network tariffs in 2017 (CEER, 2017). In this report, an overview of how the current electricity distribution network tariffs are structured in different European countries is given and also the reason why there is a need for change is argued. However, the analysis did not yet provide a clear solution (CEER, 2017). The main conclusions are the regulatory principles that were discussed in the previous section.

In 2020 the CEER published a paper on electricity distribution tariffs to support the energy transition (CEER, 2020). This paper aims to help stakeholders and national regulatory agencies in their thinking on tariff design. The CEER concludes that there is no one-size-fits-all solution for the European Member States. Furthermore, they primarily conclude that network tariffs should be targeted at reducing system and individual peaks, and should give strong incentives for efficient usage of the grid (CEER, 2020).

2.6.3 Analysis of European research centers

The Florence School of Regulation aims to improve the quality of European regulation and policy and is located in Florence, Italy. The Vlerick Business School is mainly located in Belgium and focuses on post-university research. The repositories of both research centres are used for the analysis.

The main publications in the area of network tariff design are written by Leonardo Meeus, both professor at the Florence School of Regulation and the Vlerick Business School. The analysed research shows that it makes sense to move away from the historical volumetric distribution network tariffs with net-metering (Schittekatte & Meeus, 2018b) and that consumers in general benefit from more cost-reflective tariffs (Schittekatte & Meeus, 2018a). But issues of efficiency and equity can arise between active and passive consumers (Schittekatte & Meeus, 2018a; Schittekatte et al., 2018). Furthermore, cost-reflective tariffs can help to reduce the complexity for both regulator and grid user (Meeus et al., 2020). The nature of the analysed literature is relatively general and does not investigate very specific changes or solutions to the current network tariff design.

2.6.4 Analysis of publications of European Regulators

Publications from regulators in Norway and Belgium which show the relevance of the topic in these countries are analysed in this section.

The Norwegian Energy Regulatory Authority (RME) published a report with their proposed changes to the network tariff structure for LV-network users in May 2020 (Bjelland Eriksen & Mook, 2020). In this report, the RME points out multiple reasons why the current network tariff has become unfit. These reasons include: changing electricity consumption, electrification of transport and self-generation of electricity (Bjelland Eriksen & Mook, 2020). They propose three possible tariff structures: a tariff based on measured capacity, a tariff based on a subscribed capacity and a tariff based on (virtual) fuse size. Figure 2 below illustrates the three main options. With these options, the RME proposes to shift from a predominantly volume-based network tariff structure to a capacity based tariff structure.

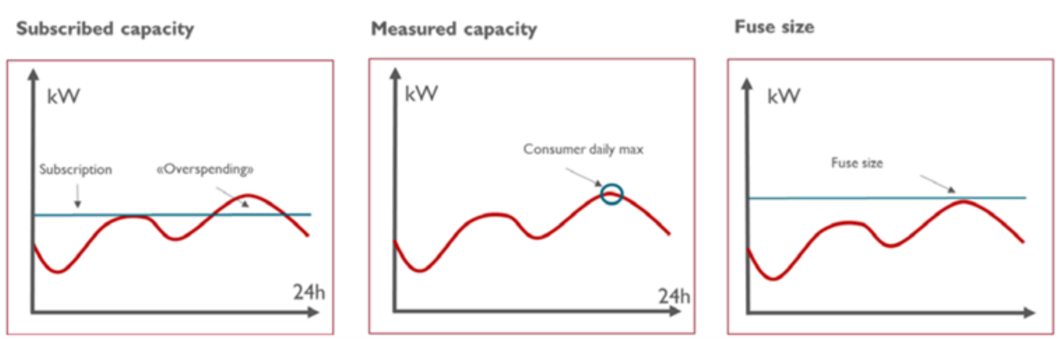


Figure 2: Illustration of the three main models that the RME proposes (Bjelland Eriksen & Mook, 2020)

Also in Belgium, the restructuring of the distribution network tariff is relevant. Two of the three Belgian Energy Regulators, the VREG for Flanders and Brugel for Brussels have changed or have decided to change their tariff structure already.

Brugel has changed its tariff structure for the period 2020-2024 and has implemented a capacity component to achieve more cost-reflective tariffs and accompany the energy transition (Brugel, n.d.).

The VREG published the results of a consultation about the tariff structure in May 2020 (VREG, 2020b). In this report, the VREG proposed a distribution network tariff structure based on maximum measured capacity. In this case, the maximum measured capacity is calculated by averaging the monthly maximum measured capacity over the last twelve months, with a minimum of 2,5 kW per month (VREG, 2020b). Flanders recently announced the implementation of this network tariff based on maximum measured capacity, which will make its entry in 2022 (Hylkema, 2020). However, only 80 percent of the final electricity bill is made up by the capacity component, the other 20 percent are made up by a volumetric component (VREG, 2020a).

2.7 Network tariff design in The Netherlands

Currently, the network tariff in the Netherlands for small-scale consumers with a connection till 3x80 Ampere is a uniform capacitive tariff based on the connection type. The connection types with their corresponding calculation values are shown in table 2 below.

The majority of the Dutch households are situated in customer category three, with a calculation value of 4 kW and a connection of 3x25 A (Droste et al., 2018). The maximum capacity of such a connection is approximately 17,3 kW. This means that a consumer can consume up until 17,3 kW while only being charged for 4 kW. The prospect is that more and more consumers will be exceeding the 4 kW capacity (Droste et al., 2018).

Customer category	Transmission value of the connection	Calculation value [kW]	€ per year incl. tax
1	Till 1x6A	0,05	
2	1-phase till 1x10A	0,5	
3	1-phase>10A & 3-phase>3x25A	4	160
4	3x25A till 3x35A	20	800
5	3x35A till 3x50A	30	
6	3x50A till 3x63A	40	
7	3x63A till 3x80A	50	

Table 2: Calculation values per customer category (Droste et al., 2018)

2.7.1 Possible options for the future

Possible different options for the future are a capacity bandwidth tariff, a personal peak charge, based on measured capacity, and the current fixed tariff. The capacity bandwidth tariff and the personal peak charge emerged as most feasible in the analysis of potential barriers in network tariffs in the Netherlands (Droste et al., 2018). Furthermore, these two tariff structures are also mentioned in Norway and Belgium (Bjelland Eriksen & Mook, 2020; Brugel, n.d.). Since this showed that these options are the most realistic future network tariff structures, these options were chosen to be examined.

Capacity bandwidth tariff Capacity bandwidth tariffs are currently discussed and examined as potential future network tariff options in the Netherlands (D-Cision, 2019; Droste et al., 2018). A capacity bandwidth tariff is a tariff where consumers contract a certain bandwidth in which they are free to consume electricity. However, if they exceed their maximum contracted capacity, they will be fined a certain amount per kWh or automatically get bumped up to the next higher bandwidth. This corresponds with the first option that the RME proposed, shown in Figure 2. The reason why consumers get fined a certain amount or get bumped up to a higher bandwidth is to make sure that consumers do not exceed their bandwidth limit.

The final bandwidth levels are not decided upon yet. But options are having bandwidths of 2, 4, 8 and 17 kW, or having 4, 8, 12 and 17 kW.

Considering the assumption that the costs incurred on the network depend on the capacity and not on the volume of the used electricity, a capacitive network tariff is expected to be more cost-reflective compared to the current tariff structure (Droste et al., 2018).

Personal peak charge A tariff structure under which a consumer pays for the maximum amount of capacity required per month is also an option. Such a tariff structure is called a personal peak charge. There are multiple ways in which a personal peak charge can be implemented. The charge could be based on a single maximum peak value each month. But it could also be based on an average over the maximum daily or weekly peak. The final consumer charge is computed by multiplying the value for the personal peak with a constant charge.

A personal peak charge provides an incentive to minimize the peak capacity to the maximum needed capacity of the inflexible load, as opposed to minimising to the contracted bandwidth level. This tariff corresponds with the second option that the RME proposed, shown in Figure 2.

Fixed tariff The last examined tariff structure is a fixed tariff, which is currently in place in the Netherlands. It is always possible to decide to not change the current network tariff structure. This option can function as a lower level benchmark and with this be able to make claims about the relative effect of the other tariff structures.

2.7.2 Effects of different options

Implementing any of the previously discussed alternatives for the current uniform capacitive tariff will have its effects. Classical passive consumers are expected to stay within a 4 kW capacity bandwidth if a capacity bandwidth tariff is implemented. (Droste et al., 2018). Indicating that for this group of consumers, the effects of the implementation of a capacity bandwidth tariff is expected to be negligible (Droste et al., 2018). However, that is in the case of a 4 kW bandwidth being the lowest option. When a bandwidth of 2 kW is also an option, consumers with low electricity usage might save costs. Classical passive consumers are consumers who do not produce electricity with PV and do not have an EV.

Secondly, in the case of a personal peak charge, the legal framework is not yet in place to accommodate this tariff option (Droste et al., 2018; Hylkema, 2020). However, with the new Electricity Law, this is expected to change in the near future (Hylkema, 2020).

2.8 Conclusion of literature review

This literature review aimed to sketch both the technical and institutional framework that this thesis operates in. This was done by investigating the structure of the electricity bill of Dutch consumers and the structure of the Dutch electricity network. Furthermore, the legal framework was analysed. This resulted in the regulatory principles that network tariff design must adhere to. The notion of fairness was also reflected upon. Hereafter, the network tariff design in other European countries was analysed. Lastly, an overview of the different options for network tariff design was given.

Dutch electricity bill The Dutch electricity bill is made out of three different components. These components are delivery charges, network costs and taxes. The Dutch consumer can influence the amount due for delivery charges by using less electricity. Currently, Dutch consumers cannot influence the number of network costs that have to be paid. By changing the network tariff structure this becomes possible, and therefore the network tariff structure can be designed in such a way that it incentives efficient network usage.

Dutch electricity network The Dutch electricity network consists of the HV, MV and LV-network. The LV-network is within the scope of this thesis. A transformer is used to transform the electricity from the MV-network to the LV-network, from where lines connect to the households. The needed capacity of the LV-network is currently computed by multiplying the calculation value with the number of connected households, the current calculation value is 4 kW (Droste et al., 2018).

Legal framework Network tariffs are mainly discussed in the most recent European Regulation 2019/943. Since this is a regulation, this is directly applicable in the Netherlands. The regulatory principles originate from European law and regulation and also appear in the Dutch electricity law. The identified regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency.

Regulatory principles The regulatory principles originate from European and Dutch law and regulation. The ACM bases their approval for a distribution network tariff on these regulatory principles.

Traditionally, the main goal of electrical companies was cost-recovery. But nowadays, because of the unbundling of electricity production and transport, the relevance of other principles has increased (Ortega et al., 2008). The current network tariffs are predominantly determined by the principles of non-discriminatory and cost-reflectiveness (Droste et al., 2018). But also the other principles must be taken into account. The principle of cost-reflectiveness does not hold perfectly, therefore costs must be allocated in a way that they reflect the marginal costs as closest as possible (Reneses & Ortega, 2014).

Some trade-offs can be identified between these regulatory principles. For example, transparent tariffs might not be very cost-reflective. This suggests that it is highly unlikely that one single best tariff structure exists. Furthermore, a trade-off exists between short term market efficiency and long term network efficiency (Vogelsang, 2006).

Lastly, different regulatory principles can be linked to fairness. For example, the principles of non-discriminatory, cost-recovery, cost-reflectiveness and promoting efficiency can all be linked to fairness.

Fairness in network tariffs Fairness in network tariffs is defined differently in literature. Fairness is related to the predictability of the network tariff, the cost-reflectiveness and to the way it interacts with different consumer groups. Fairness is not a criterion that is stipulated in Dutch or European law and regulation.

Within the scope of this research, it is assumed that the concept of fairness in network tariffs is encapsulated within the different regulatory principles and that it is mainly represented through the principle of cost-reflectiveness.

Network tariff design in other European countries The network tariff design in other European countries was analysed on four different fronts.

The analysis of the existing literature showed that even though the topic is relevant in some European countries, the research and their results are very general. In general, capacitative tariffs are shown to be more cost-reflective and efficient (Azarova et al., 2018; Nijhuis et al., 2017; Schittekatte et al., 2018; Simshauser, 2016).

The analysis of the publications of the Council of European Energy Regulators did not provide specific solutions and acknowledges that a one-size-fits-all solution does not exist (CEER, 2020).

The recent literature published by the Florence School of Regulation and the Vlerick Business School acknowledges that consumers would benefit from more cost-reflective tariffs, but that trade-offs between cost-reflectiveness and fairness exist (Schittekatte & Meeus, 2018b).

The publications from the Norwegian and Belgium energy regulators showed clear evidence that the topic of restructuring the distribution network tariffs is very relevant. In Belgium they already implemented changes for 2020 in Brussels (Brugel, n.d.) and for 2022 in Flanders (Hylkema, 2020).

In general, all four fronts show and acknowledge the relevance of researching potential future network tariff design options. Furthermore, Belgium has already made decisions to change its network tariff structures, Norway seems to be in a similar position as the Netherlands.

Network tariff design in The Netherlands Currently, the network tariff in The Netherlands is a fixed uniform capacitive tariff based on the connection type of Dutch consumers. The calculation value for these small-scale consumers is only 4 kW, while the maximum possible capacity is 17,3 kW.

The three tariffs that are currently discussed and examined in the Netherlands and in this thesis are capacity bandwidth tariffs, a personal peak charge and the current uniform capacitive tariff.

3 Research approach and methods

The research question that was derived at the end of the introduction of this thesis is the following:

What are the effects of different capacity based distribution network tariff structures on electricity demand, expected network charges and network peak load in the service area of Stedin?

In the following sections, the research approach and methods are elaborated on. First, the sub-questions are drafted and explained. Hereafter, the chosen research approach, suited for answering the research questions, is discussed. Third, the used methods and followed research steps are described. Lastly, the limitations of the chosen research approach are discussed.

3.1 Sub-questions & main research question

The objective of this research is to be able to compare different network tariff structures with each other to be able to give policy advice considering the most applicable network tariff structure in the Netherlands. To be able to compare the different network tariff structures with each other the five key regulatory principles are used. These regulatory principles have to be quantified first. The first sub-question aims to do this:

Sub-question 1

How can the five key regulatory principles, to which network tariff design must adhere to, be quantified?

When the criteria on which the comparative analysis is based on are clear, the simulation model can be run and the results can be used to answer the second sub-question. The simulation model is elaborated upon in the next section. The second sub-question is the following:

Sub-question 2

How do different distribution network tariff structures influence the electricity demand of consumers?

This sub-question is exploratory in nature and aims to give insights into the difference in electricity consumption patterns of consumers when subject to different network tariff structures. The results of this sub-question are the characteristics of the expected electricity consumption patterns consumers under different network tariff structures. By answering this sub-question it is possible to conclude concerning the peak shaving capacity of each network tariff structure.

With the help of the results of the first sub-question, the expected effects on the network are investigated. This is done by answering the following sub-question:

Sub-question 3

How do different distribution network tariff structures influence the maximum network peak load?

This third question uses the expected consumption pattern of different neighbourhoods under different tariff structures in combination with the capacities of the corresponding LV-transformers of these neighbourhoods. When comparing the maximum peak load of these neighbourhoods with the LV-transformer capacities when the consumers are subject to different network tariff structures, the third sub-question can be answered. The results of this question can also be used to draw conclusions about the potential to postpone investments related to network expansion.

Next to the expected effects of different tariff structures on the maximum peak load of different neighbourhoods, also the financial effects of different network tariff structures on consumers are investigated. This corresponds with the following sub-question:

Sub-question 4

What are the financial effects of different distribution network tariff structures on consumers?

The financial effects of different tariff structures on consumers are derived by calculating the expected network charge of consumers for different tariff structures. Subsequently, statistical analyses are used to analyse what the main indicators are for the expected network charge under each network tariff structure. Lastly, it is analysed how the expected network charge is different for active and passive consumers.

By answering the last sub-question, the different network tariff structures are related to the regulatory principles that they must adhere to. The criteria used to quantify these principles are discussed in the first sub-question. Relating the different network tariff structures to these criteria is done by answering the following question:

Sub-question 5

How do different distribution network tariff structures relate to the regulatory principles that they must adhere to?

By answering this sub-question the different network tariff options are compared based on these regulatory principles.

3.1.1 Main Research Question

The main research question is answered by answering the different sub-questions. The final result of the research is a comparison of different network tariff structures based on the effects on electricity demand, expected network charge and maximum network peak load. The regulatory principles are also used to compare the different network tariff structures. Based on this comparison, policy advice considering the most applicable network tariff structure in the Netherlands is given.

3.2 Research approach

The research approach chosen to answer the research question is a modelling approach. Since the main research question is exploratory, a modelling approach is suitable. The analysis of existing work showed that modelling similar problems is common (Hoarau & Perez, 2019; Ruppert et al., 2016; Schittekatte & Meeus, 2018a; Schittekatte et al., 2018). Hoarau and Perez modelled the process of designing network tariff structures as a non-cooperative game between various network users and a regulator (2019). Schittekatte et al. (2018) and Schittekatte and Meeus (2018a) used a similar method, where they modelled the interaction between the cost-recovery problem of the regulator and the height of the network tariffs with the use of game theory. Ruppert et al. used different simulation models to simulate residential electricity demand and electricity generation from PV systems (2016).

The objective of this research is to simulate the expected electricity demand of consumers and the corresponding network peaks, based on different network tariff structures and EV charging strategies, and to recommend certain network tariff structures in the Netherlands. The cost-recovery problem of DSOs cannot accurately be modelled, since the available data is no accurate representation of the consumers in the service area of a DSO or the Netherlands. Therefore the cost-recovery problem of the DSOs is left out of consideration and a model based on game theory is not necessary.

Schittekatte et al. used an optimisation model to simulate the electricity demand of consumers when subject to different network tariff structures (2018). Similar mathematical models have already been applied in literature, where the behaviour of consumers is simulated with the use of optimisation models (Momber et al., 2015; Saguan & Meeus, 2014; Zugno et al., 2013). These optimisation models assume that consumers change their behaviour to minimise their overall (network) costs. Since this is in line with the research objective, an optimisation model that simulates the electricity demand under different network tariff structures is used. The main limitation of this approach is that a very complex phenomenon, the behaviour of consumers, is modelled through a very simple and straightforward assumption.

3.2.1 Simulating electricity demand through optimisation modelling

The optimisation model is used to simulate the expected electricity demand of consumers. It is assumed that in the future consumers can schedule their electricity demand to minimise costs through smart home systems and smart meters. However, the assumption that every consumer can schedule all of their demand does not hold. Therefore, the electricity demand of consumers is divided into two groups, flexible and inflexible demand. The inflexible demand is directly derived from the measured electricity demand of consumers. The flexible demand is simulated by allocating EV charging demand to consumers. This way the model simulates the expected electricity demand of consumers when subject to different network tariff structures.

The peak load of a network is simulated with the help of the expected electricity demand. With this, conclusions can be drawn concerning the peak shaving capacity of different network tariff structures. The simulation model is also used to compute the expected network charge of consumers. The expected network charge is used to reflect upon the different network tariffs structures in terms of the financial impact on consumers. Also, the network tariffs structures are compared based on the regulatory principles that network tariff design must adhere to. By doing so, all sub-questions can be answered.

3.2.2 Optimisation modelling in Python

The used optimisation model is constructed in Python using the Pyomo package and is solved using the GPLK solver. Pyomo is an open-source software package that enables us to formulate, solve and analyse optimisation models (Pyomo.com, n.d.). GLPK is a package intended for the solving of large-scale linear and mixed integer programming (GNU.org, n.d.). The primary constructor of the used optimisation model is Roman Hennig, a PhD candidate at the Faculty of Technology, Policy and Management at the TU Delft. The model is discussed in Hennig et al. (2020).

3.3 Methods and research steps

The available consumer load data is analysed before being used to create different Dutch neighbourhoods. The characteristics of these neighbourhoods, including transformer capacities and load data, serve as input for the optimisation model.

3.3.1 Data analysis: electricity demand of consumers

The used data consists of the measured electricity consumption for every fifteen minutes of 396 households in the service area of Stedin. This data set also includes information about the housing type, heating type, cooking type, the presence of PV, EV and air conditioning (AC). It contains data from the 2nd of July till the 30th of September of 2020, which accumulates to a total of 91 days. The data is provided by Stedin, is processed in Excel and analysed using SPSS.

With SPSS, the data is analysed based on the housing type and the presence of PV and an EV. Metrics, hat describes the data, are introduced to analyse the data with SPSS. The results of the data analysis influence the recreation of neighbourhoods and the inputs of the simulation model.

3.3.2 Recreation of Dutch neighbourhoods

A criterion for the recreated neighbourhoods is that they are not meshed and the transformer load characteristics must be known. The main indicator for the recreation of Dutch neighbourhoods is the housing type. Based on the housing type, consumers are drawn from the data set to recreate the neighbourhoods. It must be noted that the goal is not to exactly recreate these specific neighbourhoods, but merely to recreate neighbourhoods that could exist in the Netherlands.

The recreated neighbourhoods are validated by comparing the simulated electricity pattern of the recreated neighbourhoods with the data of the transformers in the actual neighbourhoods.

3.3.3 Investigating the effect of different network tariff structures

The electricity demand of the consumers in these neighbourhoods functions as one of the primary inputs of the model. The initial electricity demand is assumed to be inflexible. Which means that under different network tariff structures, consumers do not change this part of their demand. The inflexible demand is not subject to the optimisation problem.

The flexible demand is simulated on top of the inflexible load. This is done by simulating the demand corresponding to the charging of EVs.

3.3.4 Simulating demand corresponding to the charging of EVs

The demand corresponding to the charging of EVs is simulated based on the 25 synthetic driving profiles derived by Remco Verzijlbergh (Verzijlbergh, 2013). These 25 synthetic driving profiles, in combination with some randomness, result in realistic driving patterns. These driving patterns are translated to charging patterns of EVs. The demand corresponding to the charging of these EVs is subject to the optimisation problem of the model. This means that consumers will schedule the charging of their EV to minimise network costs.

The EV charging patterns are allocated randomly to the consumers in the neighbourhoods. Consumers who already own an EV are not used when recreating the neighbourhoods. This would create unrealistic load data when the demand of another EV is simulated on top of their inflexible demand. The electricity pattern of the consumers that own an EV is used to validate the allocation of demand corresponding to the charging of EVs.

3.4 Limitations

The discussed methods mostly consist of literature research and modelling. Per definition, since every model is a simplification of reality, every model is wrong (Box, 1976) and therefore the results can never be directly applied to reality and can not simply be assumed to be true.

The specific limitation of an optimisation model is the assumption that consumers behave rationally, which might not hold in reality. Also, the fact that consumers know the future electricity prices beforehand forms a limitation. This results in all consumers being able to optimise their EV charging perfectly. This leads to all consumers charging at the same time steps, which would probably not be the case in reality.

Furthermore, the limited amount of data also forms a significant limitation. The limited amount of data results in more uncertainty while analysing the data, but also while recreating the neighbourhoods. Also, the data originates from the months July, August and September, which are three summer months. The electricity usage of consumers is higher during the winter, and therefore this could also have significant effects on the results.

4 Criteria to compare network tariff structures

This chapter gives insight into the normative criteria that are used to compare different network tariff structures with each other, and with this answer the first sub-question. The first sub-question is the following:

How can the five key regulatory principles, to which network tariff design must adhere to, be quantified?

The five key regulatory principles are previously discussed in Chapter 2. These principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency. In this chapter, each principle is discussed and normative criteria for each principle are defined.

4.1 Non-discriminatory

Non-discriminatory cost allocation means that seen from the perspective of the network, users of the network are handled equally in equal circumstances (Droste et al., 2018).

It is assumed that a network tariff structure is either discriminatory or non-discriminatory. To determine if a network tariff structure is non-discriminatory the following question is used:

Are consumers that have the same electricity pattern charged differently?

If this question can be answered with "no", it is determined that a network tariff structure is non-discriminatory.

4.2 Cost-recovery

Cost-recovery through network tariffs means that the total costs of the electricity distribution network are recouped through the network charges (Droste et al., 2018). The cost-recovery principle states that each DSO should be able to recover their efficient cost through the network tariffs.

Because the electricity network is a natural monopoly, rules are in place to protect consumers. The Dutch ACM determines the maximum height of the tariffs that any DSO is allowed to charge consumers (Autoriteit Consument & Markt, 2020). The ACM does this based on a system of yardstick competition to protect consumers while giving incentives to DSOs to become more efficient (Authoriteit Consument & Markt, 2016).

This subsequently means that the heights of the current tariffs are set such that all efficient costs are recouped through the network charges. This inherently means that under the current network tariff structure the cost-recovery principle holds.

This implies that for another network tariff structure to satisfy the principle of cost-recovery, the sum of total network charges of all consumers in the service area of that DSO should stay approximately the same. Furthermore, this should be the case for all DSOs separately, since they all play a key role in maintaining and monitoring the critical infrastructure that is the electricity network.

4.3 Cost-reflectiveness

The principle of cost-reflectiveness states that costs are allocated to those who impose costs on the network (CEER, 2017).

In literature, network tariffs are sometimes assumed to be either cost-reflective or not cost-reflective. In these cases, a capacity based tariff is cost-reflective (Hall et al., 2016). Meeus et al., define a cost-reflective network tariff as a tariff structure consisting of a forward-looking cost model, in combination with a fixed charge to recover the residual costs (2020).

Passey et al. analysed the cost-reflectiveness of different capacity based network charges (2017). They defined cost-reflectiveness in capacity based tariffs as the linear Pearson's correlation between the network charge and the average of the applicable peak demand over each month. In this case, the applicable peak demand is the share of the total co-incidental network peak of that month (Passey et al., 2017). The advantage of defining cost-reflectiveness with the definition of Passey et al. is that it becomes possible for a tariff structure to be more cost-reflective than another tariff structure. This makes comparing the cost-reflectiveness of different tariff structures a lot easier.

Section 2.4.3 already discussed the fact that a network tariff structure will never be fully cost-reflective. This also means that the above definition of calculating cost-reflectiveness does not hold perfectly. However, to be able to compare different network tariff structures based on cost-reflectiveness, a criterion or definition has to be defined. In this thesis, cost-reflectiveness is defined through the definition of Passey et al. (2017). Since the cost-reflectiveness is dependent on the peak load of the network, the cost-reflectiveness of a network tariff structure is calculated for each created neighbourhood and the data set as a whole.

4.4 Transparency

Transparency in network tariffs means that it should be clear to consumers what they are paying for (Droste et al., 2018). A transparent network tariff also means a transparent methodology (CEER, 2017; Reneses & Ortega, 2014). The literature review showed that, although transparency is one of the key regulatory principles and is mentioned in both European and Dutch law and regulation, it is not clear what a transparent network tariff structure exactly entails and what criteria could be used to determine this.

In this thesis, it is assumed that a network tariff is either transparent or not transparent. To determine if a network tariff structure is transparent the following question is used:

Is the tariff methodology clear and unilateral interpretable?

If this question can be answered with "yes", it is determined that a network tariff structure is transparent.

4.5 Promoting efficiency

Network tariffs should promote both efficient trade and competition and efficient network usage (Droste et al., 2018).

Since it is difficult to determine if a network tariff structure promotes efficient trade and competition, it is assumed that this is the case when a tariff does not hinder efficient trade and competition. Therefore, the following question is used:

Do competitive advantages arise when implementing the network tariff structure?

If this question can be answered with "no", it is determined that efficient trade and competition will not be negatively influenced by the alternative tariff structure.

To examine to which degree a network tariff structure promotes efficient network usage, the percentage change in load factor of the network, in comparison with the load factor of the network when consumers are subject to the current tariff structure, is used.

The load factor of a network under a tariff structure is calculated by dividing the average load of the network by the maximum load of the network. It is assumed that with higher load factors the network capacity is used more efficiently and herewith a network tariff structure better promotes efficiency.

It would be less efficient if a network tariff structure incentivises more demand response than is necessary. In that case, the overall system costs will increase since the network costs would be the same and the consumer costs would be higher. However, it is not possible to differentiate the network tariff for each low voltage grid separately. Within the scope of this thesis, it is assumed that when reductions of peak load are not incentivised, significant problems arise for the distribution grid. Herewith it is assumed that the more a network tariff structure incentivises demand response the more efficient that structure is. This trade-off between short and long term goals and efficiency is more elaborately discussed in Chapter 12.

5 Electricity demand of consumers

In this fifth chapter, the electricity demand of consumers is analysed. This is done to get a good overview of the characteristics of the data and to see which characteristics significantly influence the electricity demand of consumers. The results are directly used during the recreation of the neighbourhoods, which are one of the main inputs of the model next to the electricity demand itself.

The data is analysed using the smart-meter data from 396 Dutch consumers in the service area of Stedin. First, the data set is described. Second, the method that is used to analyse and clean the data is elaborated. Third, the data set is analysed using SPSS, based on the known characteristics.

5.1 Description of the data format

The load data of the 396 consumers was made available by Stedin in Excel files. Each Excel file contained the smart-meter values for every fifteen minutes of a single day, for both the consumption and the generation separately. With the help of Excel, the data is transformed and merged to generate a CSV file containing the net electricity usage of all consumers. This CSV file is used as input for the simulation model in Python. The used data are the data from 91 days between 02-07-2020 and 30-09-2020.

5.1.1 Cleaning of the data

During the data transformation, some minor errors became apparent. First of all, the files containing the meter data did not consists of 396 different households, but only 390. This means that the data of six households was not read out correctly.

A second issue was that the household load of 12 of these 390 households had an accuracy of 1 kW instead of 1 W. This most likely has to do with the type of electricity meter that is installed and results in an unrealistic demand pattern. Figure 3 below shows a snapshot of the electricity demand pattern on the 5th of July of one of these 12 households, compared with the average demand of all households during this same day.

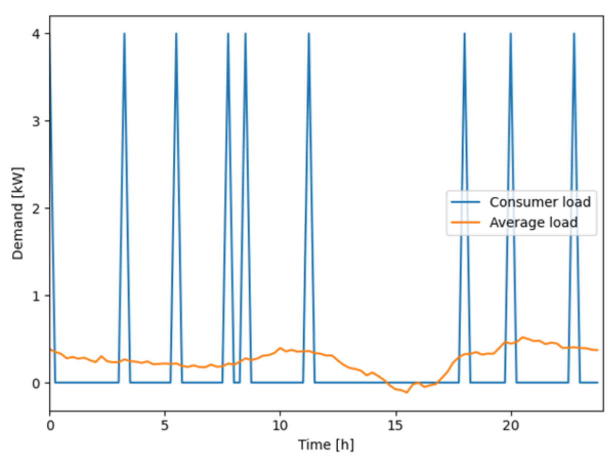


Figure 3: Daily demand pattern of a consumer with a electricity meter with low accuracy

The total daily electricity demand of the two lines in the graph is very comparable. However, it clearly shows that the blue line, with the data of the consumer that has an electricity meter with lower accuracy, is not an accurate representation of the actual electricity demand. Therefore, the 12 consumers that experience this problem are removed from the data set. This results in a finalised data set containing the data of 378 consumers.

The total summed load of the whole data set is shown in Figure 4 below. The average load is 173,74 kW, the absolute maximum load is 274,52 kW and the absolute maximum load that is fed back into the grid is 169,27 kW.

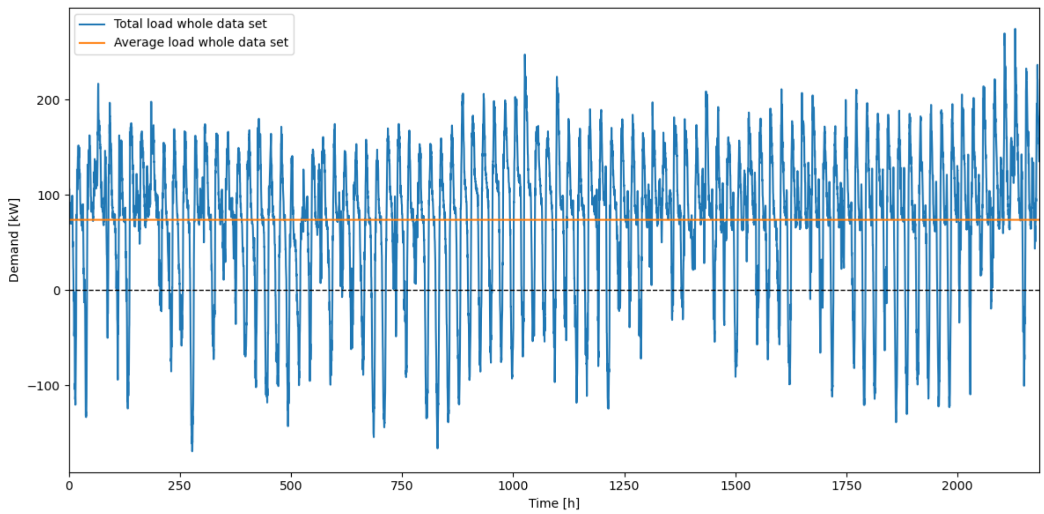


Figure 4: The total summarised load of the whole data set of 378 consumers

5.2 Characteristics of the consumers in the data set

The finalised data set contains the smart-meter data of 378 consumers. In Figure 5 on top of the next page the known characteristics of the consumers, and how these characteristics are represented in the data set, are shown. It can be seen that the data set is not necessarily an accurate representation of the Netherlands or the service area of Stedin. For example, the number of consumers that have PV installed in the Netherlands is about 13 percent (Solarmagazine.nl, n.d.-b), while in the data set it is almost triple that amount. Also, the number of consumers that own an EV is a bit higher in the data set, since in the Netherlands this is 5,3 percent (Rijksdienst voor Ondernemend Nederland, n.d.).

5.3 Analysing the data set with SPSS

The data set is analysed with the help of SPSS. SPSS allows performing a wide range of statistical analyses relatively easily (Aldrich, 2018; Hinton et al., 2014). The data set is analysed based on the housing type, the presence of PV and the presence of EV. Since these results are directly used for recreation of the neighbourhoods in the next chapter.

For all analyses, an α of 0,05 is used. α denotes the level of significance, and it serves as a criterion to determine whether to reject or accept the null hypothesis (Aldrich, 2018).

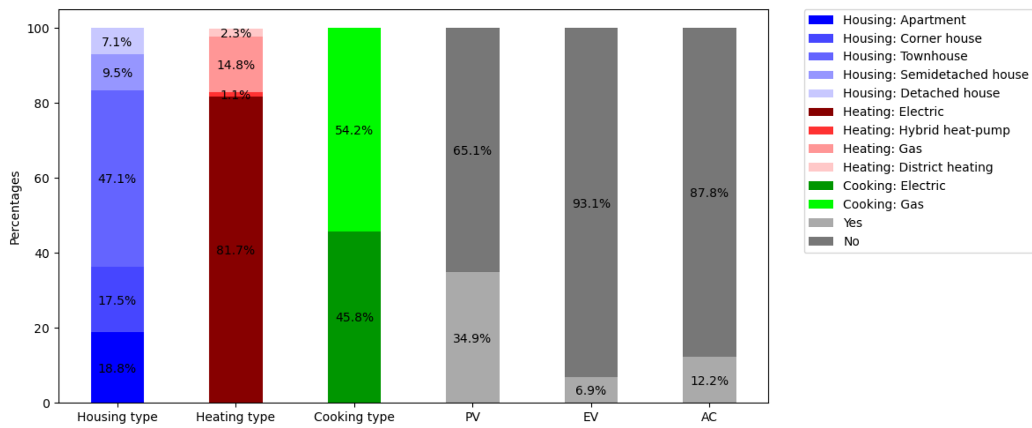


Figure 5: Known characteristics and their representation in the data set

It is important to note that the size of the data set is relatively small, it only contains data of 378 consumers. Furthermore, to analyse the data, metrics are introduced. The use of metrics results in an aggregation of the total data and herewith results in fewer data in general. Both these things result in more uncertainty in the statistical results and less significant results in general.

5.3.1 Independence of characteristics

Before analysing the data set based on the characteristics, the independence of these characteristics is analysed. If certain characteristics are not independent on each other this has to be kept in mind while interpreting the results of the data analysis. The chi-square test of independence is a test designed to determine whether two categorical variables are related or independent (Aldrich, 2018). The null hypothesis corresponding to the chi-square test is the following:

$$H_0 : Characteristic_1 \textit{ is not dependent of } Characteristic_2$$

In this case, $Characteristic_1$ and $Characteristic_2$ represent the two characteristics that are tested for their independence. The results of the chi-square test are shown in Table 3 below.

	Housing	PV	EV
Housing		**0,000**	**0,002**
PV	**0,000**		**0,000**
EV	**0,002**	**0,000**	

Table 3: The results of the chi-square test, α-values lower than 0,05 in bold

The above results show that the characteristics are not independent of each other. This means that with a certain housing type also the probability that a consumer has PV or an EV rises. The fact that the characteristics are not independent of each other is something that has to be kept in mind while performing the data analysis and drawing conclusions from the results.

5.3.2 Metrics

To be able to analyse the data set with SPSS, metrics are introduced. The metrics are chosen in such a way that they all describe a different part of the electricity pattern of a consumer, and together represent the electricity pattern as a whole. The following metrics are used to perform the statistical analyses:

- **Average load:** The average load in fifteen minutes. The average load corresponds with the total electricity use of consumers and with that describes the volumetric component of the electricity demand of a consumer.
- **Maximum load:** The absolute maximum load in fifteen minutes. This describes the maximum capacity that consumers need.
- **Average maximum load:** The average daily maximum load in fifteen minutes. This metric also describes the capacity component of the electricity use of a consumer. This metric is an average of the maximum needed capacity of each day.
- **Percentage of load in peak:** The percentage of the total load that is used during peak hours (between 17:00 and 23:00). This metric is calculated based on consumption only and ignores the amount of produced electricity. This metric aims to describe the extent to which consumers account to the overall network peak.
- **Number of times 4 kW is exceeded:** The average amount of times per day a consumer exceeds 4 kW demand in fifteen minutes. This is the last metric that describes the capacity component of the electricity demand. The 4 kW limit is chosen since the current calculation value for consumers is 4 kW.

Since this thesis investigates capacity based network tariffs there is an explicit focus on describing the capacity component of the electricity pattern.

5.3.3 Correlation between metrics

To examine if the metrics indeed describe different aspects of the electricity pattern of a consumer, a correlation analysis is performed. The null hypothesis with a correlation analysis is the following (Aldrich, 2018):

$$H_0 : \rho = 0$$

ρ is the hypothesized population correlation coefficient. If the significance value α is lower than 0,05, the null hypothesis can be rejected. The results of the correlation analysis are shown in Figure 6 on the next page. The correlation coefficients are shown in Table 4.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
AvgLoad		**0,229**	0,076	**-0,332**	0,016
MaxLoad	**0,229**		**0,668**	**0,122**	**0,508**
AvgMaxLoad	0,076	**0,668**		**0,170**	**0,669**
PercentInPeak	**-0,332**	**0,122**	**0,170**		-0,034
Over4kW	0,016	**0,508**	**0,669**	-0,034	

Table 4: Overview of the correlation coefficients of the analysis, significant correlations in bold

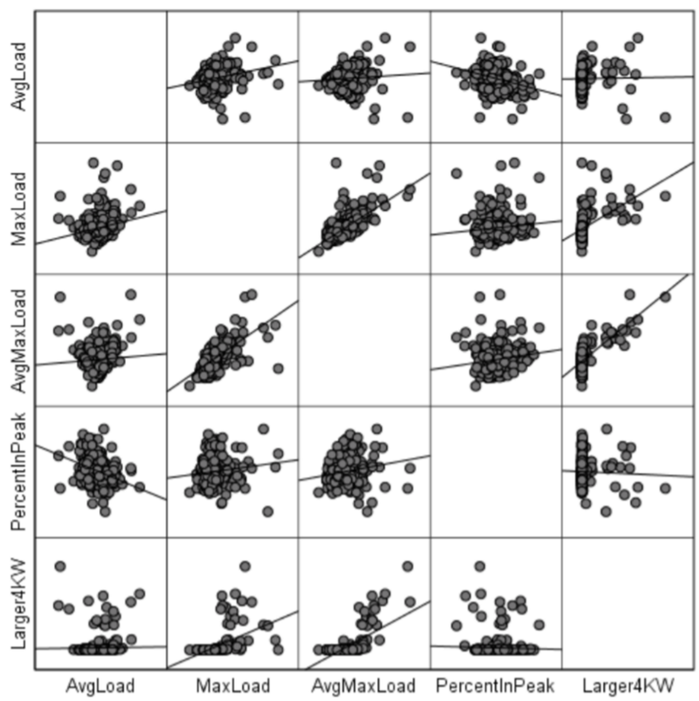


Figure 6: Overview of the correlation between the metrics

The correlation coefficients show that some of the metrics do correlate with each other. This was expected since all metrics are derived from the same data set. For example, the three metrics that describe the capacity component of the electricity pattern all have significant correlations between them. Since the metrics correlate with each other they have to be seen as a whole instead of as independent metrics.

5.3.4 Description of the data set

First, the whole data set is described based on the previously chosen metrics. This is done to give a general overview of how the data set looks like. The descriptive statistics of the whole data set are shown in Table 5 below.

Metric	Minimum	Maximum	Mean	Std. Deviation
Average load [kW]	-0,90	1,30	0,199	0,254
Maximum load [kW]	0,51	14,9	4,351	1,683
Average maximum load [kW]	0,02	6,97	2,037	0,814
Percentage of load in peak	0,14	0,58	0,352	0,064
Times over 4kW	0,00	12,7	0,315	1,333

Table 5: Descriptive statistics of whole data set with 378 consumers

These results show that the average load per fifteen minutes of the consumers in the data set is 0,20 kW, the average maximum load is 4,4 kW and the daily average maximum load is 2,0 kW. Furthermore, it also shows that on average the consumers exceed the 4 kW limit 0,32 times a day. Lastly, the average percentage of consumed electricity between 17:00 and 23:00 is 35,2 percent. The average load of Dutch consumers throughout a year is approximately 0,31 kW (Centraal Bureau voor de Statistiek, 2020). This indicates that the average load of the data set is relatively low. However, since the data in the data set originate from three summer months this was to be expected.

The results show that the maximum load has the highest standard deviation, and the percentage of load in peak the lowest. This means that in general consumers are very comparable based on the percentage of electricity they use during peak hours, but differ a lot when looking at the maximum load.

In the next sections, the data set is analysed based on three of the known characteristics. These characteristics are the housing type, the presence of PV and the presence of an EV. The results of these analyses are directly used in the recreation of the neighbourhoods in the next chapter.

5.3.5 Housing type

Table 6 below describes the data set based on the housing type. The metrics that describe the amount of network capacity needed generally rise for larger housing type. However, the average load does not. This might have something to do with the number of houses that have PV installed. Since those households have lower net electricity usage. Lastly, it can be seen that the percentage of electricity used during peak hours is roughly the same for different housing types.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Apartment (N=71)	0,227	3,685	1,478	0,335	0,035
Townhouse (N=178)	0,214	4,209	1,998	0,357	0,115
Corner house (N=66)	0,187	4,595	2,263	0,359	0,531
Semidetached house (N=36)	0,229	5,246	2,391	0,345	0,555
Detached house (N=27)	0,124	5,252	2,749	0,355	1,522

Table 6: Descriptive statistics of the data set based on housing type

To analyse if the above differences are significant for different housing types, an analysis of variance (ANOVA) test is performed. Because the housing type consists of more than two different options, an ANOVA test is the most suitable to statistically compare the means of these different groups with each other (Aldrich, 2018). The results of the ANOVA test are shown in Appendix B.1. The null hypothesis corresponding to the ANOVA test is the following (Aldrich, 2018):

$$H_0 : \mu_{App} = \mu_{TH} = \mu_{CH} = \mu_{SH} = \mu_{DH}$$

μ denotes the mean of the specific group of consumers that corresponds with the housing type.

The results of the ANOVA test show that the α-values for the average load and the percentage of electricity used during peak hours is larger than 0,05. This means that based on the ANOVA test, it can be assumed that the housing type is an indicator for the maximum load, the average maximum load and the number of times that the 4 kW limit is exceeded. Which means that the three metrics that relate to the needed capacity are significantly influenced by housing type.

Since it is determined that the electricity pattern is significantly different for different housing types, based on the three metrics that are related to the used capacity, it is analysed if all five types of housing are different from each other. This is done by performing an independent samples t-test for each pair of housing types. An independent samples t-test checks if there is statistical evidence that two population means are significantly different (Aldrich, 2018). This independent samples t-test is performed for all metrics but the average load and the percentage of electricity used during the peak, since the ANOVA test showed that these two metrics were not significantly different for the different housing types. The null hypothesis for the independent t-tests are is the following (Aldrich, 2018):

$$H_0 : \mu_1 = \mu_2$$

In this case, μ_1 and μ_2 correspond to the mean of the two groups that are compared with each other in the t-test. The result from the independent t-tests are shown in Table 7 below.

Pair	MaxLoad	AvgMaxLoad	Over4kW
Apartment–Townhouse	0,029	0,000	**0,112**
Apartment–Corner house	0,002	0,000	0,020
Apartment–Semidetached house	0,002	0,000	0,039
Apartment–Detached house	0,000	0,000	0,000
Townhouse–Corner house	**0,086**	0,008	0,006
Townhouse–Semidetached house	0,000	0,001	0,003
Townhouse–Detached house	0,002	0,000	0,000
Corner house–Semidetached house	**0,164**	**0,468**	**0,940**
Corner house–Detached house	**0,065**	**0,074**	**0,060**
Semidetached house–Detached house	**0,989**	**0,195**	**0,116**

Table 7: The results of the independent t-tests for all combinations of housing type, α-values larger than 0,05 in bold

The results of the independent t-tests indicate that three types of housing statistically belong to the same group. These are corner houses, semidetached houses and detached houses. The ANOVA analysis showed that the average load and the percentage of load used during peak hours are not significantly different for different housing types. The other three metrics are not significantly different between these three types of housing. This results in the following conclusions:

- The average load of consumers is not significantly different for different housing types.
- The percentage of the total load that is used during peak hours is not significantly different for different housing types.

- The maximum load of consumers who live in an apartment or a townhouse is significantly lower than that of consumers who live in a corner house, a semidetached house or a detached house.
- The average maximum load of consumers who live in an apartment or a townhouse is significantly lower than that of consumers who live in a corner house, a semidetached house or a detached house.
- Consumers that live in a corner house, a semidetached house or a detached house significantly more often exceed the value of 4 kW in comparison with consumers that live in a townhouse or an apartment.
- The electricity demand of consumers that live in a corner house, a semidetached house or a detached house is not significantly different for different housing types.

5.3.6 Presence of PV

The characteristics of the data set based on the presence of PV is shown in Table 8 below.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
No (N=246)	0,317	4,217	1,829	0,332	0,160
Yes (N=132)	-0,0230	4,601	2,426	0,389	0,604

Table 8: Descriptive statistics of the data set based on the presence of PV

Since the cooking type is only divided into two distinct categories, an independent t-test can be performed directly to see whether the minor differences in Table 8 are significant. The results of the independent samples t-test for the presence of solar panels can be found in Appendix B.2. A summary of the results of this t-test is shown in Table 9 below. It must be noted that the results are based on the months July, August and September, which are summer months. Therefore it is expected that the differences between consumers that have or do not have solar panels are smaller when the load pattern of consumers over a full year is analysed.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Significance	0,000	0,034	0,000	0,000	0,002
Mean difference	0,340	-0,384	-0,596	-0,056	-0,443

Table 9: The results of the independent t-test for the presence of PV

The results of the t-test for the presence of PV show that the α-values are smaller than 0,05 for every metric, and the mean differences are quite high. This means that for all metrics there is a significant difference between consumers that have PV and do not have PV. This results in the following conclusions:

- The average load of consumers with solar panels is 0,34 kW lower than the load of consumers that do not have solar panels.

- The maximum load of consumers with solar panels is 0,38 kW higher than the load of consumers that do not have solar panels.
- The average maximum load of consumers with solar panels is 0,60 kW higher than the load of consumers that do not have solar panels.
- The amount of times that a consumer exceeds the 4 kW limit each day is 0,44 higher with consumers that have solar panels.
- The percentage of electricity used during peak hours is 5,6 percent point higher with consumers that have solar panels.
- The electricity demand of consumers with solar panels is significantly different from the electricity demand of consumers that do not have solar panels.

5.3.7 Presence of an EV

Table 10 shows the characteristics of the data set based on the presence of an EV.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
No (N=352)	0,187	4,048	1,776	0,352	0,041
Yes (N=26)	0,303	7,270	3,304	0,346	2,930

Table 10: Descriptive statistics of the data set based on the presence of an EV

Also for the presence of an EV, there are only two options and therefore an independent t-test can be performed directly to test if the differences in Table 10 are significant. The results of the independent samples t-test for the presence of an EV can be found in Appendix B.3. A summary of the results of this t-test is shown in Table 11 below.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Significance	0,031	0,000	0,000	0,636	0,000
Mean difference	-0,116	-3,222	-1,528	0,006	-2,889

Table 11: The results of the independent t-test for the presence of EV

The above results of the independent t-test show that the consumers with an EV and without an EV differ significantly from each other, based on all metrics but the percentage of electricity used in peak hours. This results in the following conclusions:

- The average load of consumers with an EV is 0,11 kW higher than the load of consumers that do not have an EV.
- The maximum load of consumers with an EV is 3,13 kW higher than the load of consumers that do not have an EV.
- The average maximum load of consumers with an EV is 1,36 kW higher than the load of consumers that do not have an EV.
- The amount of times that a consumer exceeds the 4 kW limit each day is 2,81 higher with consumers that have solar panels.

5.4 Conclusions of the data analysis

The analysed data set consist of the data of 378 consumers in the service area of Stedin. For each consumer, the electricity demand for every fifteen minutes is known for a total of 91 days. Besides, some characteristics of each consumer are known. These characteristics are housing type, heating type, cooking type and the presence of PV, EV and AC.

To analyse the data set in SPSS, some metrics were introduced. These metrics aimed to describe the electricity pattern of the consumers on different aspects. The introduced metrics are the average load, the maximum load, the average maximum load, the number of times per day that a consumer exceeded the limit of 4 kW and the percentage of electricity that was used between 17:00 and 23:00. It was decided to deliberately focus on describing the capacity component of the electricity pattern, since in this thesis capacity based network tariff structures are examined. Since the metrics are based on the same data, some significant correlations between these metrics were expected. The correlation analysis of the metrics showed that this is indeed the case.

The electricity pattern was analysed for the housing type, for the presence of PV and the presence of an EV, since these results are directly used for the recreation of the neighbourhoods in the next chapter. It can be concluded that the housing type, the presence of an EV and the presence of PV significantly influences the electricity demand of consumers. Consumers with larger houses, an EV and PV have a higher peak demand, their daily peak is higher and they exceed the limit of 4 kW a lot more often. However, it must be said that the presence of EV and PV also occurs more often in larger houses.

Furthermore, the data analysis showed that the percentage of the load used during peak hours does not differ greatly between consumers. Only consumers that have PV installed significantly use a larger percentage of their load during peak hours. This result is caused by the fact that their electricity use during the day is a lot lower because of the generation of electricity.

The data analysis also points out the difference between the average load and the peak load of consumers that have PV installed. The results show that consumers that have PV installed use more network capacity, but their average load is less than the average load of consumers who do not have PV. If it is assumed that the main driver behind network costs is the amount of capacity a consumer needs during the coincident maximum network peak, a volumetric network tariff is not expected to be cost-reflective. Since consumers that have PV have very low electricity usage whilst using large amounts of network capacity.

In the next chapter, different neighbourhoods are created based on the housing type. The statistical analysis showed that the electricity pattern of corner houses, semidetached houses and detached houses are not significantly different. Therefore, during the recreation of these neighbourhoods, consumers that live in a corner house, a semidetached house or a detached house can be used interchangeably. This increases the possible neighbourhoods that could be recreated.

The fact that the electricity demand of consumers with solar panels is significantly different means that a difference in the number of households with solar panels in the actual and the recreated neighbourhood also results in differences in electricity patterns.

Lastly, since the electricity pattern of consumers with an EV is significantly different and the simulation model simulates the load corresponding to charging EVs on top of the inflexible load, consumers that have an EV are not used as an input for the model. This means that consumers that have an EV are also not used during the recreation of the neighbourhoods.

6 Creating different neighbourhoods

To analyse the effects of different network tariffs structures on the LV-grid, typical Dutch neighbourhoods are recreated. These neighbourhoods are subsequently coupled with the actual LV-transformer and line capacities. The finalised recreated neighbourhoods form an important input for the model. In the next section, the used approach to recreate these neighbourhoods is discussed. Hereafter, the recreated neighbourhoods are shortly described. Lastly, the neighbourhoods are validated based on the actual transformer load characteristics of the neighbourhood on which they are based.

6.1 Approach

The data analysis showed that the electricity demand of consumers is significantly influenced by the housing type. However, there is no difference between the electricity demand of corner houses, semidetached house and detached houses. A typical Dutch residential neighbourhood generally consists of houses of mixed housing type.

To be able to validate the created neighbourhoods, the actual load characteristics of the LV-transformers need to be known. This data is known for 590 of the LV-transformers in the service area of Stedin. The total number of connected households and the specific network layout of these LV-networks are also known. The network layout is combined with an ArcGis map that specifies the housing type of every house in the Netherlands (ArcGis.com, n.d.), to be able to determine the housing type of the recreated neighbourhoods.

Different consumers from the data set are combined to create a group with the same size and share of housing types as the actual neighbourhood. The data analysis showed that the presence of an EV significantly influences the electricity demand. Since the recreated neighbourhoods are an input of the simulation model, and the model simulates the electricity demand corresponding to the charging of EVs, consumers that own an EV are left out during the creation of the neighbourhoods.

The data analysis also showed that the presence of PV influences electricity demand. The actual number of consumers that have PV installed in the recreated neighbourhoods is also known. However, since the percentage of Dutch consumers that have PV installed is about 12 percent (Solarmagazine.nl, n.d.-b), and in the data set it is about 35 percent, this is not kept the same for all recreated neighbourhoods. This is done to make sure that certain consumers, in this case, consumers without PV, are not over-represented in the creation of different neighbourhoods, and that all consumers appear in a maximum of two neighbourhoods.

Therefore, in most of the recreated neighbourhoods, the number of consumers that have PV installed is higher than in the actual neighbourhood. It is expected that the fact that more consumers have PV installed, combined with the fact that the data is from three summer months, results in minor differences in the final electricity demand of the actual and recreated neighbourhoods. However, the goal is not to exactly recreate the actual neighbourhoods, but to create neighbourhoods that could realistically exist in the Netherlands.

The neighbourhoods on which the recreated neighbourhoods are based are selected based on multiple factors. First, the neighbourhood had to be mostly residential. Because otherwise, a part of the transformer load cannot be recreated, which complicates the validation. Second, the neighbourhood cannot be meshed, since this would make it unsure which transformer supplies which household. Third, creating a neighbourhood where the load profile of one single consumer from the data set had to appear more than once is unwanted.

This results in a strong limitation on the possible neighbourhoods that can be recreated. For example, since only 71 consumers that live in an apartment are present in the data set, typical flats cannot be recreated, since these often have more than 71 households. However, a single consumer may appear in multiple neighbourhoods, in fact, all consumers in the data set are used in either one or two different neighbourhoods.

The fact that a consumer can not appear twice in a single neighbourhood in theory also strongly limits the possible neighbourhoods that can be recreated when looking at the amount of semidetached and detached houses in the data set. Since only 29 consumers that do not own an EV live in a semidetached house and only 24 live in a detached house. However, from the results of the data analysis in Section 5.3.5 it became apparent that the electricity demand of corner houses, semidetached houses and detached houses can be used interchangeably. Therefore, a neighbourhood with a total of 50 detached houses can be recreated by using 24 consumers that live in a detached house and 26 consumers that live in a semidetached house.

6.2 Recreated neighbourhoods

In this section, the four recreated neighbourhoods are discussed. These neighbourhoods are all mostly residential neighbourhoods and have been selected based on the previously mentioned limitations. Since the actual layout of the neighbourhoods in combination with the location of the cables and the LV-transformer are sensitive information, the actual location of the neighbourhoods is not specified.

6.2.1 1: Small neighbourhood consisting of townhouses and corner houses

The recreated neighbourhood consists of 39 townhouses and 12 corner houses. With a total of 51 houses, the size of the neighbourhood is quite small. A schematic of this neighbourhood and the corresponding load pattern is given in Figure 7.

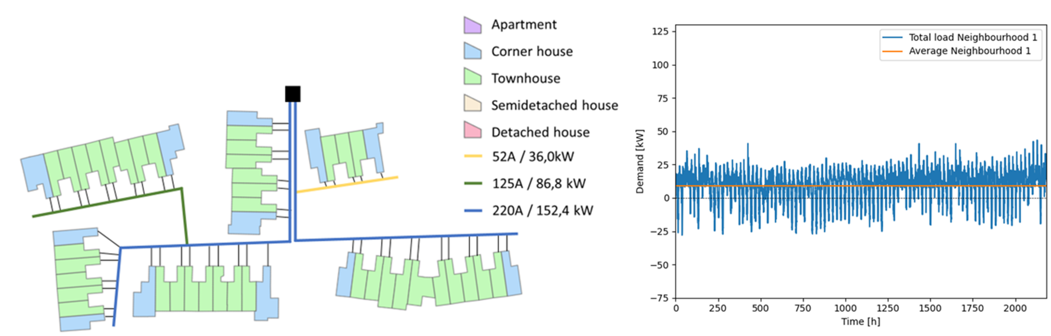


Figure 7: Schematic and corresponding load pattern of the first neighbourhood, acquired and adapted from (ArcGis.com, n.d.)

This neighbourhood is recreated by selecting 12 corner houses and 39 townhouses from the data set. The maximum load of this recreated neighbourhood is 43,3 kW. The average load of the neighbourhood is 9,0 kW and the maximum feed-in peak of solar energy is 28,0 kW.

In reality, only 9 households in this neighbourhood have PV installed, while in the recreated neighbourhood 22 households have PV. Is expected that this difference with the actual neighbourhood results in a difference in the load pattern of the recreated and the actual neighbourhood.

6.2.2 2: Medium size neighbourhood with predominantly small houses

The second recreated neighbourhood is a medium-sized neighbourhood with all types of houses. The neighbourhood consists of 50 apartments, 16 townhouses, 12 corner houses, 16 semidetached houses and 3 detached houses, which makes a total of 97 houses. A schematic of this neighbourhood and the corresponding load pattern is shown in Figure 8 below.

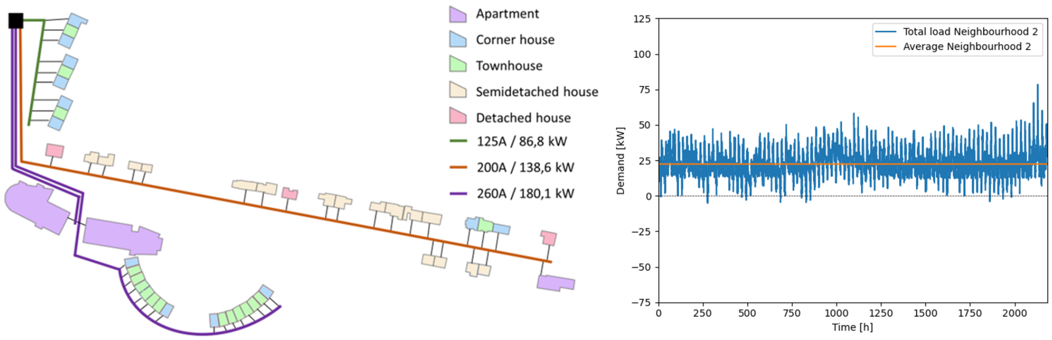


Figure 8: Schematic and corresponding load pattern of the second neighbourhood, acquired and adapted from (ArcGis.com, n.d.).

This neighbourhood is recreated by selecting the load of 50 apartments, 16 townhouses, 12 corner houses, 10 semidetached houses and 9 detached houses. This means that 6 semidetached houses are represented by the load of 6 detached houses. The maximum load of this recreated neighbourhood is 78,5 kW. The average load of the neighbourhood is 22,4 kW and the maximum feed-in peak of solar energy was 5,2 kW.

In the recreated neighbourhood 14 households have PV installed, which is the same amount as the actual neighbourhood.

6.2.3 3: Medium size neighbourhood with predominantly large houses

The third neighbourhood that is recreated consists of 18 townhouses, 9 corner houses and 65 detached houses, which makes a total of 92 houses. A schematic of this neighbourhood and the corresponding load pattern is shown in Figure 9 on the next page.

Because the total number of detached houses in the neighbourhood is higher than the total number of detached houses in the data set, the load profiles of some semidetached houses and corner houses are used instead. For the recreation of this neighbourhood 18 townhouses, 21 corner houses, 29 semidetached houses and 24 detached houses are used. The maximum load of this recreated neighbourhood is 91,44 kW. The average load of the neighbourhood is 15,4 kW and the maximum feed-in peak of solar energy was 73,3 kW.

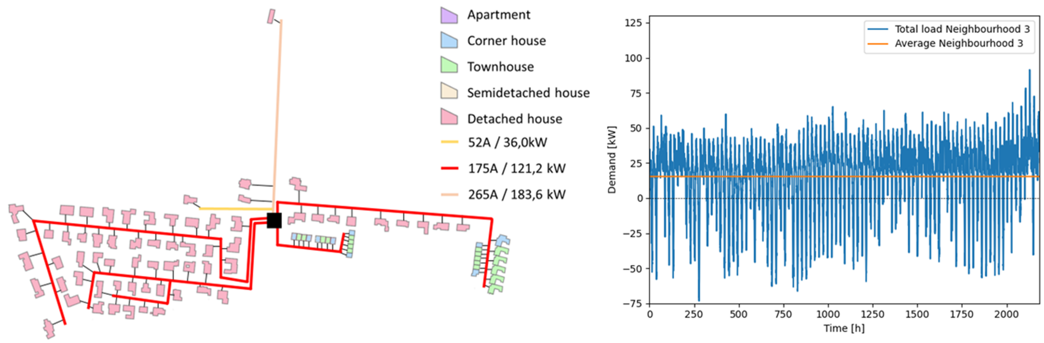


Figure 9: Schematic and corresponding load pattern of the third neighbourhood, acquired and adapted from (ArcGis.com, n.d.).

In the recreated neighbourhood 39 households have PV installed, while in reality only 16 households have PV installed. This large difference will likely result in a difference between the simulated load pattern and the actual load pattern of the neighbourhood. It will also be interesting to compare this neighbourhood with the second neighbourhood since the total number of households is roughly the same, but the third neighbourhood has larger houses and more houses with solar panels on top of them.

6.2.4 4: Large neighbourhood consisting of small houses

The recreated neighbourhood consists of 50 apartments, 116 townhouses and 31 corner houses. With a total of 197 consumers in the neighbourhood, it is a lot larger than the first three neighbourhoods. A schematic of this neighbourhood and the corresponding load pattern is shown in Figure 10 below.

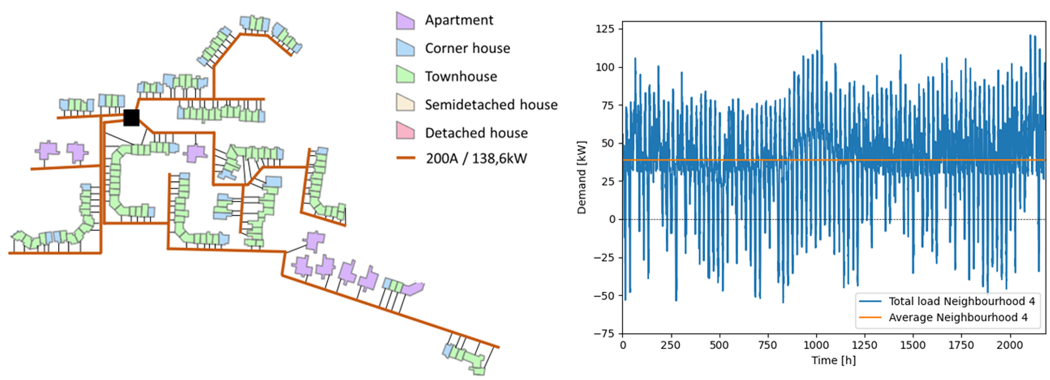


Figure 10: Schematic and corresponding load pattern of the fourth neighbourhood, acquired and adapted from (ArcGis.com, n.d.).

The neighbourhood is recreated by selecting the same amount of houses from each housing type from the data set. The maximum load of this neighbourhood is 135,6 kW. The average load of the neighbourhood is 38,8 kW and the maximum feed-in peak of solar energy is 54,9 kW.

In the recreated neighbourhood 56 households have PV installed, while in reality only 30 households have PV installed. This difference will likely result in a difference between the simulated load pattern and the actual load pattern of the neighbourhood.

6.2.5 Network characteristics for each neighbourhood & comparison

The network characteristics of each neighbourhood, including transformer capacities, are shown in Table 12 below. This table also shows the number of consumers in each neighbourhood, the average and maximum load of each neighbourhoods. Lastly, it shows the percentage of used transformer capacity, according to Stedin data and according to the electricity demand of the simulated neighbourhoods. The Stedin data is based on a day in the middle of winter.

NBH	Households	Avg load	Max load	T_{cap}	T_{stedin}	T_{sim}
1	51	9,0 kW	43,3 kW	200 kW	26%	21,7%
2	97	22,4 kW	78,5 kW	400 kW	29%	19,6%
3	92	15,4 kW	91,44 kW	400 kW	38%	22,9%
4	197	38,8 kW	135,6 kW	300 kW	65%	45,2%

Table 12: Overview of neighbourhood and corresponding transformer characteristics

Table 3 shows that the maximum load of the transformer is not necessarily higher for larger neighbourhoods. Furthermore, the used transformer capacity also differs between neighbourhoods. This has multiple explanations.

One explanation is the historical development of each neighbourhood. Another explanation is the fact that there used to be a lot smaller DSOs whom all had their own transformer types and customs.

When looking at the percentage of the used transformer capacity, it can be seen that the peak load of the generated neighbourhoods should be higher in most neighbourhoods. However, the used data is from the months July, August and September, which are summer and autumn months. Electricity use in the winter is higher than during the summer. Also, the actual LV-transformers sometimes supplied electricity to non-residential buildings which also creates minor differences in actual and generated electricity usage. Lastly, when creating the neighbourhoods, consumers with EVs were left out. The data analysis showed that consumers that own an EV use more electricity and have higher electricity peaks. This results in the load of the created neighbourhoods being a bit on the lower side. In the next section, the validation of the simulated neighbourhoods is discussed more extensively.

The above results also show that amount of congestion is not the same in each neighbourhood in the Netherlands. In some neighbourhoods, transformer overloading is expected to occur sooner under the current network tariff than in others. Furthermore, it is expected that network expansion is still needed when a different network tariff structure is implemented.

Because of the limitations of the optimisation model and the scope of this thesis, it is decided to not take the line capacities into account during the modelling. The main research question and the sub-questions relate to the comparison of different network tariff structures. This comparison can still be properly done when this simplification is made. However, the line capacities and network layout are given for future research. Appendix C shows an overview of the neighbourhoods in another format, including line capacities and number and type of households connected to each line.

6.3 Validation

In the previous section, four different neighbourhoods were recreated. The goal was to recreate neighbourhoods that could exist. The recreated neighbourhoods are based on actual existing neighbourhoods. Therefore, the recreated neighbourhoods also corresponded with an actual LV-transformer.

The actual load data of these LV-transformers is known. The electricity demand of the simulated neighbourhoods is compared with the measured load of the specific LV-transformers to validate the recreated neighbourhoods. Unfortunately, the data for 2020 is not yet available. Therefore the data from the same period in 2019 is used. Table 13 shows the average load, the maximum load and minimum load for the four simulated neighbourhoods and the four corresponding actual neighbourhoods.

	1_s	1_a	2_s	2_a	3_s	3_a	4_s	4_a
Minimum [kW]	-28,0	2,9	-5,2	22,4	-73,3	-30,9	-54,9	-15,0
Average [kW]	9,0	18,7	22,4	36,6	15,4	40,2	38,8	51,7
Maximum [kW]	43,3	44,5	78,5	85,6	91,4	97,7	135,6	140,3

Table 13: Overview of neighbourhood and corresponding transformer characteristics. Subscript 's' denotes the simulated neighbourhoods, subscript 'a' denotes the actual neighbourhoods.

In Table 13 it can be seen that for all neighbourhoods differences exist. To see if the load-distribution of both the simulated and the actual neighbourhoods is comparable, load-distribution curves are generated. These load-distribution curves are shown in Figure 11 on the next page.

The load-distribution curves show some differences in the load pattern of the simulated and the actual neighbourhoods. In all four cases, the amount of times that electricity is being fed back into the grid is a lot higher than in reality. This can be partly attributed to the fact that more consumers have PV installed in three of those neighbourhoods than in the actual neighbourhoods.

To show the difference between a simulated neighbourhood with a lot more solar panels and with the same number of solar panels, the first neighbourhood is recreated in such a way that the same number of solar panels exist in both the actual and the simulated neighbourhood. In Figure 12 the three load-distribution curves are shown. This figure shows that at least the amount of times electricity is being fed back into the grid is caused by the difference in consumers that have solar panels. Furthermore, it also shows that part of the general differences is also caused by this. However, also in this case the load of the simulated neighbourhood is a bit lower than that of the actual neighbourhood.

The average load of the actual neighbourhoods being higher could be caused by the fact that the transformers also supply electricity to non-residential buildings, which is something that can not be replicated in the recreated neighbourhoods. Another explanation is the number of consumers in the neighbourhoods that have an EV. The recreated neighbourhoods are recreated without consumers with an EV. The data analysis showed that the

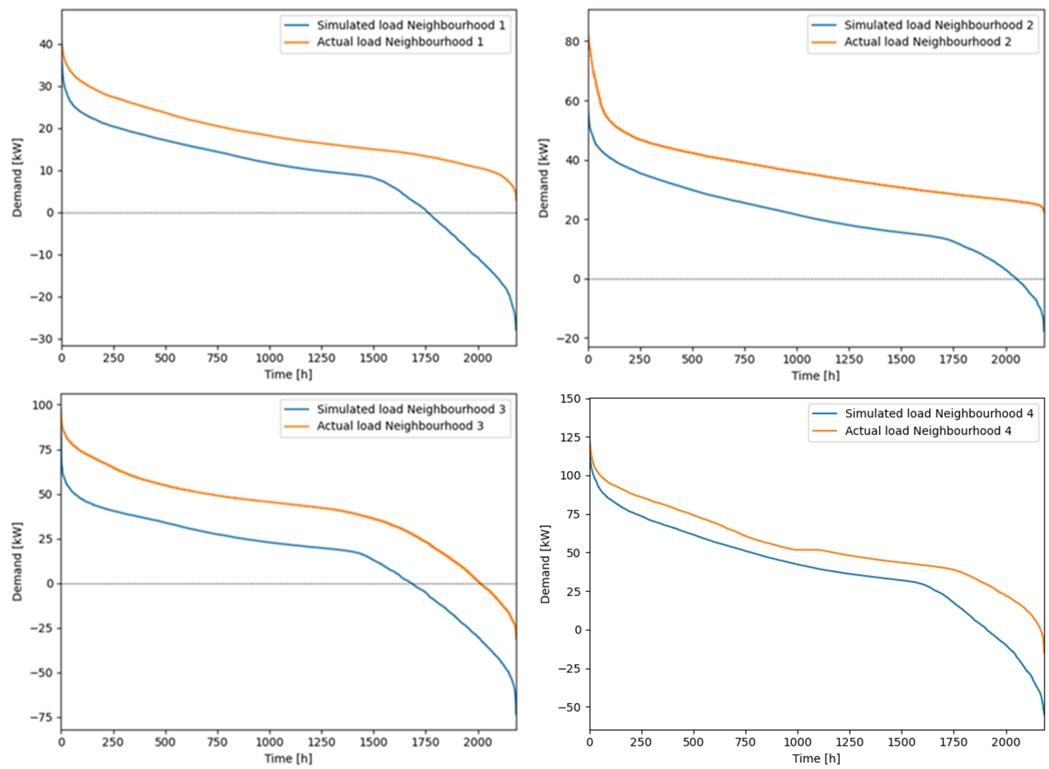


Figure 11: Load-distribution curves of simulated and actual neighbourhoods

demand of consumers with an EV is 0,11 kW higher. Moreover, since the data from the consumers is measured at the households and the load of the neighbourhoods is measured at the transformers, also the cable losses play a part in the difference of the two load curves in each neighbourhood. Although the cable losses normally are a lot lower than 25 percent. Lastly the fact that the load data originates from 2019, and the consumer load data originates from 2020 could result in some minor differences.

The validation of the recreated neighbourhoods shows that the created load patterns of all four neighbourhoods are similar. However, there also still exist some differences. These differences are explained by the fact that most simulated neighbourhoods contain a lot more consumers with solar panels. The number of consumers with solar panels in the simulated neighbourhoods are a factor 1,4 - 2,5 higher than in reality in neighbourhoods for neighbourhoods 1, 3 and 4. However, also neighbourhood 2 shows a significantly lower average load, even though the number of households that have PV installed is the same as in reality.

The goal of creating the neighbourhoods was to recreate neighbourhoods that could exist, and not necessarily exactly recreate the actual neighbourhoods. The validation of the neighbourhoods made clear that although the simulated electricity patterns are a bit lower, they still are very comparable. Therefore, there is no need to adjust the recreated neighbourhoods to better match the actual electricity pattern of the neighbourhoods on which

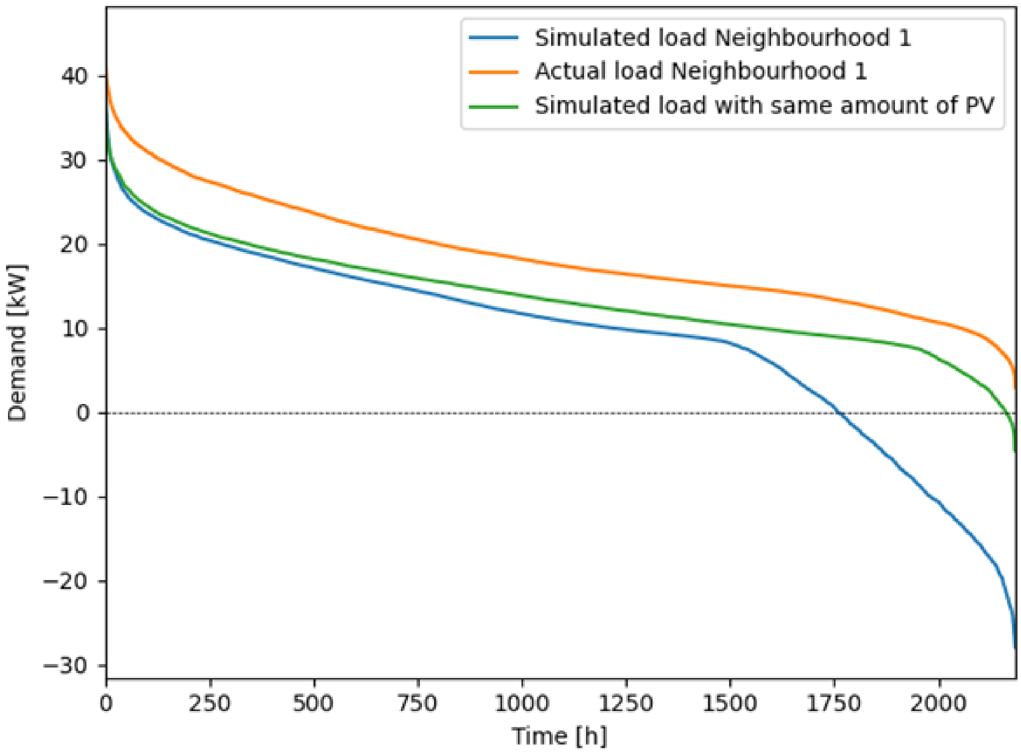


Figure 12: The load-distribution curves for the first neighbourhood, with an extra curve with the same number of consumers that have PV as the actual neighbourhood

the recreation is based.

Furthermore, it must be taken into account that the recreated neighbourhoods have more households with solar panels installed than the actual neighbourhoods, this could be taken as unrealistic. However, the amount of PV penetration is expected to keep rising in the future (Solarmagazine.nl, n.d.-a). This means the recreated neighbourhoods could very well realistically describe a neighbourhood in a few years or an already existing neighbourhood where a significant portion of the consumers have solar panels installed. Since the goal was not to exactly replicate the existing neighbourhoods, this is not seen as a problem. Furthermore, the second neighbourhood can be compared with the other neighbourhoods to see if the effects of different network tariff structures are different for different amounts of PV penetration.

7 Model description

To answer the main research question and the corresponding sub-questions, a simulation model is used. This model is described in this fifth chapter. First, a general model description is given. Second, the inputs of the model are described based on different parts of the model. Third, the outputs of the model are described. Lastly, the validation of different parts of the model is discussed.

7.1 General model description

The used model to answer the main research question and the corresponding sub-questions is constructed in Python. The model objective is to simulate how different network tariff structures influence the electricity demand of consumers. The model does so under the assumption that consumers allocate their EV charging demand to minimise network costs. The allocation of EV charging demand to minimise costs is modelled as an optimisation problem using the Pyomo package. These optimisation problems are subsequently solved using the GLPK solver.

The model is mainly constructed by Roman Hennig, a PhD candidate at the Delft University of Technology. The model is discussed in Hennig et al. (2020). The construction of the model was mainly supported by testing and validating different parts of the model, as well as implementing minor changes in the way the model outputs are generated by the model.

The model simulates the electricity demand of consumers in a neighbourhood. The initial demand of the consumers is assumed to be non-changeable. The electricity demand corresponding to the charging of EVs is assumed to be changeable, and therefore subject to the optimisation model. The optimisation model optimises the EV charging behaviour of consumers under different network tariff structures and different charging strategies.

The model simulates an increasing number of consumers that have an EV to analyse the effects on the network peak. The results of the simulation for the different network tariff structures and charging strategies can be compared with each other. Also, based on the initial electricity demand of consumers, the model can compute the expected network charge for different tariff structures.

The different examined network tariff structures are the current fixed tariff, two different configurations of a capacity bandwidth tariff and a personal peak charge. The different charging strategies are charging on arrival and individually optimisation. The different network tariff structures and charging strategies are further explained in the next sections. To sketch a full overview of all possible effects, all different network tariff structures will be combined with the different EV charging strategies.

7.1.1 Network tariff structures to be examined

The examined network tariff structures are two configurations of a capacity bandwidth tariff, a personal peak charge and the current uniform capacitive tariff. These network tariff structures are chosen to be examined based on the results of the literature review in Chapter 2. Capacity based network tariff structures are currently most predominantly examined in the Netherlands. A capacity bandwidth tariff and a personal peak charge are the most discussed options.

Capacity bandwidth tariff The first examined tariff structure is the capacity bandwidth tariff, with an exceedance fee for usage outside the band. Because of the uncertainty about the differences between a minimum bandwidth of only 2 kW compared with a minimum bandwidth of 4 kW, both options are examined. The characteristics of these two models are found in Table 14 below. The exceedance fee in both options and is 0,50 €/kWh.

Table 1 showed that the current capacity dependent rate for consumers in the service area of Stedin is €160,30 (Stedin, 2020). The calculation value for this charge is 4 kW, which corresponds to €40,08 per kW of used capacity. The prices for the capacity bandwidth tariff with a minimum bandwidth of 4 kW are chosen in such a way that the charge per kW bandwidth is equal to the current charge, which results in approximately €40 per kW. This means that the charge for the 4 kW bandwidth is kept equal to the charge of the current fixed tariff. This would result in a lot higher income for DSOs if a lot of consumers will choose higher bandwidths, but it is assumed that not a lot of consumers will choose a bandwidth higher than 4 kW.

For the capacity bandwidth tariff where the smallest bandwidth is 2 kW, the price per kW of bandwidth is chosen to be a bit higher at €45 per kW. This is done to prevent the total income of DSOs from being a lot lower when a bandwidth of 2 kW is an option. It is expected that a significant amount of consumers will choose a 2 kW bandwidth, if available. The prices shown in Table 14 are the prices for the capacity rate only. It is assumed that the other components, the standing charge, the measurement rate and the periodic connection fee remain constant. All prices are chosen in accordance with Stedin.

The value of 0,50 €/kWh is chosen for the height of the exceedance fee, which is following Hennig et al. (2020). The purpose of the exceedance fee is to incentivise consumers to stay within their bandwidth limit. Furthermore, the exceedance fee must be set in such a way that the exceedance fee is greater than the maximum difference in wholesale prices. If the difference in wholesale price is greater than the exceedance fee, consumers that store electricity could minimise their total costs by exceeding their bandwidth limit. With an exceedance fee of 0,50 €/kWh the difference in wholesale prices should be at a maximum 500 €/MWh. It is assumed that with an exceedance fee of 0,50 €/kWh consumers do not exceed their bandwidth level if they minimise costs.

Cap. BW. min 2kW		Cap. BW. min 4kW	
Bandwidth	Price	Bandwidth	Price
2 kW	€90	4 kW	€160
4 kW	€180	8 kW	€320
8 kW	€360	12 kW	€480
17 kW	€765	17 kW	€680

Table 14: The two bandwidth models and their characteristics

Personal peak charge The second investigated tariff structure is a personal peak charge. With a personal peak charge, the network charge of consumers is dependent on the average monthly maximum needed capacity. The charge per needed kW of capacity is kept proportionally to the charge of the current tariff structure. This corresponds to €40 per kW of used capacity. This means a consumer with a maximum capacity of 5 kW will have to pay €200 for the capacity rate, which will result in a total charge of approximately €270,06.

When subject to a personal peak charge, consumers optimise their charging in a way that they do not exceed their maximum monthly capacity, and with that do not increase their network costs. This means that a consumer has full information about what their monthly maximum capacity is going to be.

Fixed tariff The third examined tariff structure is a fixed tariff, the current uniform capacitive tariff. This tariff functions as a benchmark for the other tariff structures. When subject to the uniform capacitive tariff, consumers pay €160,30 for the capacity rate. The total charge for consumers when subject to the uniform capacitive tariff is €230,36 for consumers in the service area of Stedin (Stedin, 2020). The fixed tariff gives no incentive to consumers to change their behaviour.

7.1.2 Different charging strategies

Next to the different tariff structures, also two different charging strategies are implemented in the model. These different charging strategies are: charging on arrival and individual optimisation.

Charging on arrival With this charging strategy, a consumer starts charging their EV as soon as they get home. The EV then starts charging as fast as possible until the EV is fully charged while keeping the capacity under the maximum allowed limit. In this case, the maximum allowed limit is equal to the applicable bandwidth or the maximum monthly peak. When consumers are subject to the current network tariffs structure, there is no maximum allowed limit.

Individual optimisation In the individual optimisation charging strategy, it is assumed that consumers charge when the wholesale electricity prices are the lowest. Therefore consumers individually optimise their charging behaviour. Also in this case consumers do not exceed their network constraints. The corresponding network constraints are the subscribed bandwidth or the maximum monthly peak capacity of the inflexible load.

In reality, consumers can follow this charging strategy when they are subscribed to an aggregator. Since it is assumed that consumers would not optimise themselves unless dynamic commodity prices are introduced. This way of charging through an aggregator is already possible, for example when subscribing to Jedlix (Jedlix.nl, n.d.). In the model, consumers know what the future wholesale prices are going to be. In reality, future wholesale prices are not known, and therefore in reality it is not possible to optimise the EV charging perfectly. This results in all consumers charging at the same time. However, when all the consumers would be subscribed to a single aggregator this would also be the case.

Furthermore, it is expected that the wholesale prices would be affected when a large amount of EVs all start charging simultaneously. However, this interaction between the change in electricity demand and the wholesale price is not included in the model.

For these reasons, the model is not run over the full three months, since this would only result in unrealistic results. It is decided to run the model over one week, surrounding the already existing network peak in each neighbourhood.

7.2 Model inputs

This section describes the model inputs. The model inputs are the consumer load data, the EV driving profiles, the wholesale price series, the LV-transformer capacities, the network tariff structure and the used charging strategy. The different network tariff structures and charging strategies were already discussed in the previous section.

7.2.1 Load input of consumers

The load data serves as the main input for the model. Chapter 5 extensively analysed the characteristics of the load data. Based on the statistical analysis, four different neighbourhoods were created. The load data of the consumers in each neighbourhood is the main input of the optimisation model.

7.2.2 Synthetic EV charging profiles

To generate the load that corresponds to the charging of the EVs, 25 synthetic EV driving profiles are used and translated to charging profiles. These driving profiles are created by Remco Verzijlenbergh and, when combined with some randomness, results in very realistic driving patterns (Verzijlbergh, 2013). Appendix D.1 shows an overview of these driving profiles. After translating the 25 driving profiles to charging profiles, these charging profiles are allocated randomly to the consumers to simulate their EV charging demand. The ratio of these profiles is kept equal, i.e. a charging profile is only allocated for the second time after all other profiles are allocated.

To translate the synthetic driving profiles to charging profiles, some assumptions are made. The arrival time of the synthetic driving profiles is used as the time that the charging can start. Since the exact arrival time would realistically differ each day, this arrival time is combined with a standard deviation of one hour. The departure time of the synthetic driving profile corresponds with the time that the charging must stop. In this case, there is no standard deviation, since departure time is assumed to be more constant. Also, in the case of the individual optimisation strategy, the consumer has to know their departure time beforehand, and therefore combining this with a standard deviation is not realistic.

The battery size of the EVs is assumed to be 60 kWh and the maximum charging rate is assumed to be 11 kW, this is comparable with the battery size and charging rate of the Tesla model 3 (EV-database.nl, n.d.). Also, the expected range per kWh is based on the maximum range of the Tesla Model 3. The Tesla Model 3 has been chosen for the comparison because it is currently the best sold EV and historically the most sold EV in the Netherlands (Rijksdienst voor Ondernemend Nederland, n.d.). To make sure the driving distance is a little bit different each day, the expected daily driving distance is combined with a standard deviation of 15 percent of the total distance.

Furthermore, it is assumed that the charging efficiency is 90 percent and that the minimum needed charge of each day is equal to 25 percent plus the needed charge to travel the expected distance. In this case, the 25 percent serves as a buffer, to make sure that in case of emergencies consumers would not be left without charge in their EVs. The starting charge at the start of the simulation is assumed to be 40 percent. The full overview of the model inputs for the EV charging patterns is shown in Appendix D.2.

7.2.3 Wholesale price series

The wholesale prices are acquired from the ENTSO-E Transparency Platform (ENTSO-E Transparency Platform, n.d.). This platform publishes the wholesale prices of electricity for the Netherlands for every hour. The wholesale prices for the period 02-07-2020 until 30-09-2020 are shown in Figure 13 on top of the next page. The average price of electricity in this period was 35,29 €/MWh, the maximum price was 200,04 €/MWh and the minimum price was -20,83 €/MWh. This also shows that the maximum difference between the wholesale prices is 220,87 €/MWh, which corresponds with 0,22 €/kWh. Since the exceedance fee is 0,50 €/kWh, consumers minimise their costs by not exceeding their bandwidth level.

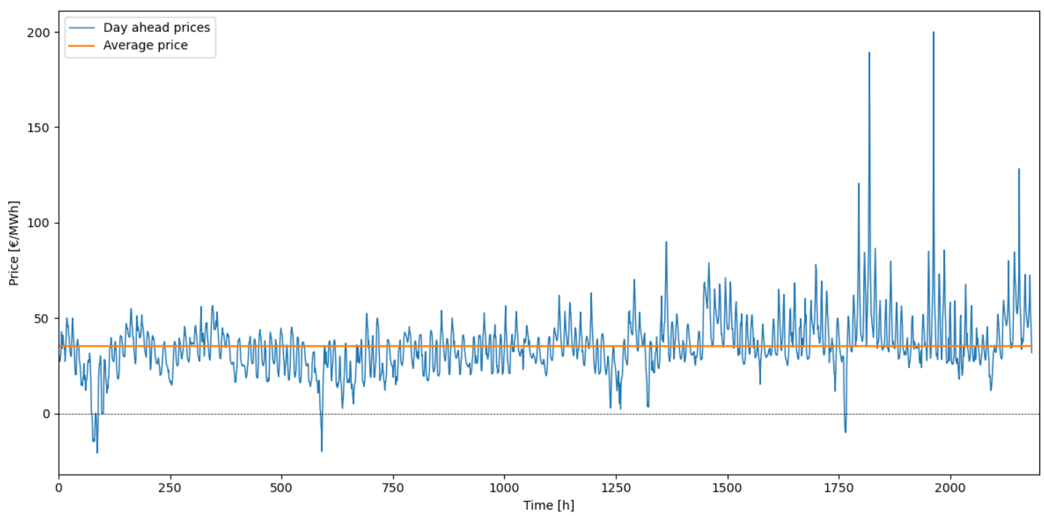


Figure 13: Day ahead prices in the Netherlands from 02-07-2020 until 30-09-2020 (ENTSO-E Transparency Platform, n.d.)

7.2.4 LV-transformer capacities

The LV-transformer capacities of each neighbourhood are discussed in the previous chapter. The LV-transformer capacities are used to compute the maximum transformer loading for each simulation.

7.2.5 Network tariff structure

The network tariff structure, and the corresponding assumptions, are also an input of the model. For the capacity bandwidth model and the personal peak charge model, it is assumed that charging an EV does not increase network costs. This means the allocated bandwidth and the max capacity limit can not be exceeded.

7.2.6 EV charging strategy

The last input of the model is the chosen charging strategy. Consumers either charge on arrival or individually optimise. The chosen charging strategy influences the way the optimisation model allocates the electricity demand corresponding to the charging of EVs. The different charging strategies are used to see if the effects on the electricity demand and the used LV-transformer capacity are different if consumers behave differently.

7.3 Model outputs

The model outputs play a large role in answering the main research question and the corresponding sub-questions. The model outputs are the flexible electricity demand of the consumers, the expected network charge for each consumer and the corresponding allocated bandwidth (if applicable), the maximum transformer capacity as a function of added EVs and the load factor of the network.

7.3.1 Flexible electricity demand of consumers

The flexible electricity demand of all consumers is the first output of the model. The model allocates the flexible demand, corresponding to the EV charging, differently based on the charging strategy and the network tariff structure.

The total electricity demand of the consumers, including the allocation of the EV charging demand, is used to compare the different network tariff structures and different charging strategies with each other. For example, based on the expected electricity demand, conclusions can be drawn about the peak shaving capacity of each network tariff option.

7.3.2 Expected network charge

The expected network charge for all consumers is the second output of the model. The model calculates the expected network charge based on the characteristics of the network tariff structure in place. For a capacity bandwidth tariff, the model also calculates the most suitable bandwidth. In that case, the most suitable bandwidth is also an output.

7.3.3 Maximum used transformer capacity as a function of added EVs

The third output of the model is the maximum transformer capacity as a function of the number of added EVs. This result is highly dependent on the network tariff structure in place and used charging strategy. This output also corresponds to the capability to postpone infrastructure expansion investments. With a higher number of EVs that can be accompanied without overloading of the LV-transformer, investments can be postponed further.

7.3.4 Load factor of the network

Next to the maximum transformer capacity also the load factor of the network is calculated. The load factor of the network is calculated through the following formula:

$$LF = \frac{Average\,load}{Maximum\,load}$$

In this formula, LF denotes load factor. The load factor of the network is used to see the effects of different network tariff structure on the efficiency of the network usage.

7.4 Model validation

This section validates different parts of the model. Validation concerns the fitness for purpose of the model (Nikolic et al., 2019).

The validation of the EV charging profiles and charging strategies is discussed in the first paragraph. The second paragraph discusses the validation of the allocation of the correct bandwidths by the model. The workings of the different charging strategies and tariff models do not have to be validated since these are hardcoded into the model and therefore always behave as they should.

7.4.1 Validation of EV charging profiles and charging strategies

The used driving patterns are derived from the dissertation of Remco Verzijlbergh (Verzijlbergh, 2013). The synthetic driver profiles are shown in Appendix D.1. In his dissertation, Verzijlbergh showed that the probability distributions of the three parameters (departure time, arrival time and distance) all have a roughly similar shape when compared with real data. He concludes that the main characteristics of the driving data have been preserved in the synthetic driver profiles and with that, he validated the driver profiles (Verzijlbergh, 2013). This section discusses the validation of the translation of the driving profiles to charging profiles and the two charging strategies.

Because the model simulates EV charging demand on top of the already existing consumer demand, the consumers that own an EV were removed from the data set. This applied to 26 consumers. The real electricity demand of these 26 consumers is used to validate the simulation of the electricity demand corresponding to EVs from the model, and with that validate if the EV charging profiles are applied correctly and if the charging strategies simulate charging behaviour accurately.

This is done by simulating the final electricity demand of 100 consumers and analysing the difference in characteristics of both this group and the group of 26 consumers that own an EV. These 100 consumers are chosen in such a way that they match the group of 26 consumers as good as possible. This is done by looking at the housing type and the presence of PV, because the data analysis showed that these two characteristics significantly influence the electricity demand.

The final electricity demand of 100 consumers is simulated for the current fixed tariff structure, this is done for both charging strategies. Table 15 below shows the characteristics of the two groups of consumers.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Data set	0,303	7,270	3,304	0,346	2,930
Simulation (CoA)	0,339	13,589	9,415	0,572	2,223
Simulation (IO)	0,338	12,570	5,128	0,236	2,269

Table 15: Descriptive statistics of the group from the data set and the simulated group of EV owners

Table 15 shows some large differences in the maximum load and the average maximum load. Also, the percentage of electricity used during peak hours appears to be a lot higher in the group with the simulated load profiles for the charge on arrival strategy and a lot lower for the individual optimisation strategy.

An independent samples t-test is performed to analyse if the simulated results and the real measured load data could originate from the same group. The results of this independent samples t-test are shown in Table 16.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Significance (CoA)	0,651	0,000	0,000	0,000	0,156
Significance (IO)	0,672	0,000	0,000	0,000	0,193
Mean difference (CoA)	-0,037	-6,319	-6,112	-0,225	0,707
Mean difference (IO)	-0,035	-5,300	-1,824	0,110	0,661

Table 16: The results of the independent t-test for the validation of the simulation of the EV charging demand

From the results in table 16, it can be seen that for the average load and the number of times the value of 4 kW is exceeded, the two different groups do not differ significantly. However, for the other three metrics, this is not the case. According to the analysis, the maximum load, the average maximum load and the percentage of electricity used during peak hours are significantly different. The fact that the average load does not differ significantly shows that the 25 EV driving profiles do indeed accurately describe the driving behaviour of EV owners, or at least accurately describe the driven distances.

One of the main assumptions while translating the 25 synthetic driver profiles to the 25 charging profiles was that all EVs charge at 11 kW. However, it seems like this value is higher than in reality. The maximum load suggest that in reality, consumers charge their EV with an average capacity of about 5 kW. Older EVs and plug-in hybrid EVs often do not charge at 11 kW. It could be possible that a lot of consumers do not charge on all three phases but only on one or two, resulting in a charging speed of only 3,7 or 7,2 kW. To see if this indeed is the reason behind the differences, in Table 18 the results are shown for when the 25 charging profiles are adapted to match the average charging speed. The charging speed is changed to 3,7 kW for the first 18 charging profiles and changed to 7,4 kW for the last 7. The finalised model inputs for the validation are shown in Appendix D.3. The descriptive statistics and the results of the independent t-test with the adapted charging profiles are shown in Tables 17 and 18.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Data set	0,303	7,270	3,304	0,346	2,930
Simulation (CoA)	0,339	7,597	4,914	0,650	2,744
Simulation (IO)	0,337	6,703	3,290	0,235	1,876

Table 17: Descriptive statistics of the group from the data set and the simulated group of EV owners

From the results of the t-test, it can be seen that for the charge on arrival strategy, the maximum load does not significantly differ between both groups. However, the average maximum load is still higher, and the percentage of electricity that is used during peak hours has risen to 65 percent. For the individual optimisation strategy, all the values for the three metrics that describe the capacity component of the electricity demand are more comparable. However, the percentage of electricity used during peak hours is a lot lower.

Changing the maximum charging speed in the 25 EV charging profiles did not result in the same characteristics as the demand of the consumers who have an EV in the data set.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
Significance (CoA)	0,651	0,541	0,000	0,000	0,775
Significance (IO)	0,675	0,183	0,959	0,000	0,109
Mean difference (CoA)	-0,037	-0,327	-1,610	-0,304	0,185
Mean difference (IO)	-0,037	-0,327	-1,610	-0,304	0,185

Table 18: The results of the independent t-test for the validation of the simulation of the EV charging demand

However, the average load, the maximum load and the number of times the 4 kW value is exceeded was validated. Furthermore, the individual optimisation strategy also resulted in comparable average maximum loads. Only the amount of electricity used during peak hours was not validated correctly.

Since it was possible to validate most metrics, it is decided to continue with the current EV charging profiles. Furthermore, since the model aims to simulate a future increase in EV penetration, and most newer cars do charge at 11 kW, it is decided to continue with the original inputs, where the maximum charging speed of all EVs is 11 kW. It is expected that in reality, the charging behaviour of consumers lies somewhere in between the charge on arrival and individual optimisation strategy. This would logically result in a situation where consumers do not charge their EV daily and charge partly during peak hours and partly outside of peak hours.

7.4.2 Allocation of bandwidths to consumers

The validation of the allocation of the most applicable bandwidths is illustrated with an example of four specific consumers and their electricity demand. In Figure 14 on the next page, the electricity demand and the possible bandwidths are shown.

The allocation of the bandwidths by the model indeed seems like the best options based on the electricity demand of the consumers. Also, when manually recalculating the expected network charges for each bandwidth, the same bandwidths were found to be the most applicable. Therefore, it is concluded that the model correctly allocates the best possible bandwidths for each consumer.

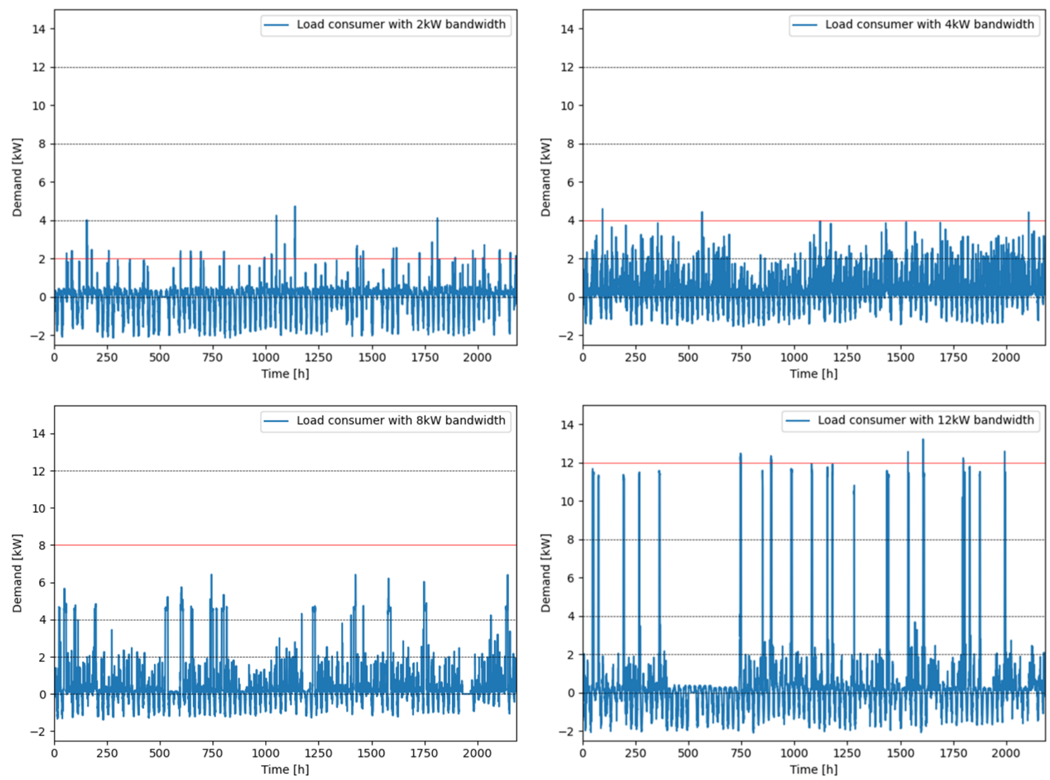


Figure 14: The load profile for four consumers and the possible bandwidth options, allocated bandwidth shown in red

8 Effect on electricity demand of consumers

This chapter analyses the effects of different network tariff structures on the individual electricity demand of consumers. This is done by looking at the characteristics of the electricity demand of consumers when subject to different network tariff structures.

The characteristics of the electricity demand are described using the metrics that were derived in Chapter 5. To simulate the expected electricity demand, the model is run once over the whole time period. This is done for two different scenarios, 0 percent EV penetration, and 100 percent EV penetration.

The first scenario aims to describe the current electricity pattern of a consumer that does not own an EV. The 100 percent EV scenario is used to describe the average electricity pattern of a consumer that does have an EV. The results of the 100 percent EV scenario are used to compare the effects of the different examined network tariff structures. The results are based on the average electricity demand of 352 consumers, which are consumers from the data set that do not have an EV.

8.1 Results

This section discusses the effects of different network tariff structures on the electricity demand of consumers. First, the current electricity demand of the consumers without an EV in the data set is described. Hereafter, the expected electricity demand of consumer that purchase an EV when subject to the current fixed tariff is examined. Next, the expected electricity demand of consumer when a capacity bandwidth tariff and a personal peak charge tariff is implemented is analysed.

8.1.1 Base case

The first scenario aims to describe the electricity demand of consumers without an EV. The characteristics of the electricity demand in this first scenario are shown in Table 19 below. Since only the demand corresponding to the charging of EVs is subject to the optimisation problem, the base case is the same under all examined network tariff structures.

	AvgLoad	MaxLoad	AvgMaxLoad	PercentInPeak	Over4kW
0% EVs	0,187	4,048	1,776	0,352	0,041

Table 19: Descriptive statistics of the data set for the 0% EV scenario

8.1.2 Current fixed tariff

The expected electricity demand is simulated to analyse how the electricity demand of consumers with an EV looks like when subject to the current network tariff structure. The results, for both the charge on arrival and the individual optimisation strategy, are shown on top of the next page.

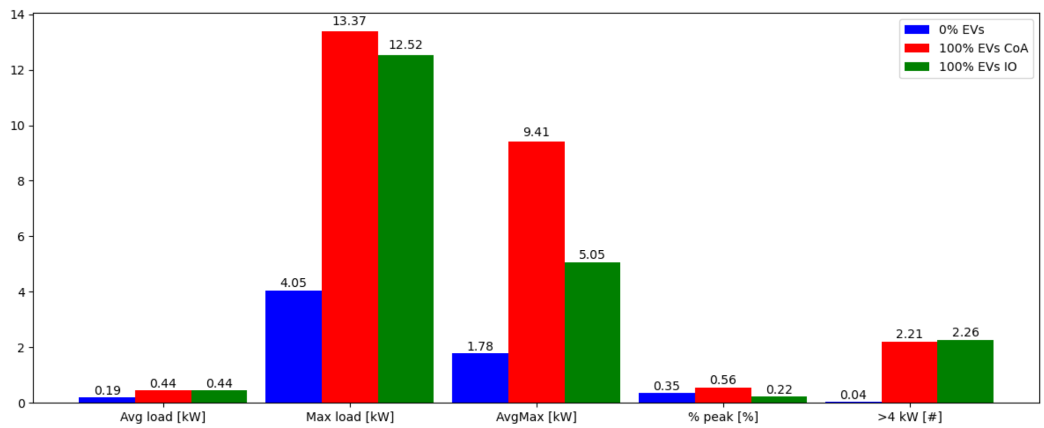


Figure 15: Descriptive statistics of the data set for the 100% EV scenario under the current fixed tariff

The results in Figure 15 clearly show that the values for all metrics increase when consumers also charge an EV, as would be expected. The average load increases with approximately 0,25 kW. This means that on average the electricity demand corresponding to the charging of an EV corresponds with a demand of 0,25 kW. This value should logically be more or less the same in each scenario and for every charging strategy. However, minor differences can occur due to randomness that is included in the model.

It can be seen that the absolute maximum load, the average maximum load and the number of times that the 4 kW limit is exceeded is significantly higher when the electricity demand of an EV is simulated on top of the inflexible demand. The maximum load for both charging strategies is approximately the same, but the average maximum load is a lot lower for the individual optimisation strategy. This is because, in the individual optimisation strategy, consumers do not charge their EV daily.

Lastly, the percentage of electricity used during peak hours rises from 35 to 56 percent when consumers charge on arrival but declines to 22 percent in the individual optimisation strategy. This suggests that consumers mainly charge their EVs during peak hours in the charge on arrival strategy, but during off-peak hours in the individual optimisation strategy.

8.1.3 Capacity bandwidth tariff

To analyse the effect of implementing a capacity bandwidth tariff on the electricity demand of consumers, the model is used to simulate the expected electricity demand when all consumers have an EV. This is done for both options of the capacity bandwidth model. The first option is a capacity bandwidth model with bandwidths of 2, 4, 8 and 17 kW. The second option is a capacity bandwidth model with bandwidths of 4, 8, 12 and 17 kW. The characteristics of the electricity demand of the consumers when subject to a capacity bandwidth tariff with a smallest bandwidth of 2 kW are shown in Figure 16, the results of the capacity bandwidth tariff with a smallest bandwidth of 4 kW are shown in Figure 17.

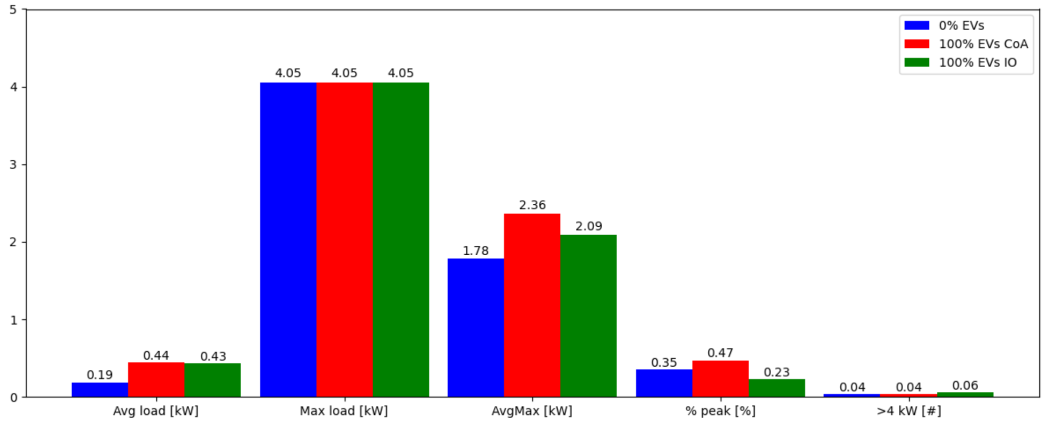


Figure 16: Descriptive statistics of the data set for the 100% EV scenario under a capacity bandwidth tariff with a smallest bandwidth of 2 kW

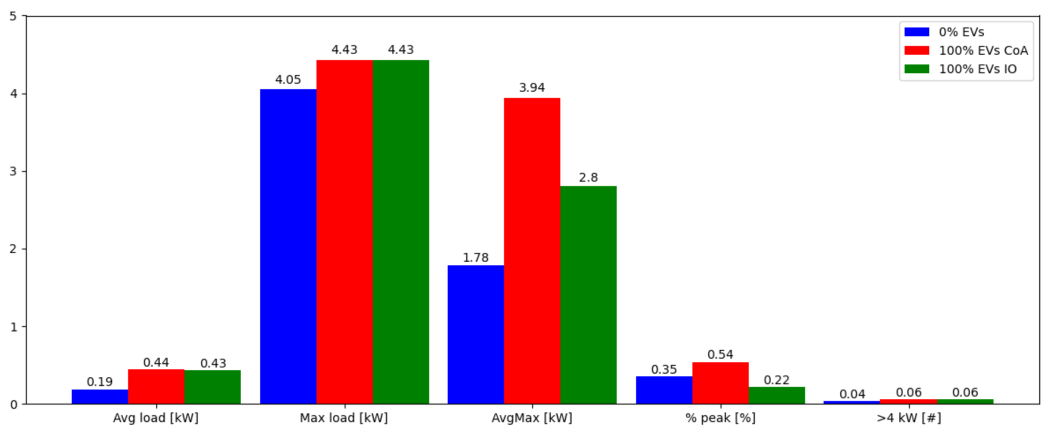


Figure 17: Descriptive statistics of the data set for the 100% EV scenario under a capacity bandwidth tariff with a smallest bandwidth of 4 kW

From the results in Figure 16 and 17 it can be seen that the average load increased with approximately the same amount as it did when consumers were subject to the current fixed tariff. This was expected since the total amount of energy needed to charge the EVs does not change.

Furthermore, it can be seen that the maximum load and average maximum load are only a bit higher in comparison with the situation where a consumer does not have an EV. This shows the effect of implementing a capacity bandwidth tariff on the maximum load and the average maximum load. The maximum load under the current fixed tariff rises with approximately 8 kW, and the average maximum load rises with 7,5 kW for the charge on arrival strategy and with 3,2 kW for the individual optimisation strategy. When a capacity bandwidth tariff is implemented, the maximum load is expected to stay equal for the option with a smallest bandwidth of 2 kW, and rise 0,38 kW for the option with the smallest bandwidth of 4 kW. Furthermore, the average maximum load under a capacity bandwidth tariff structure is expected to be significantly lower in comparison with the current fixed tariff.

The amount of electricity used during peak hours under the capacity bandwidth tariff structures is a bit lower than under the current fixed tariff for the charge on arrival option, and a bit higher for the individual optimisation strategy. This indicates that under a capacity bandwidth tariff the individual peaks of consumers will be a little bit more spread out over longer periods. These results indicate that, when subject to a capacity bandwidth tariff with a smallest bandwidth of 2 kW, this effect is more significant than for the other configuration of a capacity bandwidth tariff.

The number of times that the 4 kW limit is exceeded increases a bit when consumers have an EV. This is because consumers never exceed their bandwidth limit with the charging of their EV, and almost all consumers choose a bandwidth of 2 or 4 kW.

8.1.4 Personal peak charge

The model is also used to simulate the expected electricity demand of consumers when they are subject to a personal peak charge, and have an EV. The characteristics of the electricity demand of the consumers when subject to a personal peak charge are shown in Figure 18.

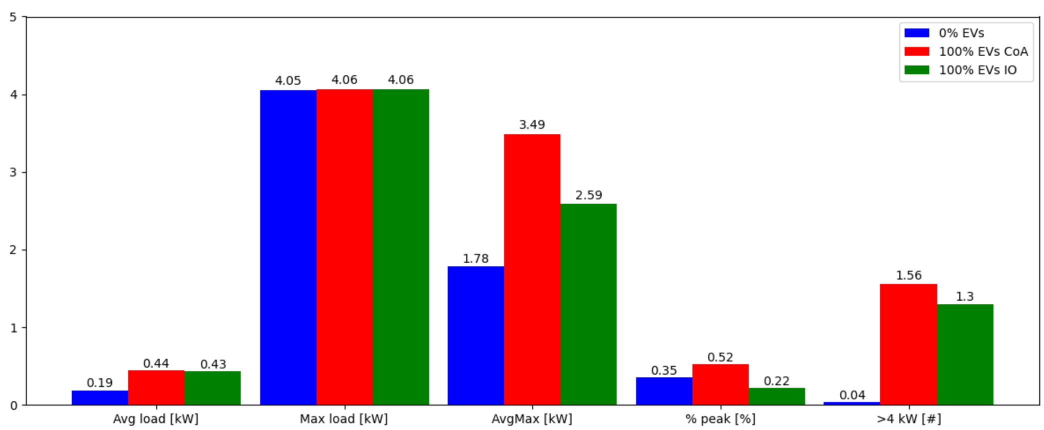


Figure 18: Descriptive statistics of the data set for the 100% EV scenario under a personal peak charge

From the results in Figure 18 it can be seen that, although the average load is not different from the results of the current fixed tariff, implementing a personal peak charge also results in a significant reduction of maximum and average daily maximum load. The growth of 0,01 kW can be accounted to the model sometimes rounding certain values up or down. Because the maximum load should, in theory, be the same when consumers are subject to a personal peak charge.

The percentage of electricity used during peak hours is very comparable with the results of the current fixed tariff, where the charge on arrival strategy results in more electricity used between 17:00 and 23:00, and the individual optimisation strategy results in less electricity used during peak hours.

Lastly, on the contrary to the capacity bandwidth models, the amount of times that the 4 kW limit was exceeded rises when a personal peak charge tariff structure is implemented. rises when a personal peak charge tariff structure is implemented.

8.2 Answer to the second sub-question

In this chapter, the effects of different capacity based network tariff structures on the individual electricity demand of consumers were analysed. This corresponds with answering the second sub-question:

How do different distribution network tariff structures influence the electricity demand of consumers?

The effects of different distribution network tariff structures on the electricity demand of consumers were analysed by comparing the characteristics of the electricity demand when consumers have an EV and were subject to different tariff structures.

8.2.1 Effects under the current network tariff structure

The results showed that when subject to the current network tariff structure, the maximum load and the average maximum load are expected to rise significantly when consumers also charge an EV. This is because consumers charge their EVs at a rate of 11 kW. When the individual optimisation charging strategy was selected, consumers do not charge their EV daily, in contrast to the charge on arrival strategy. This leads to a lower average maximum load for the individual optimisation strategy.

The results showed that the for the individual optimisation charging strategy, consumers do not often charge their EV between 17:00 and 23:00, while for the charge on arrival charging strategy they do.

8.2.2 Effects of implementing a capacity bandwidth tariff

The effects of two different configurations of a capacity bandwidth tariff structure were analysed. The first option has a minimum bandwidth of 2 kW, whereas the second option has a minimum bandwidth of 4 kW. In most instances, consumers in the data set got allocated a bandwidth of either 2 or 4 kW.

The results showed that under both options, the expected maximum load of consumers is significantly lower than under the current fixed tariff. Furthermore, the results showed that the peak shaving capacity of the individual electricity demand of a capacity bandwidth tariff with a smallest bandwidth of 2 kW is larger than that of the option with a smallest bandwidth of 4 kW. This mainly became apparent by comparing the average maximum load under the different tariff structures.

When comparing the two different charging strategies with each other, charging on arrival resulted in a higher average maximum load, and also in more electricity used during peak hours. This indicates that the individual optimisation model has a better peak shaving capacity and also contributes to using electricity outside of peak hours.

8.2.3 Effects of implementing a personal peak charge

The results in Figure 18 showed that the expected average daily maximum load and absolute maximum load are significantly lower when a personal peak charge is implemented in comparison with the results from the current fixed tariff structure.

Furthermore, the results showed that the amounts of times the 4 kW limit is exceeded rises under a personal peak charge. However, it does not rise as much as under the current fixed tariff.

8.2.4 Comparison of different network tariff structures

When comparing the effects of the different network tariff structures on the electricity demand of consumers with each other, it becomes clear that implementing a capacity bandwidth tariff or the personal peak charge both have a significant peak shaving capacity of the individual electricity demand. Both types of tariffs significantly reduce the values for the capacity-related metrics.

The results of implementing a capacity bandwidth tariff with the smallest bandwidth of 4 kW and the results of implementing a personal peak charge are almost identical. The only significant differences are the number of times the 4 kW limit is exceeded. The results suggest that the electricity peaks are a bit larger when consumers are subject to a personal peak charge. Furthermore, the average maximum load is a bit lower in comparison with the capacity bandwidth tariff with a smallest bandwidth of 4 kW, suggesting that the peaks are also a bit more infrequent.

In conclusion, the effects of a capacity bandwidth tariff with a smallest bandwidth of 4 kW and a personal peak charge tariff are very comparable. The results from all three examined tariff structures showed that the effects are significant in comparison with the current fixed tariff. Based on the effects of the different network tariff structures on the expected electricity demand of consumers, the capacity bandwidth tariff with a smallest bandwidth of 2 kW was the most influential.

9 Effect on network peak load

This chapter analyses the effects of the examined network tariff structures on the network peak load of the four recreated neighbourhoods. These effects are analysed by simulating the electricity demand of the neighbourhoods for an increasing number of consumers that have an EV when subject to different network tariff structures, and subsequently looking at the maximal transformer loading.

9.1 Results

To simulate the electricity demand of the four neighbourhoods, the simulation is run over one week and repeated 40 times for each combination of network tariff structure, charging strategy, neighbourhood and number of consumers with an EV. This simulated week is chosen in a way that the already existing network peak of each neighbourhood is situated around the middle of this week.

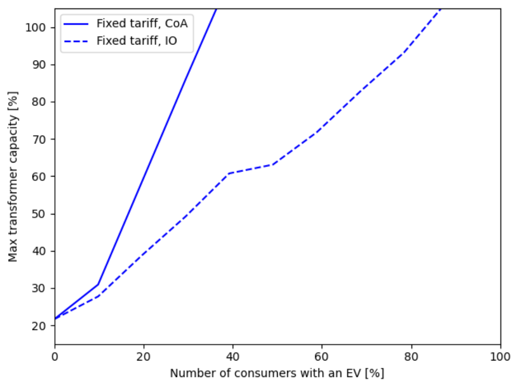
One of the main assumptions underlying the individual optimisation charging strategy is that wholesale prices are already known beforehand. This means that consumers already know what wholesale electricity prices are going to be in the future. Since it is not realistic that consumers would know the wholesale electricity prices more than a week before, this results in an unrealistic simulation. Furthermore, the main analysed output is the maximum network peak, which can still be done by only simulating one week. Lastly, by simulating only a week instead of three months, more replications can be done. This subsequently means that the results will be more accurate.

The following dates have been simulated for the different neighbourhoods:

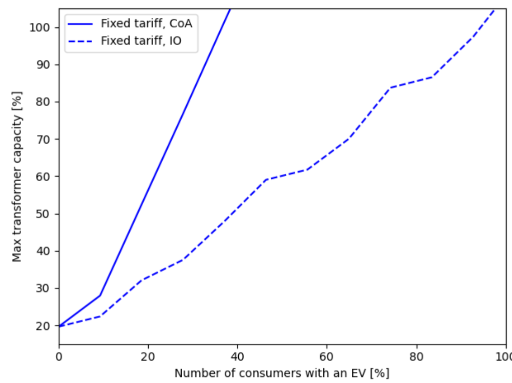
- 24-09-2020 till 30-09-2020 for neighbourhoods 1, 2 and 3
- 11-08-2020 till 17-08-2020 for neighbourhood 4

9.1.1 Current fixed tariff

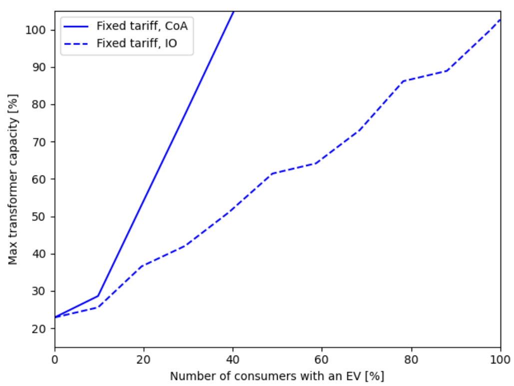
This section discusses the results when consumers are subject to the current tariff structure. This is done by looking at the maximum transformer capacity as a function of the amount of EVs that are added. Table 12 showed that in the base case, without any EVs being present in the neighbourhoods, between 19 and 46 percent of the transformer capacities were used. In Figure 19 on the next page, the maximum transformer capacity as a function of the amount of EVs for each neighbourhood is shown.



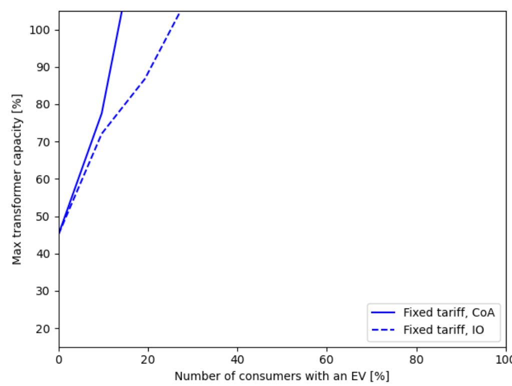
(a) Results neighbourhood 1



(b) Results neighbourhood 2



(c) Results neighbourhood 3



(d) Results neighbourhood 4

Figure 19: The maximum transformer capacity as a function of the percentage of consumers in the neighbourhoods that have an EV when subject to the current fixed tariff structure

From the results of Figure 19, it can be seen that for three neighbourhoods, transformer overloading occurs before 100 percent EV penetration for both charging strategies. In all neighbourhoods, there is a significant difference between the results of the individual optimisation and the charging on arrival strategy.

Because all consumers have full information about the future wholesale prices, every consumer charges at the same time when the individual optimisation charging strategy is selected. Since not everyone arrives home at the same time, the coincidence factor is a lot lower when this charging strategy is selected. For the charging on arrival strategy, even though consumers charge more during peak hours, transformer overloading occurs after a higher amount of EV penetration. This shows the importance of the coincidence factor of the electricity demand of consumers.

In the fourth neighbourhood, the transformer is overloaded after approximately 25 percent of EV penetration when charging on arrival is selected. When consumers individually optimise, the transformer is already overloaded at approximately 15 percent of EV penetration. This raises the question if another network tariff structure can significantly postpone infrastructural investments in such neighbourhoods.

The second neighbourhood was the only neighbourhood which was recreated to match the exact number of consumers that have PV in comparison with the actual neighbourhood. However, it does not seem like this results in any significant differences when comparing this neighbourhood with the other neighbourhoods. The third neighbourhood has approximately the same number of consumers and the same transformer capacity. The results show that these two neighbourhoods yield very similar results, despite the difference in consumers with PV.

9.1.2 Capacity bandwidth tariff

To analyse the effect of implementing a capacity bandwidth tariff on the network peak load, the electricity demand of consumers is simulated for an increasing number of consumers with an EV. As discussed in Section 7.1.1, two different capacity bandwidth tariff structures are examined. The first option includes bandwidths with sizes of 2, 4, 8 and 12 kW. The second option includes bandwidths with sizes 4, 8, 12 and 17 kW.

The expected effects of introducing a capacity bandwidth tariff are analysed by looking at the sum of bandwidths in each neighbourhood. The optimisation model optimises in such a way that consumers will minimise their network costs, and therefore the charging of EVs will never result in consumers exceeding their allocated bandwidth. The sum of the allocated bandwidths of all consumers is an indicator for the expected effect of introducing a capacity bandwidth tariff. Because the sum of bandwidths represents the maximum demand of all consumers if the coincidence factor is 1. In Table 20 below the sum of the bandwidths of the consumers in each neighbourhood and the corresponding transformer capacities are shown. Table 20 also shows the sum of bandwidths in a neighbourhood as a percentage of the transformer capacity.

		2, 4, 8, 17 kW		4, 8, 12, 17 kW	
	T_{cap}	$\sum BW$	%	$\sum BW$	%
1	200	106	53,0	204	102,0
2	400	212	53,0	392	98,0
3	400	204	51,0	372	93,0
4	300	406	135,3	792	164,0

Table 20: Sum of bandwidths of all consumers per neighbourhood. 'T_{cap}' denotes the transformer capacity. '$\sum BW$' denotes the sum of all bandwidths of all consumers in a neighbourhood. % denotes this sum of bandwidths as a percentage of the transformer capacity.

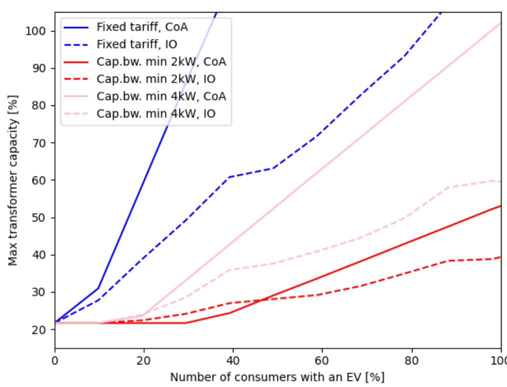
It can be seen that the sum of bandwidths per neighbourhood is relatively low, especially in the first three neighbourhoods. This was expected when looking at the maximum transformer loading since these were already relatively low in the base case.

The fact that the total sum of bandwidths is low does not mean that the neighbourhood load in the simulation will never surpass the total sum of all bandwidths. If the non-changeable demand of a consumer is already higher than their contracted bandwidth limit, this would still be the case in the simulation. However, it is to be expected that the absolute maximum needed capacity that the neighbourhood can reach under a capacity bandwidth tariff is not much higher than the sum of the bandwidths. This suggests that the peak shaving capacity of a capacity bandwidth model is significant. The fact that the total sum of bandwidths is higher than the transformer capacity in some cases does not mean that transformer overloading has to occur. If the coincidence factor is low, the total neighbourhood load will most likely be a lot lower than the sum of all bandwidths of all consumers.

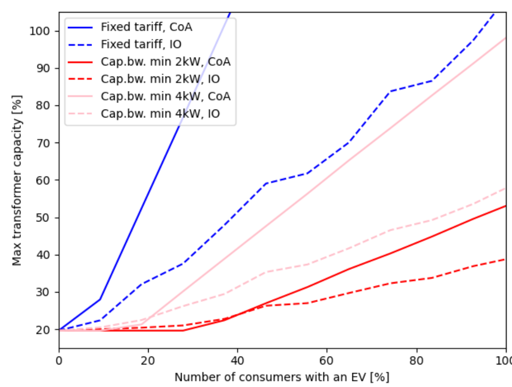
The bandwidths are allocated to the consumers based on their current non-changeable demand, originating from three summer months. It can be expected that the electricity demand of consumers is higher in the winter and it is disputed if consumers would choose a bandwidth of only 2 or 4 kW if they purchase an EV.

The differences between the two different capacity bandwidth models also become clear. Since a majority of the consumers would choose the smallest possible bandwidth, the peak shaving capacity is higher when choosing a 2 kW bandwidth is a possibility.

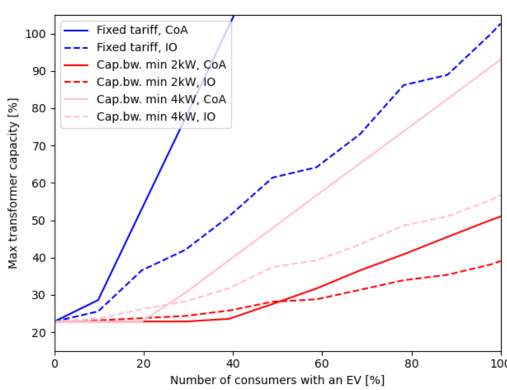
In Figure 20, the results of the simulations for the two different configurations of a capacity bandwidth tariff are added to the results of the fixed tariff.



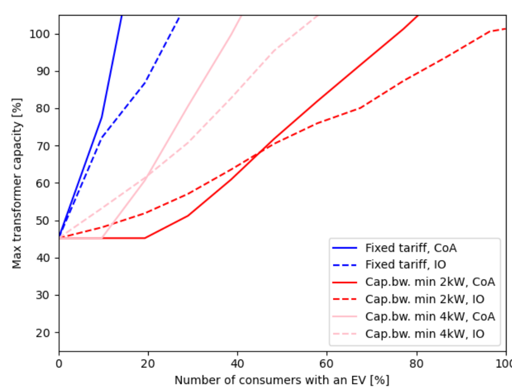
(a) Results neighbourhood 1



(b) Results neighbourhood 2



(c) Results neighbourhood 3



(d) Results neighbourhood 4

Figure 20: The maximum transformer capacity as a function of the amount of added EVs when subject to the current fixed fixed tariff and a capacity bandwidth tariff

The results clearly show that the maximum transformer loading is a lot lower than without the introduction of a capacity bandwidth tariff. In the first three neighbourhoods, the amount of EV penetration could be almost as high as 100 percent before transformer overloading occurs when a capacity bandwidth tariff structure is implemented.

The results also show that the capacity bandwidth tariff with a 2 kW bandwidth, shown in red, has a higher peak shaving capacity than the capacity bandwidth tariff with the smallest bandwidth of 4 kW. Although, the results of the charging on arrival strategy for the two different capacity bandwidth tariffs are comparable in most cases.

The difference between the results of the two charging strategies is smaller when a capacity bandwidth tariff is implemented. The differences between the results of the simulation of two charging strategies are the smallest under the capacity bandwidth tariff with the 2 kW bandwidth. This suggests that this tariff structure does not only reduce the peak load but also reduces the impact of the coincidence factor.

Furthermore, with low amounts of EV penetration, the individual optimisation strategy outperforms the charging on arrival strategy in most cases. However, with high amounts of EV penetration, this is not the case. Because consumers charge outside of the already existing network peak with the individual optimisation strategy, the total network peak is not that high at low amounts of EV penetration. With higher amounts of EV penetration, because of the high coincidence factor under this charging strategy, the network peak is primarily caused by the coincident charging of all consumers. This results in higher peaks.

The effects of implementing a capacity bandwidth tariff on the maximum network peak are significant. The high peak shaving capacity of a capacity bandwidth tariff becomes apparent when the results of a capacity bandwidth tariff are compared with the results of the current fixed tariff. Furthermore, the results show that the effects of a capacity bandwidth tariff with a smallest bandwidth of 2 kW are more significant than the effects of a capacity bandwidth tariff with a smallest bandwidth of 4 kW.

9.1.3 Personal peak charge

The electricity demand of consumers is simulated for an increasing number of consumers with EV when subject to a personal peak charge tariff to analyse its effects.

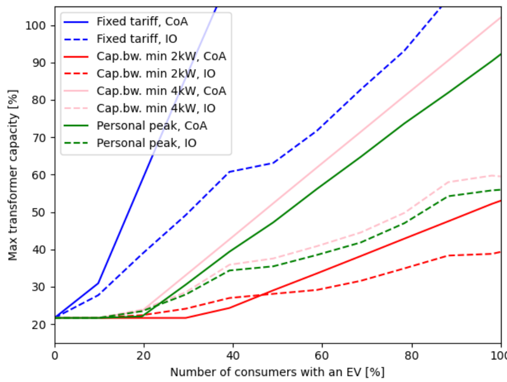
Because the optimisation model optimises in such a way that consumers will never exceed their maximum peak, an estimation can be made about what the maximum transformer loading will be. This is done by comparing the sum of the maximum peak values of all consumers in each neighbourhood. In Table 21 below the sum of all personal peaks for the consumers in each neighbourhood are shown.

	T_{cap}	$\sum PP$	%
1	200	204,9	102,4
2	400	391,3	97,8
3	400	422,0	105,5
4	300	781,1	260,4

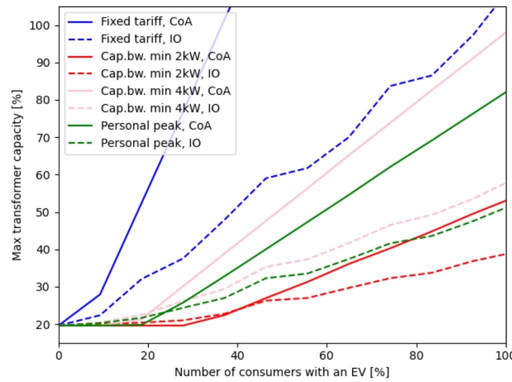
Table 21: Sum of personal peaks of all consumers per neighbourhood.'T_{cap}' denotes the transformer capacity. '$\sum PP$' denotes the sum of all peak values of all consumers in a neighbourhood. % denotes this sum of all peak values as a percentage of the transformer capacity.

Based on the results in Table 21, the peak shaving capacity of a personal peak charge is expected to be very comparable with that of a capacity bandwidth tariff with a smallest bandwidth of 4 kW. Also in this case, the total load of a neighbourhood will only be equal to the values shown in Table 21 if the coincidence factor is 1.

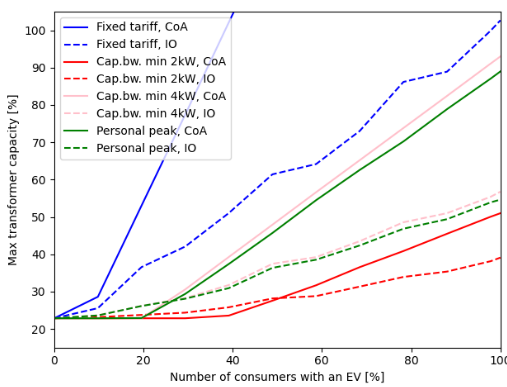
In Figure 21 on top of the next page, the results of the simulation, when consumers were subject to the personal peak charge, are added to the already existing results from Figure 20.



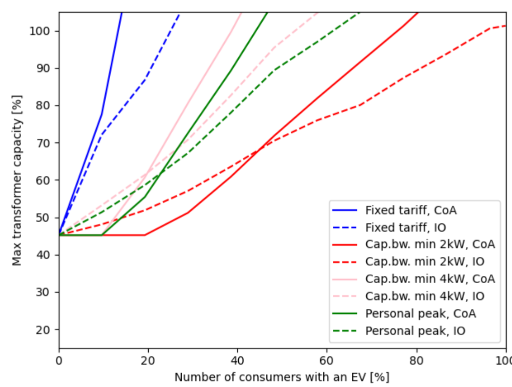
(a) Results neighbourhood 1



(b) Results neighbourhood 2



(c) Results neighbourhood 3



(d) Results neighbourhood 4

Figure 21: The maximum transformer capacity as a function of the amount of added EVs when subject to all examined tariff structures

It can be seen that the results of the simulations are very comparable with the results of when consumers were subject to a capacity bandwidth tariff with a smallest bandwidth of 4 kW. However, in all four neighbourhoods, the effects of implementing a personal peak charge are a bit more impactful. When looking at the results from Tables 20 and 21 this was not necessarily expected. Although it can be explained by the fact that consumers minimise their electricity demand based on their network peak each month, and not based on their absolute maximum network peak.

The results in Figure 21 clearly show the peak shaving capacity of the personal peak charge tariff. Furthermore, the effects on the network peak of implementing a personal peak charge are very comparable with the effects of a capacity bandwidth tariff where the smallest bandwidth is 4 kW.

9.2 Answer to the third sub-question

This chapter analysed the effect of different capacity based network tariff structures on maximum network peak of different neighbourhoods. This corresponds with answering the third sub-question:

How do different distribution network tariff structures influence the maximum network peak load?

The effects of different distribution network tariff structures on the maximum network peak were analysed by simulating the load of different neighbourhoods, for an increasing number of consumes that have EVs, for different network tariff structures. The examined network tariff structures are two different configurations of a capacity bandwidth tariff, a personal peak charge and the current fixed tariff. The results are generated for two different charging strategies. Consumers either all charge on arrival or they all individually optimise their charging behaviour based on the wholesale prices.

9.2.1 Effects under the current network tariff structure

The results of the simulations show that under the current network tariff structure, the network peak load is expected to rise significantly when more consumers have an EV. Since this tariff structure gives no incentive to change the charging pattern, all consumers charge with a capacity of 11 kW. This results in very high network peaks for both charging strategies.

Even though consumers charge their cars during the already existing network peak in the charge on arrival strategy, the results show that the individual optimisation strategy leads to even higher percentages of transformer loading. This can be attributed to the influence of the coincidence factor on the maximum network peak. The coincidence factor is a lot higher with the individual optimisation strategy.

9.2.2 Effects of implementing a capacity bandwidth tariff

When looking at the maximum transformer loading of the different neighbourhoods, when the consumers are subject to a capacity bandwidth tariff, the peak shaving capacity of this tariff structure becomes clear. For all simulated percentages of consumers that have an EV, the maximum transformer loading under both configurations of the capacity bandwidth tariff is a lot lower in comparison with the simulated results of the current tariff structure.

The difference between a capacity bandwidth tariff with a smallest bandwidth of 2 kW and that with a smallest bandwidth of 4 kW also became apparent from the results. The network peaks under the tariff with the smaller bandwidths are lower, and so are the differences between the two charging strategies.

9.2.3 Effects of implementing a personal peak charge

The expected effects of implementing a personal peak charge were very comparable with the effects of the capacity bandwidth tariff when the smallest bandwidth is 4 kW. The results of the simulation when the consumers in the neighbourhoods are subject to a personal peak charge also showed significant peak shaving capacity and also comparable differences between the two charging strategies.

9.2.4 Comparison of different network tariff structures

The results of the personal peak charge are very comparable with the results of the capacity bandwidth tariff with a minimum bandwidth of 4 kW. When looking at the maximum transformer loading, both tariff structures were outperformed by the capacity bandwidth tariff with a smallest bandwidth of 2 kW.

The differences between the results of the charge on arrival strategy of the three investigated tariffs are not that large. The charging on arrival strategy has a lower coincidence factor, and even though consumers charge their EVs during the already existing network peak, results in lower network peak demand than the individual optimisation charging strategy in situations with high amounts of EVs under all three tariff structures.

The fact that the third neighbourhood has a lot more consumers with PV in comparison with the second neighbourhoods does not influence the results very much. The second and third neighbourhood have approximately the same number of consumers and the same transformer capacity. The results of these two neighbourhoods are also almost identical.

Although the capacity bandwidth tariff with a smallest bandwidth of 2 kW showed the most promising results, it can be disputed if consumers contact a 2 kW bandwidth if they have an EV. When looking at the expected bandwidths of consumers in the data set that already have an EV, it can be seen that their expected bandwidth, in general, is a lot larger than that of consumers who do not have an EV.

Furthermore, the current simulation is based on three months during the summer, in which electricity usage is lower. By looking at the differences between both options of the capacity bandwidth tariff, it can be concluded that the peak shaving capacity is directly related to the sum of the bandwidths in a neighbourhood. Therefore, it can be expected that if consumers contract a larger bandwidth, the peak shaving capacity will be a bit lower.

However, all three examined network tariff structures showed significant improvements when compared to the results of the current fixed tariff. When specifically looking at the results of the fourth neighbourhood, where congestion is most prevalent, it can be seen how implementing a capacity based network tariff structure can reduce congestion. By significantly reducing congestion, implementing a capacity based network tariffs structure can also significantly postpone infrastructure investments. Although, within the scope of this research, no exact estimations can be made about the number of costs that could be saved for each network tariff structure.

10 Financial effects on different consumer groups

This chapter analyses the financial effects of different network tariff structures on consumers. This is done by calculating the expected network charge of consumers for different network tariff structures. Hereafter, the correlation between the expected network charges and the metrics that describe the electricity demand is analysed to see which metrics are indicators for higher or lower expected network charges. Furthermore, the effects on two different consumer groups are analysed. The first group consists of active consumers, which are consumers that either have PV, an EV, or both. The second group consists of passive consumers, which are consumers that PV or an EV.

The expected network charge is only based on the capacity rate. It is assumed that the standing charge, the periodic connection fee and the measurement rate do not change for different network tariff structures. Section 7.1.1 discussed the used capacity rates for the different network tariff structures.

10.1 Results

The expected network charges are computed for every consumer in the data set. Because of the assumption that consumers minimise their network costs, the network costs do not change when EVs are allocated to the consumers.

10.1.1 Expected network charge for the consumers in the data set

Table 22 below shows the descriptive statistics of the expected charges for all consumers in the data set.

	Minimum	Mean	Maximum	St. dev
Current fixed tariff	€160,30	€160,30	€160,30	€0,00
Cap. BW. min 2kW	€90,00	€127,17	€765,00	€70,11
Cap. BW. min 4kW	€160,00	€169,00	€484,06	€40,03
Personal peak charge	€14,32	€150,72	€501,64	€54,74

Table 22: Descriptive statistics of the expected network charges of the consumers in the data set for different network tariff structures

The descriptive statistics show that differences exist in the expected network charge for consumers for different examined network tariffs. However, it must be noted that the data is based on summer months, this will likely result in lower expected charges.

It can be seen that the average expected charge is the lowest under the capacity bandwidth tariff with a smallest bandwidth of 2 kW, but the standard deviation under this tariff structure is also the highest, meaning that the differences in expected charges are the largest. Furthermore, the average charge of the capacity bandwidth tariff with a smallest bandwidth of 4 kW and the average charge under the personal peak charge is comparable with the current charge under the fixed tariff.

These results are highly dependent on the assumptions made in Section 7.1.1. The capacity bandwidth tariff with the smallest bandwidth of 2 kW has the lowest expected network charge because a large portion of consumers would choose a 2 kW bandwidth. The price for the 2 kW bandwidth is only €90.

10.1.2 Correlation between network charge and metrics

To investigate which characteristics of the electricity demand are indicators for a higher or lower network charge, the correlations between the expected network charges and the metrics from Chapter 5 are examined. The results from this analysis are shown in Table 23 below. Since the expected charge under the current fixed tariff is constant, per definition it does not correlate with any of the metrics.

Metric	Cap. BW. min 2kW	Cap. BW. min 4kW	Personal peak
Average load	**0,346**	**0,238**	**0,368**
Maximum load	**0,751**	**0,666**	**0,851**
Average maximum load	**0,638**	**0,531**	**0,717**
Percentage in peak	-0,013	-0,020	0,097
Over 4 kW	**0,595**	**0,644**	**0,482**

Table 23: The correlation coefficients between the metrics and the expected network charges, significant correlations in bold.

It can be seen that the correlation coefficients are significant for four of the five metrics for all three different tariff structures. The fact that multiple metrics significantly correlate with the expected network charge is not entirely unsurprising, since all metrics are based on the same data and Section 5.3.3 already showed that significant correlations between the metrics itself exist. The percentage of electricity used during peak hours does not significantly correlate with the expected network charge under all three different tariff structures.

Since the correlation coefficients of the other four metrics are significant for the network charge for all three examined tariff structures. It can be concluded that when a capacity based network tariff structure is implemented, consumers with higher average load, higher maximum load, higher average maximum load and a higher number of times the 4 kW limit is exceeded are expected to have a higher network charge.

Furthermore, the results show that the correlation coefficients for the first three metrics are the smallest for a capacity bandwidth tariff with a smallest bandwidth of 4 kW and the largest for the personal peak charge tariff. This shows that consumers with a higher maximum load and a higher average load are expected to pay relatively more when this tariff structure is in place as opposed to the other two examined tariff structures.

The maximum load has the highest correlation coefficients for all three tariff structures. This means that the absolute maximum load is the best indicator for the expected network charge for all three tariff structures. Therefore, when a capacity bandwidth tariff structure is implemented, the consumers with the highest maximum load also have the highest expected network charge.

10.1.3 Difference between active and passive consumers

This section analyses the financial effects of different tariff structures on two different groups of consumers. The two distinct groups of consumers are active and passive consumers. Active consumers are consumers who produce electricity with the help of PV or have an EV. Passive consumers are consumers who do not produce electricity with the help of PV and do not drive an EV. The average expected charges for both consumer groups under the different tariff structures are shown in Table 24. Just like with the correlation analysis, the expected charges under the current fixed tariff structure are not analysed, since they are the same for each consumer.

The differences in expected network charges show that under all three tariff structures, active consumers are expected to pay more than passive consumers. Furthermore, since a consumer is either an active consumer or a passive consumer, an independent t-test can be performed directly to test if the differences in Table 24 are significant. The results of the independent samples t-test can be found in Appendix B.4. A summary of the results of this t-test is shown in Table 25.

	Cap. BW. min 2kW	Cap. BW. min 4kW	Personal peak
Active (N=140)	€145,23	€179,19	€166,71
Passive (N=238)	€116,55	€163,02	€141,32

Table 24: Descriptive statistics of the expected charges of the data set based on the division in active and passive consumers

	Cap. BW. min 2kW	Cap. BW. min 4kW	Personal peak
Significance	0,001	0, 002	0,000
Mean difference	€28,68	€16,17	€25,40

Table 25: The results of the independent t-test for the expected network charges for the division in active and passive consumers

The results from Table 25 show that the network charges for active consumers are significantly higher for all three network tariff structures. This means that, when subject to a capacity based tariff structure, active consumers are going to be paying more than passive consumers. When assuming that the average prices of the current network tariff structure and a future network tariff structure of all consumers stays equal, because of the cost-recovery principle, this inherently means that passive consumers are going to be paying less than they currently do, and active consumers are going to be paying more than they currently do.

However, it must be said that the data analysis showed that the different characteristics are not independent. In fact, active consumers are often consumers with a larger housing type. Therefore these differences cannot be fully accounted to the sole difference of being an active or a passive consumer. That being said, consumers with a larger housing type also use more capacity.

10.2 Answer to the fourth sub-question

This chapter analysed the effect of different capacity based network tariff structures on the maximum network peak of different neighbourhoods. This corresponds with answering the third sub-question:

What are the financial effects of different distribution network tariff structures on consumers?

The results show that the expected network charge for consumers in the data set is the lowest for the capacity bandwidth tariff with a smallest bandwidth of 2 kW, and the highest for a capacity bandwidth tariff with a smallest bandwidth of 4 kW. These results are highly influenced by the assumptions made in Section 7.1.1 and by the characteristics of the data set. Furthermore, since this analysis is based on the data of summer months, it is expected that the actual charge under all three capacity based network tariff structures would be higher.

Despite the results being heavily influenced by the made assumptions, it became clear that consumers with a higher average load, a higher maximum load, a higher average maximum load and a higher number of times the 4 kW limit is exceeded are expected to be paying more when a capacity based network tariff structure is in place.

Furthermore, the analysis of the expected network charge for active and passive consumers showed that in all cases active consumers are expected to be paying more under a different network tariff structure. Because the growing amount of RES and growing electricity usage due to electrification of heating and transport are partly causing the increasing amount of challenges for the distribution network (Mahmud & Zahedi, 2016; Moraga-González & Mulder, 2018), the fact that active consumers are expected to be paying more under a different tariff structure can be seen as positive.

11 Relating examined network tariff structures to the five key regulatory principles

In Chapter 4 the criteria which are used to quantify the five key regulatory principles were derived. In this chapter, the examined network tariff structures are related to the key regulatory principles and with that, the fifth sub-question is answered. The fifth sub-question is the following:

How do different distribution network tariff structures relate to the regulatory principles that they must adhere to?

The five key regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency. In this chapter, each principle is shortly discussed, including the criteria that are used to define the principle. Hereafter, the current fixed tariff, the two different capacity bandwidth tariffs and the personal peak charge are related to each of the five key regulatory principles.

11.1 Non-discriminatory

Non-discriminatory network tariffs mean that users are handled equally in equal circumstances (Droste et al., 2018). It is assumed that a network tariff structure is either discriminatory or non-discriminatory. To determine if a network tariff structure is non-discriminatory the following question was drafted in Chapter 4:

Are consumers that have the same electricity pattern charged differently?

Both options of the capacity bandwidth tariff and the personal peak charge have not shown any instance where consumers with the same electricity pattern are charged differently. Furthermore, since the height of the tariffs is solely based on the electricity pattern itself, there will never be any instances where this would be the case. Therefore it is determined that for all examined options, consumers that have the same electricity pattern are not charged differently. This means that both options of the capacity bandwidth tariff and the personal peak charge are non-discriminatory.

11.2 Cost-recovery

Cost-recovery through network tariffs means that each DSO should be able to recover their efficient costs fully through the network charges (Droste et al., 2018). It is assumed that the current network tariff structure adheres to the principle of cost-recovery. Therefore, for another network tariff to satisfy the principle of cost-recovery, the total sum of all network charges in the service area of all DSOs should at least be equal to the total sum of all network charges under the current fixed tariff.

In the previous chapter, the expected network charges of the examined tariff structures were analysed. The results in Table 22 showed that only the average expected network charge of a capacity bandwidth tariff where the smallest bandwidth of 4 kW is higher than that of the current fixed tariff.

However, the heights of the used tariffs were based on multiple assumptions. If higher tariffs were assumed, also the expected network charge would have been higher.

Second, it is expected that more consumers might contract a larger bandwidth since the allocation of bandwidths is based on the electricity demand of three summer months. This also means that the expected average charge of a personal peak charge could be higher than the current charge of the fixed tariff.

Lastly, it can not be assumed that the used data set is an actual representation of the consumers in the service area of Stedin. Therefore, the results in Table 22 do not say much about the ability to recover costs in the service area of Stedin. Moreover, nothing can be said about the expected network charges in the service areas of the other Dutch DSOs.

Within the scope of this thesis, no conclusions can be drawn about the ability to recover the efficient network costs for each Dutch DSO for each examined tariff structure. When another tariff structure is implemented in the future, the tariffs must ideally be set in such a way that all Dutch DSO are exactly able to recoup their efficient costs. A capacity based network tariff results in an income risk for DSOs, since the tariffs in a capacity based tariff structure are dependent on the behaviour of consumers, whereas this is currently not the case.

This might influence the preference of a DSO. The service areas of all Dutch DSOs are different and these different consumers have different characteristics and behave differently, this could result in a DSO preferring a certain network tariff structure over another. Furthermore, a tariff structure that minimises these risks could also be preferred by DSOs. The existing literature does not focus on the needs of a DSO, which indicates a mismatch between the literature and the needs of a DSO. Literature often discussed network tariff design from the perspective of the consumer or from the regulator. The fact that certain network tariff structures increase certain risks for DSOs is often not mentioned.

When it is assumed that the current data set is an accurate representation of the Netherlands or the service area of Stedin and that the data originating from July till August accurately represents the electricity demand of consumers for a whole year. The heights of the tariffs that enable a DSO to recoup their efficient costs can be calculated by simulating this problem as a non-cooperative game between the consumers and the regulator (Hoarau & Perez, 2019; Schittekatte & Meeus, 2018a; Schittekatte et al., 2018). For the capacity bandwidth tariff model with a minimum bandwidth of 2 kW, this would result in a charge of approximately 59 €/kW. For the capacity bandwidth tariff model with a minimum bandwidth of 4 kW, this would result in a charge of only approximately 38 €/kW. This suggests that a consumer that chooses a 4 kW bandwidth has to pay respectively €236 if a 2 kW bandwidth is a possibility, while only paying €152 if this is not the case. However, the differences in prices between the two bandwidths also determine which bandwidth a consumer chooses.

11.3 Cost-reflectiveness

The regulatory principle of cost-reflectiveness states that costs must be allocated to those who impose costs on the network (CEER, 2017). As earlier discussed in Chapter 4, cost-reflectiveness is defined by the definition of Passey et al. (2017). Passey et al. defined cost-reflectiveness as the linear Pearson's correlation between the network charge and the average of the applicable peak demand over each month. In this definition, the applicable demand is the demand of a consumer during the total coincidental network peak of that month (Passey et al., 2017).

To calculate this correlation, the average of the applicable peak demand over each month is calculated for each consumer. Because the cost-reflectiveness is dependent on the network peak, the cost-reflectiveness is different for each neighbourhood. Therefore, the cost-reflectiveness is calculated for each neighbourhood separately, as well as for the entire data set.

Because consumers with an EV were not represented in the different neighbourhoods, the cost-reflectiveness is also calculated for the entire data set. The results of the linear Pearson's correlation between the expected network charge and the average of the applicable peak demand over each month for the different network tariff structures in the different neighbourhoods and the entire data set are shown in Table 26.

	Cap. BW. min 2kW	Cap. BW. min 4kW	Personal peak
NBH1	**0,530**	0,322	0,498
NBH2	0,645	0,484	**0,688**
NBH3	**0,705**	0,573	0,627
NBH4	**0,399**	0,261	0,375
Data set	0,361	0,292	**0,419**

Table 26: The Pearson's correlation coefficients between expected network charge and average applicable peak demand, highest correlation in each calculation in bold. All correlation coefficients are significant.

The results in Table 26 show that in neighbourhoods 1, 3 and 4, the capacity bandwidth tariff with a smallest bandwidth of 2 kW is the most cost-reflective. In neighbourhood 2 and the situation that it is assumed that the entire data set is one neighbourhood, the personal peak charge is the most cost-reflective.

When the averages of the correlation coefficients are taken over the different neighbourhoods and the data set, the most cost-reflective tariff is the capacity bandwidth tariff with the smallest bandwidth of 2 kW. The average correlation coefficient of this tariff is 0,528. The second most cost-reflective tariff is the personal peak charge, with an average of 0,521. The least cost-reflective tariff is the capacity bandwidth tariff with a smallest bandwidth, with an average of 0,386.

These results are based on four fictive neighbourhoods and one data set of only 378 consumers. The results show that for five different networks, no single tariff structure is the most cost-reflective in all networks. The cost-reflectiveness is determined by the maximum network peak of each neighbourhood, which is caused by the coincidence of all independent electricity patterns of all consumers in that neighbourhood. This shows the difficulty in calculating the cost-reflectiveness of a network tariff structure and the difficulty of designing cost-reflective tariffs.

Nevertheless, the results showed that in all situations, for all three tariff structures, the Pearson's correlations are significant. This shows that all examined network tariff structures are at least more cost-reflective than the current fixed tariff. This confirms the results of Nijhuis et al. (2017), Ren et al. (2016) and Simhauser (2016). The capacity bandwidth tariff with the smallest bandwidth of 2 kW is more cost-reflective than the other configuration of a capacity bandwidth tariff. On average, this capacity bandwidth tariff is also a bit more cost-reflective than the personal peak charge.

11.4 Transparency

Transparency in network tariffs means that it should be clear to consumers what they are paying for (Droste et al., 2018). And a transparent network tariff means that the methodology to calculate the height of the tariffs should be transparent (CEER, 2017; Reneses & Ortega, 2014). To determine if a network tariff structure is transparent, the following question was drafted in Chapter 4:

Is the tariff methodology clear and unilateral interpretable?

The current methodology for calculating the tariffs is very simple since everyone pays the same fixed amount. If the current network tariff structure would be changed, this always means that the methodology will become at least a bit more complicated.

The examined tariff structures are a capacity bandwidth tariff and a personal peak charge. The network charge under the capacity bandwidth tariff is determined by the contracted bandwidth and the number of charges due for exceeding the bandwidth. Since the bandwidth is based on capacity and the exceedance fee is calculated by the amount of electricity used above the bandwidth, this tariff structure has two tariff carriers. The personal peak charge is only dependent on the maximum peak and therefore only has one tariff carrier.

This means that by looking at the number of tariff carriers for each network tariff structure, the capacity bandwidth tariff is more complicated. However, that does not mean it is not transparent. Since the methodology itself is transparent and calculating the expected network charge based on an electricity pattern is simple for both tariff structures. Therefore it is concluded that both options of the capacity bandwidth tariff and the personal peak charge are transparent.

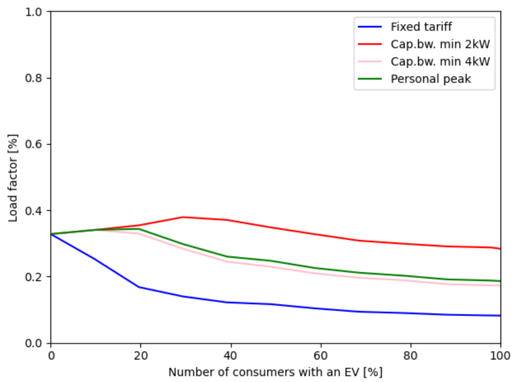
This is conflicting with the results of, Droste et al. (2018). Who concluded that a capacity bandwidth tariff is more transparent than a personal peak charge and that a personal peak charge is conflicting with the chain transparency principle of the Dutch ACM. The chain transparency principle of the ACM states that energy retailers should be able to relate the original quotation to the final consumer bill. However, since the personal peak model only consists of one charge carrier, this might even be easier to do for a personal peak charge.

11.5 Promoting efficiency

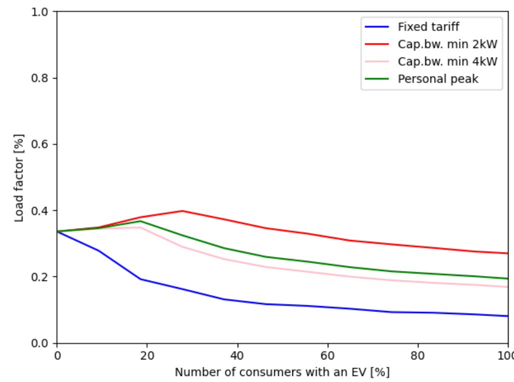
Network tariffs should promote efficient trade and competition as well as promote effective network usage. It was decided that this is the case if a tariff does not hinder efficient trade and competition. Therefore the following question was drafted in Chapter 4:

Do competitive advantages arise when implementing the network tariff structure?

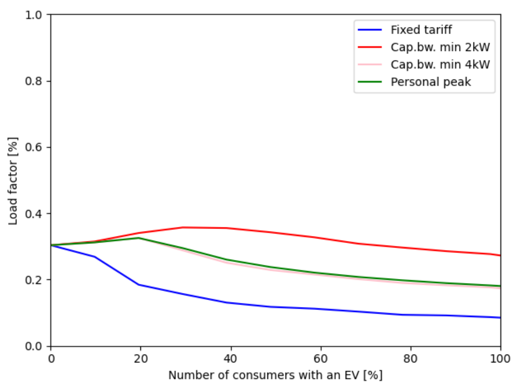
For all examined network tariff structures, no competitive advantages became apparent. Herewith it is assumed that all examined network tariff structures promote efficient trade and competition. To examine to the degree to which a network tariff structure promotes efficient network usage, the percentage change in load factor of the network under a certain network tariff structure in comparison with the load factor of the network under the current tariff structure is computed. Figure 22 shows the load factor for the four neighbourhoods as a function of the percentage of consumers that have an EV.



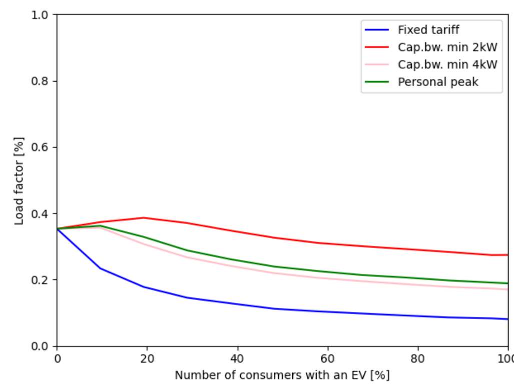
(a) Results neighbourhood 1



(b) Results neighbourhood 2



(c) Results neighbourhood 3



(d) Results neighbourhood 4

Figure 22: The load factor as a function of the amount of added EVs for all examined tariff structures

The average percentage change over both charging strategies and all neighbourhoods in the situation with 100 percent EV penetration for the capacity bandwidth tariff with a smallest bandwidth 2 kW is 218 percent. For the other capacity bandwidth tariff, it is 97 percent. For the personal peak charge, the percentage change is 113 percent.

This means that based on the regulatory principle of promoting efficiency, the capacity bandwidth tariff with a smallest bandwidth of 2 kW is the best, followed by the personal peak charge tariff, and lastly the capacity bandwidth tariff with a smallest bandwidth of 4 kW.

11.6 Conclusion

In the previous sections, the different examined network tariff structures were compared with each other based on the five key regulatory principles. The examined network tariff structures are two different configurations of a capacity bandwidth tariff, with a smallest bandwidth of respectively 2 and 4 kW, and a personal peak charge.

For the regulatory principles of non-discriminatory, cost-recovery and transparency, it was determined in Chapter 4 that a tariff structure either adheres or does not adhere to these principles. All examined network tariff structures adhere to the principles of non-discriminatory and transparency.

Concerning the principle of cost-recovery, it was not possible to draw conclusions within the scope of this thesis because it is not known if the data set is an accurate representation of the service area of Stedin or the Netherlands. Furthermore, the expected network charges are highly dependent on the made assumptions in Section 7.1.1. However, if it is assumed that the data set is an accurate representation of either the service area of Stedin or of the Netherlands, based on the chosen heights of the tariffs only the capacity bandwidth tariff with the smallest bandwidth of 4 kW would adhere to the principle of cost-recovery.

Concerning the regulatory principles of cost-reflectiveness and promoting efficiency, the results showed that all capacity based network tariff structures are found to be more cost-reflective and better promote efficiency than the current fixed network tariff structure. The capacity bandwidth tariff with a smallest option of 2 kW outperformed the other two tariff structures. However, the results of the cost-reflectiveness of the different tariff structures showed that in some network the personal peak charge is most cost-reflective.

12 Discussion

The results of this thesis show that the examined capacity based tariff structures are more cost-reflective and efficient in comparison with the current fixed tariff, which confirms the findings by Nijhuis et al. (2017), Ren et al. (2016) and Simhauser (2016). Moreover, the results showed that implementing a capacity based network tariff would result in significant reductions of the maximum network peak as opposed to the current tariff structure when the amount of EV penetration is large. The results showed that a capacity bandwidth tariff with possible bandwidths of 2, 4, 8 and 17 kW shows the most potential.

However, some important limitations have to be recognised and the impact of different assumptions must be assessed. This chapter aims to reflect on the most important limitations and assumptions. First, the impact of the limited amount of data is analysed. Second, the main model assumptions are used to reflect on the results. Third, the impact of the most significant design choices is reflected upon.

12.1 Limited amount of data

The limited amount of data is acknowledged as one of the main limitations of this research. The used data contains the load pattern of 378 consumers in the service area of Stedin. Next to this, some characteristics are known for each consumer in the data set. Out of these characteristics, only the housing type, the presence of PV and the presence of an EV were analysed. The analysed data spanned from 02-07-2020 till 30-09-2020, which are three summer months. The two main issues with the limited amount of data are the effects this has on the statistical analysis and the fact that only the data of summer months were used in this research.

12.1.1 Effect on statistical analysis

The relatively low number of consumers in the data set has an impact on the results of the statistical analysis done in Chapter 5. The results of the chi-square test of independence showed that all investigated characteristics are not independent of each other. This means that the conclusion of an analysis of one of these characteristics can never be fully attributed to that specific characteristic.

If the data set would have consisted of more consumers, it would have been possible to analyse the specific impact of a certain characteristic by keeping all other characteristics constant. However, because of the relatively large number of characteristics and the small number of consumers in the data set, this would not have yielded many significant results.

12.1.2 Impact of data originating from summer months

The fact that the data originated from three summer months could influence the results highly. Since it is assumed that all consumers do not exceed their allocated bandwidth, the bandwidths that get allocated are a measure of the impact of a capacity bandwidth tariff. The same is true for the personal peak charge, where consumers do not exceed their personal peak.

The bandwidths that get allocated to the consumers in the simulation are based on the electricity demand in the summer. Therefore, it can be disputed if the generated results are realistic. The average load of all consumers in the data set is only 0,199 kW, while the average load of a Dutch consumer over a whole year is approximately 0,31 kW (Centraal

Bureau voor de Statistiek, 2020). It could be the case that the allocation of bandwidths to consumers would be done differently if based on a whole year of data. An analysis is performed to assess the impact of the used data.

According to the consumption profiles from the Dutch Association for Energy Data Exchange (NEDU), July, August and September respectively correspond with 6,5, 6,7 and 7,2 percent of the total yearly load of a typical Dutch consumer (NEDU, n.d.). October corresponds with 8,7 percent of the total yearly load. Therefore the electricity demand of October approximately represents the average of a year. Therefore, to analyse the impact of the used data, the electricity demand of October is used. The average electricity demand in October is 0,35 kW, which is closer to the yearly average of 0,31 kW.

With the electricity demand of October, the model is used to allocate the most applicable bandwidth for each consumer for both different configurations of the capacity bandwidth tariff structure. Thereafter, the sum of bandwidths and the sum of the maximum peak for all different neighbourhoods are computed and shown in Table 27. Table 27 shows the summarised bandwidths and summarised peak load of all consumers in the four different neighbourhoods. Also, the percentage change compared with the results in Tables 20 and 21 are shown.

	2, 4, 8, 17 kW		4, 8, 12, 17 kW		Pers. peak	
	$\sum Bw$	$\Delta\%$	$\sum Bw$	$\Delta\%$	$\sum PP$	$\Delta\%$
1	114	7,6	204	0,0	207,9	1,3
2	224	5,7	396	1,0	344,6	-11,9
3	224	9,8	376	1,1	406,8	-3,6
4	446	9,9	796	0,5	752,8	-3,6

Table 27: Sum of bandwidths and maximum peaks of all consumers per neighbourhood based on the data of October

The above table shows that the change in input data influences the results of the capacity bandwidth tariff with the smallest bandwidth of 2 kW a lot more than the other configuration of the capacity bandwidth tariff. This suggests that consumers that originally choose a 2 kW bandwidth more often choose a bigger bandwidth. It is expected that this results in smaller differences between the two different configurations of the capacity bandwidth models since more consumers would choose the same bandwidth for both models. The maximum peak load has decreased in most neighbourhoods compared to the data from July, August and September. Suggesting that mostly the average load has risen but not necessarily the maximum loads of consumers.

Based on this changed electricity pattern, the simulation is run for the second neighbourhood. Figure 23 shows the results of this simulation. This figure shows the average used transformer capacities for each examined tariff structure for both the data originating from the summer months and for October.

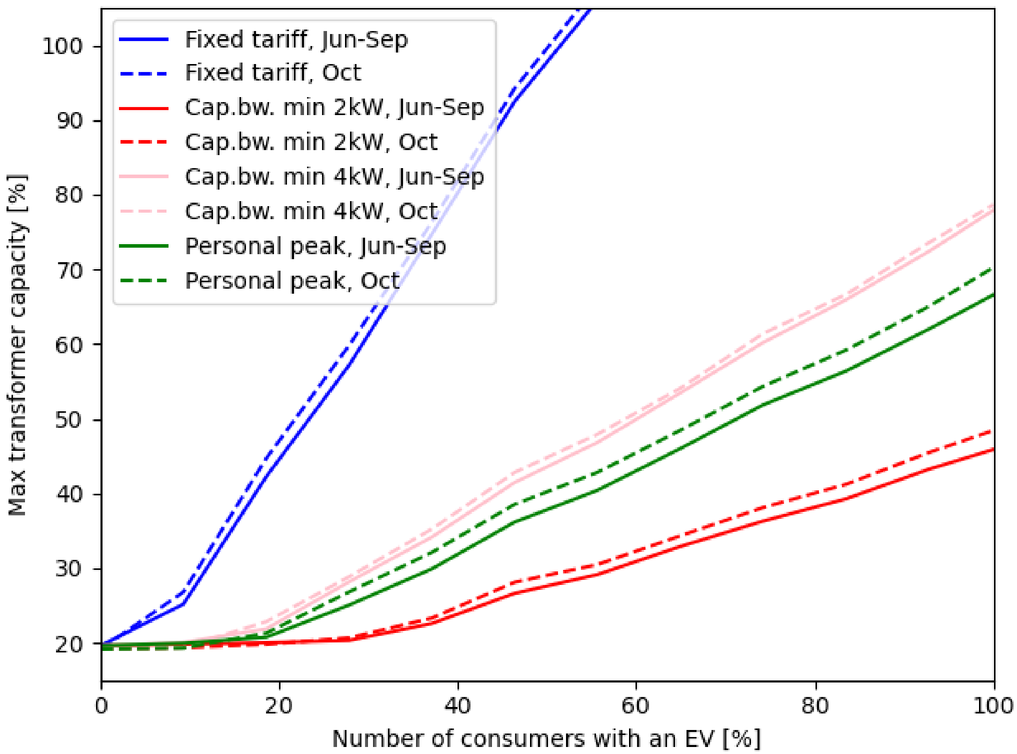


Figure 23: Average maximum transformer capacity as a function of the percentage of consumers in the second neighbourhood that have an EV under all examined tariff structures

Figure 23 clearly shows how the difference between the uninterrupted lines and the dashed lines are the largest for the capacity bandwidth tariff with the smallest bandwidth of 2 kW and the personal peak charge. The results of the three examined capacity based network tariff structures lie closer together than with the data of the three summer months. This implies that when the results are generated with a full year of data, the differences between the examined tariff structures would be smaller than suggested in the previous chapters. Furthermore, the differences for the capacity bandwidth tariffs seem to be in line with the percentage change in summarised bandwidth of Table 27.

12.2 Impact of assumptions on results

As shortly mentioned before, since every model is a simplification of reality, every model is wrong (Box, 1976). To be able to simulate the expected electricity demand of consumers when subject to different network tariff structures, important assumptions were made. This section discusses the effects of these assumptions. This is done in three paragraphs, the first paragraph discusses the assumption that consumers minimise their network costs. The second paragraph discusses the assumption that consumers either charge upon arrival or individually optimise. The third paragraph shortly discusses the interaction between the assumed tariff heights and the results.

12.2.1 Consumers minimise their network costs

It was assumed that consumers behave in a way that they will not charge their EV if this would result in higher network costs. This assumption was made to make the model more feasible since the optimisation model needs strict constraints. However, there are multiple situations, in reality, where this assumption does not hold. The two examined network tariff structures differ most from each other when this assumption does not hold.

When subject to a personal peak charge, if consumers increase their network peak, the extra amount to be paid depends on the amount of extra used capacity. When subject to a capacity bandwidth tariff, the additional network charge is determined by the exceedance fee of 0,50 €/kWh. In situations where consumers do not minimise their network costs, the cost carrier is different for the two tariff structures. When assuming that consumers minimise their network costs, the personal peak charge tariff and a capacity bandwidth tariff are very comparable.

If a consumer is willing to exceed their bandwidth limit or personal peak and increase the network costs, what they have to pay is inherently different. Imagine a consumer, who has a bandwidth of 4 kW and a maximum personal peak of 4 kW, that wants to charge their EV with an additional 10 kWh of electricity. When this consumer is subject to a capacity bandwidth tariff, this tariff gives no incentive to minimise the total amount of needed capacity, whereas the personal peak charge does. If this consumer is subject to a capacity bandwidth tariff it is possible to use 14 kW for one hour. However, when subject to a personal peak charge, it would still be cheaper if this consumer used 6 kW for five hours. This key difference between a capacity bandwidth tariff and a personal peak charge is currently not taken into account, because of the assumption that all consumers minimise their network costs.

Because of the assumption that consumers minimise their network costs, the main differences between a personal peak charge and a capacity bandwidth tariff are not captured in the simulation model. Therefore, both models give comparable incentives to reduce peak load, as in both models consumers just minimise their peak load to a certain value. This also explains why the results of a capacity bandwidth model with bandwidths of 4, 8, 12 and 17 kW and a personal peak charge model yielded such similar results. Because the average of all allocated bandwidths of all consumers present in the neighbourhoods is 4,022 kW, and the average peak load is 4,048 kW.

It would also be possible to base the exceedance fee on capacity or both capacity and exceeded volume. Both of these options are not investigated in this thesis, since consumers do not exceed their bandwidth limit. A capacity bandwidth tariff with an exceedance fee with a capacity component would also incentivise consumers to minimise their capacity when they exceed their bandwidth limit.

12.2.2 Consumers charge upon arrival or individually optimise

Secondly, it was assumed that consumers all follow the same charging strategy. Consumer either charge upon arrival or individually optimise based on the wholesale electricity prices. However, it can be expected that these two charging strategies do not accurately describe the actual charging behaviour of consumers. This was shown during the validation of the EV charging profiles in Section 7.4.1.

Since it was assumed that all consumers follow the same charging strategy, both strategies depict some kind of worst-case scenario. When all consumers charge upon arrival they mainly charge during the already existing peak hours. When all consumers individually optimise they are all charge at the same time.

In reality, it can be assumed that not all consumers follow the same charging strategy. In a situation where part of the consumers charge upon arrival and another part individually optimises, both the percentage of electricity used during peak hours and the coincidence factor is lower.

Nevertheless, the charging strategies did create some insights. For low amounts of EV penetration, it is more efficient to stimulate the charging outside of peak hours. However, for higher amounts of EV penetration, reducing the coincidence factor seems to yield more benefits.

Furthermore, it must also be taken into account that the coincidence factor is highly influenced by the assumption that all consumers know the wholesale prices beforehand. The effect of charging a whole fleet of EVs at the same time on the wholesale price is also not taken into account. Both of these simplifications result in extra high coincidence factors when consumers individually optimise their charging behaviour. Therefore, the expected maximum transformer loading of a neighbourhood might be lower in reality.

All things considered, this research aims to compare different network tariff structures with each other. Even though the examined charging strategies are not fully realistic, the results still enable for an adequate comparison. However, given the made assumptions, it is expected that the actual maximum network peak would be a bit lower since both the percentage of electricity used in the peak and the coincidence factor would probably be lower.

12.2.3 Sensitivity analysis

In Section 7.1.1, the heights of the three examined network tariff structures was assumed. Chapter 10 analysed the final expected network charge of consumers. In this chapter, the impact of the assumptions made in Section 7.1.1 was made clear. Changing the heights of the tariffs does not only change the expected charge but also influences which bandwidth would be the most suitable for a consumer.

The heights of the tariffs influences which bandwidth a consumer would choose. If the difference in price between the bandwidths is larger, consumers are more likely to choose a smaller bandwidth. The opposite is true for the exceedance fee. A larger exceedance fee would result in more consumers choosing a larger bandwidth.

The sum of bandwidths of the consumers in a neighbourhood is a good measure of the peak shaving capacity of a tariff structure. Therefore, an interaction exists between the heights of the different bandwidths, the exceedance fee, and the effectiveness of that capacity bandwidth tariff.

Figure 24 below shows the results of a sensitivity analysis between the assumed heights of the tariffs and the assumed exceedance fee for both configurations of the capacity bandwidth tariff. It is examined how this sum of bandwidth changes when the heights of the tariffs or the height of the exceedance fee changes.

The results of the sensitivity analysis show that the assumptions for the heights of the tariff and the exceedance fee have a larger impact for the capacity bandwidth tariff with a smallest bandwidth of 2 kW. In the area surrounding the current assumptions, the relation

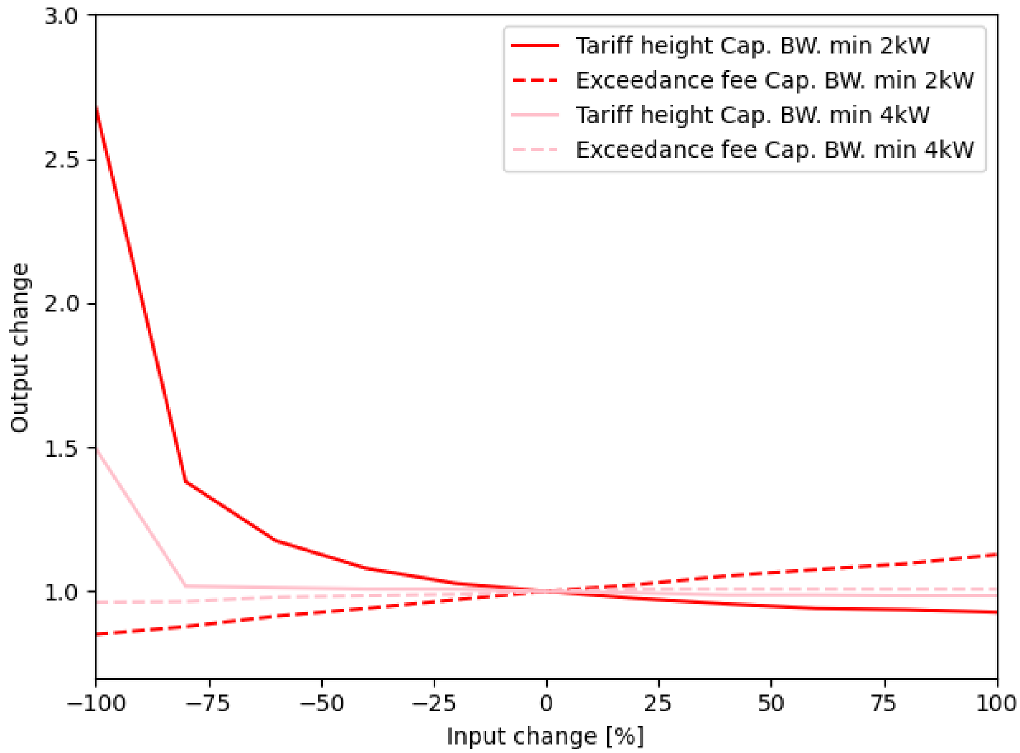


Figure 24: Results of the sensitivity analysis for the height of the tariffs and the exceedance fee for both configurations of the capacity bandwidth tariff

between the exceedance fee and the tariff heights with the total sum of bandwidths is almost linear. However, it can be seen that with a lower tariff per kW the total sum of bandwidths rises almost exponentially. This means that if the difference between the two bandwidths is getting very small, almost all consumers would choose higher bandwidths. Next to this, if the exceedance fee is chosen to be very small, more consumers choose a higher bandwidth.

The results of the sensitivity analysis show that the impact of the chosen tariff heights is larger with the capacity bandwidth tariff with the smallest bandwidth of 2 kW. Furthermore, it shows how a small change in tariff height can lead to a lot of consumers choosing a larger bandwidth.

12.3 Impact of design choices

In this last section of this chapter, the impact of the most significant design choices is reflected upon. This is done by first discussing the regulatory principles and the criteria that were used to quantify these criteria. Second, the decision to only focus on the capacity rate is discussed. Third, the impact of the decision to only focus on capacity based network tariff structures is elaborated on and analysed. Lastly, the preference of consumers, which was not taken into account, is discussed.

12.3.1 Quantifying the regulatory principles

The goal of this thesis is to compare different network tariff structures with each other. This is done based on the five key regulatory principles. Therefore, these principles were defined in Chapter 4. By doing so, some complexities were simplified. Chapter 2 discussed the academic literature concerning the key regulatory principles. In this chapter, trade-offs between the principles were identified. Some complexities surrounding the key regulatory principles, and these identified trade-offs, are not reflected upon and some did not become apparent in the results of this thesis.

First, as already briefly touched upon, the cost-recovery problem of the DSOs is not fully taken into account within the scope of this thesis. Due to the fact that the available data is no accurate representation of the service area of a DSO or the Netherlands. This thesis focused on small-scale consumers, but a lot more consumer groups exist. The current tariff structure in the Netherlands is a fixed tariff based on the connection type. In the end, a tariff structure must be cost-reflective when taken into account the generated revenue of all consumer groups. This complicates the cost-recovery problem a bit more.

The heights of the tariffs that enable a DSO to recoup their efficient costs can be calculated by simulating this problem as a non-cooperative game between the consumers and the regulator (Hoarau & Perez, 2019; Schittekatte & Meeus, 2018a; Schittekatte et al., 2018). This ideally should be expanded with the costs and revenues for the other consumer groups, which is based on the electricity demand and the expected behaviour of consumers in different consumer groups. Within the scope of this thesis, no conclusions can be drawn about the effects on other consumer groups, simply because of the limited availability of data and resources.

Second, the regulatory principle of cost-reflectiveness might have been oversimplified. The regulatory principle of cost-reflectiveness states that costs are allocated to those who impose costs on the network (CEER, 2017). Since the costs of the network are not available on the level of detail of individual users and some costs are socialised, network tariffs can never be fully cost-reflective (Droste et al., 2018). This inherently means that the used definition to quantify the cost-reflectiveness of a network tariff structure in a neighbourhood is imperfect. In this thesis, the definition of Passey et al. was used (2017).

The cost-reflectiveness was quantified as the linear Pearson's correlation between the applicable network peak and the consumer charge. Which shows the dependency of the cost-reflectiveness of the network characteristics. Furthermore, if a certain network has a linear Pearson's correlation coefficient of 1, it can be questioned if the tariff structure is perfectly cost-reflective. In theory, if you multiply all consumer charges with the same value, the correlation coefficient stays the same. This indicates that the definition of cost-reflectiveness only concerns the ratio of consumer charges to the overall network peak. Therefore the definition of Passey et al. does not specify the heights of the tariffs. Therefore, in theory, a tariff structure can be perfectly cost-reflective while the consumer charges are not even close to the marginal costs. According to the definition of Renses and Ortega, a tariff structure is cost-reflective when prices are close to marginal costs (2014).

Third, the trade-off between cost-reflectiveness and cost-recovery was not accurately represented. By defining cost-reflectiveness with the definition of Passey et al., cost-reflective charges do not represent the marginal cost of consumers. The trade-off between cost-recovery and cost-reflectiveness is a trade-off between short and long term incentives. According to the cost-recovery principle, the long-term costs have to be recouped through network tariffs. But cost-reflective tariffs should represent short-term marginal costs. This trade-off was identified by Vogelsang (2006) and interacts with the promoting efficiency principle. On the one hand, cost-reflective tariffs must promote efficient behaviour through efficient incentives with cost-reflective tariffs. On the other hand, network tariffs must be efficient on the long-term and DSOs must be able to recoup all their efficient long-term costs. Furthermore, when enough network capacity is available in a certain LV-grid, incentivising a reduction in peak load leads to higher overall costs.

The complex nature of these interactions is all dependent on the specifics of the LV-grid. In LV-grids with a high chance of congestion, it can be assumed that it is more efficient if a network tariff structure promotes the reduction of peak load. However, this same tariff structure could lead to more overall costs in networks where there is enough network capacity. This implies that it would be more efficient to implement different network tariff structures for different LV-grids. The most obvious way to do this would be to implement location-specific network tariff structures. Article 18, paragraph 7, of European Regulation 2019/943 states that national regulators should consider locational pricing.

Because of their dependence on the specific network characteristics and the trade-offs between the principles, the regulatory principles are difficult to quantify. Therefore, based on these regulatory principles, comparing different network tariff structures is also difficult. Other principles, such as simplicity, predictability and non-distortionary, are not reflected upon in this research. Although these principles do not directly originate from European or Dutch law and regulation they are identified as important by the Council of European Regulators (2017). These principles were not taken into account in the scope of this thesis.

12.3.2 Focus on capacity rate only

This thesis focused primarily on the transport-dependent rate and with that assumed that the other components of the electricity bill remain constant. However, as already mentioned before, implementing a different network tariff structure might lead to higher consumer costs. If consumers charge their car at different moments in time than they would originally have, and if the wholesale prices are higher at these moments, this leads to more consumer costs. The impact of this effect is analysed and shown in Figure 25 on the next page.

Figure 25 shows the average monthly electricity costs for charging an EV for all examined network tariff structures. The results of the individual optimisation are most important since in this case, consumers charge their EV based on the wholesale prices. When consumers charge their EV as soon as they get home, it is assumed that they do not care about the wholesale prices. The results show that implementing a capacity based network tariff structure results in an increase of €0,51 - €1,01 per consumer per month when consumers individually optimise. However, in the charge on arrival charging strategy, the total electricity costs decrease, since the network tariff structures push the charging of EVs outside of peak hours.

The results show that implementing another network tariff structure does indeed also influence other parts of the total electricity bill of Dutch consumers. However, it only influences the electricity costs with approximately €10 per consumer per year on average. The total average costs for electricity for a year are €620, this means that this difference only accounts for 1,6 percent (Milieucentraal.nl, n.d.).

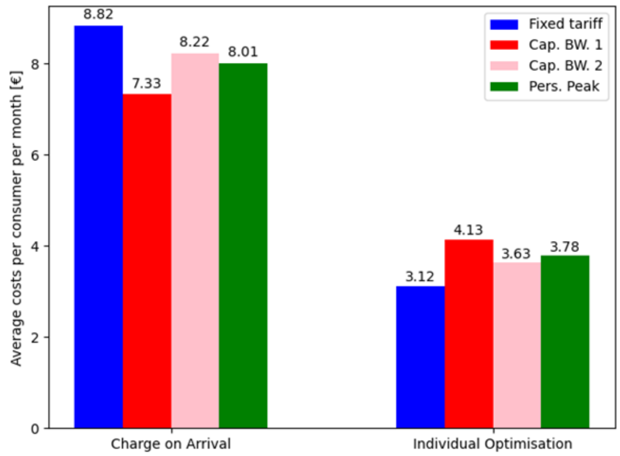


Figure 25: Average costs per consumer per month for flexible demand per tariff structure and charging strategy

12.3.3 Focus on capacity based tariff structures

This thesis focused on capacity based tariff structures only. More specifically, this thesis only investigated the effects of a capacity bandwidth tariff and a personal peak charge. With this a lot of other tariff structures were left out, the most important one being a volumetric network tariff structure. Under a volumetric network tariff structure, consumers that use more electricity are charged more. Such a volumetric tariff structure can be combined with day/night tariffs, to incentivise consumers to push their flexible demand away from the network peaks.

In the used simulation model, consumers minimise their network costs based on capacity constraints. Since these capacity constraints are not present in a volumetric network tariff structure, consumers have no incentive to change their behaviour. In the case of a day/night tariff, consumers would just wait for the moment that the lower rate applies and then start charging their EV. Based on this expected behaviour, the results would have been been very comparable to the results of the fixed tariff when consumers individually optimise. The coincidence factor would be very high and so would the maximum used capacity of the consumers. Furthermore, assuming that the lower rate only applies outside of the defined peak hours, the amount of electricity used during peak hours will probably be comparable.

Although the used simulation model does not give a lot of interesting insights when the effects of a volumetric network tariff are examined, it can be used to calculate the expected charges based on a volumetric network tariff. With the expected charges, the expected difference in charges between active and passive consumers can be computed. Furthermore, also the cost-reflectiveness can be computed for this volumetric tariff. The descriptive statistics for a volumetric day/night network tariff are shown in Table 28 on the next page. These charges are computed for 0,30 €/kWh for electricity usage between 06:00 and 23:00 and 0,15 €/kWh for electricity usage between 23:00 and 06:00. The expected charges are computed for two situations. For the situation where the price that consumers get for the electricity that they feed back into the grid is equal to the price they pay when they consume electricity

(Volumetric day/night tariff 1). The second situation is the situation where the network tariff is only based on the demand, meaning the price of electricity being fed back into the grid equals 0,00 €/kWh (Volumetric day/night tariff 2).

	Minimum	Mean	Maximum	St. dev
Volumetric day/night tariff 1	€-632,42	€104,57	€693,99	€160,58
Volumetric day/night tariff 2	€6,74	€170,99	€693,99	€91,03

Table 28: Descriptive statistics of the expected network charges of the consumers in the data set for two different volumetric day/night tariffs

In Table 28 it can be seen that the two different volumetric tariff structures differ significantly from each other. In the situation where consumers get paid for the electricity they feed back into the grid, the average expected charge is a lot lower and the minimum charge is a lot below zero. This results in the expected charges being further apart from each other, which is seen by looking at the standard deviation of both tariff structures.

When the results of Table 28 are used to reflect upon the ability to recover the efficient costs of a DSO, it can be seen that the height of the tariff must be increased to be able to let a DSO recoup their costs. if consumers get paid for the electricity they feed back into the grid. This implies that in this case, the number of network costs that passive consumers have to pay is higher because the active consumers pay less. The descriptive statistics of the expected charges for both configurations of a volumetric day/night tariff are shown in Table 29 below. The results of the independent t-test, which is used to determine if the differences between the expected charges of active and passive consumers are significantly different, are shown in Table 30.

	Volumetric day/night tariff 1	Volumetric day/night tariff 2
Active (N=140)	€-23,37	€157,53
Passive (N=238)	€177,80	€178,63

Table 29: Descriptive statistics of the expected charges for two different volumetric day/night tariffs of the data set based on the division in active and passive consumers

	Volumetric day/night tariff 1	Volumetric day/night tariff 2
Significance	0,000	0,586
Mean difference	€-201,54	€-21,10

Table 30: The results of the independent t-test for the expected network charges for two different volumetric day/night tariffs for the division in active and passive consumers

In Tables 29 and 30 it can be seen that in the case of a volumetric tariff structure, active consumers are expected to be paying less than passive consumers. Although when consumers do not get paid for the electricity they feed back into the grid, the results are not significantly different.

Based on the expected charges for both volumetric tariffs, the cost-reflectiveness can also be computed. Cost-reflectiveness is defined as the linear Pearson's correlation between the applicable network peak and the expected network charge. The results for the cost-reflectiveness of all four neighbourhoods and the entire data set are shown in Table 31 below.

	Volumetric day/night tariff 1	Volumetric day/night tariff 2
NBH1	0,231	**0,390**
NBH2	**0,527**	**0,710**
NBH3	**0,317**	**0,629**
NBH4	0,095	**0,399**
Data set	**0,226**	**0,543**

Table 31: The Pearson's correlation coefficients between expected network charge for volumetric tariffs and average applicable peak demand, significant correlation coefficients in bold.

On the contrary to the results of the capacity based network tariff structures in Table 26, not all correlation coefficients are statistically significant, specifically for the volumetric tariff structure where consumers get paid for the electricity they feed back into the grid. The average correlation coefficients are respectively 0,279 and 0,534. Based on this average, the first option of a volumetric tariff is the least cost-reflective, and the second option is the most cost-reflective when compared with the capacity based network tariff structures.

The results of the above analyses show that when a volumetric network tariff is implemented active consumers are expected to be paying less than passive consumers. Although the difference is not statistically significant when the price for electricity that is being fed back into the grid equals zero. Furthermore, the results show that this volumetric tariff is potentially even more cost-reflective than the examined capacity based network tariff structures, based on the definition of Passey et al.

Although this volumetric network tariff structure seems more cost-reflective, it can be questioned if this tariff structure is more preferable. It gives no incentives to minimise capacity, and therefore the expected effects are comparable with the current fixed tariff. Indicating that this tariff structure does not incentivise consumers to reduce the cost they incur to the network. Which indicates that this tariff structure does not postpone any infrastructural investments.

In LV-grids where there won't be any congestion soon, a volumetric tariff, which is only based on the demand, might be more preferential than a capacity based network tariff structure. Since there is no need to incentivise consumers to minimise their used capacity and it seems to be a bit more cost-reflective that the analysed capacity based network tariff structures.

It could also be the case that consumers prefer a volumetric tariff structure over a capacitive structure. The delivery charges that consumers pay for the amount of electricity they use are also volumetric, and therefore consumers might find a volumetric network tariff to be more simple and understandable.

12.3.4 Preference of consumers

The preference of consumers has not been taken into account in this research. Lu and Price concluded that consumers prefer a capacity bandwidth tariff over a personal peak charge (2018). The main reason for this is that consumers found a capacity bandwidth tariff to be more relatable and predictable. However, it might still be the case that consumers highly prefer the current network tariff structure over a capacity bandwidth tariff.

The preference of consumers was not taken into account within the scope of this research. The preference of consumers can be analysed very extensively in another research. However, a small questionnaire that only aims to give insight in if consumers prefer a capacity bandwidth tariff over a personal peak charge could have been performed and might have given interesting additional insights. Since the results showed that the effects of implementing a capacity bandwidth tariff or a personal peak charge are very comparable, the preference of consumers might be an important factor to decide which network tariff structure to implement.

13 Conclusion

In this chapter, the main research question is answered and policy advice is given. The main research question is answered based on the previously answered sub-questions. The main research question is the following:

What are the effects of different capacity based distribution network tariff structures on electricity demand, expected network charges and network peak load in the service area of Stedin?

A simulation model was used to answer the above research question and the corresponding sub-questions. This model simulated the expected electricity demand of consumers when subject to different network tariff structures. The examined network tariff structures are two different configurations of a capacity bandwidth tariff and a personal peak charge. The objective of this research is to compare different network tariff structures with each other and give policy advice considering the most applicable network tariff structure in the Netherlands. First, the answers to the sub-questions are shortly summarised. Hereafter, the main research question is answered. In the final two sections of this chapter, recommendations are made for future research and policy advice is given concerning changing the network tariff structure in The Netherlands.

13.1 Answers to the five sub-questions

In this section the answers to all five sub-question are shortly summarised.

13.1.1 Sub-question 1: defining the regulatory principles

How can the five key regulatory principles, to which network tariff design must adhere to, be quantified?

This sub-question was discussed in Chapter 4 and aimed to quantify the five key regulatory principles to which network tariff design must adhere to. The five key regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promote efficiency.

It was determined that a network tariff either adheres or does not adhere to the principles of non-discriminatory, cost-recovery and transparency, and questions were used to determine if this is the case for a certain network tariff structure.

Cost-reflectiveness was defined by the definition of Passey et al. (2017). Passey et al. defined the cost-reflectiveness of a capacity based network tariff structure as the linear Pearson's correlation between the network charge and the average of the applicable peak demand over each month.

The amount to which a network tariff structure promotes efficiency is equal to the load factor of a network, as long as competitive advantages do not arise under a certain network tariff structure.

13.1.2 Sub-question 2: effect on electricity demand of consumers

How do different distribution network tariff structures influence the electricity demand of consumers?

This sub-question was discussed in Chapter 8. The results showed that all three network tariff structures significantly reduced the maximum and average daily maximum load of consumers that have an EV. The results of the capacity bandwidth tariff with a smallest bandwidth of 4 kW and the result of the personal peak charge were very comparable. Lastly, implementing a capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW yielded the most influential results in comparison with the current network tariff structure.

13.1.3 Sub-question 3: effect on network peak load

How do different distribution network tariff structures influence the maximum network peak load?

The third sub-question was discussed in 9, in which the effects, of an increasing number of consumers that charge an EV, on the network peak load were examined in four different neighbourhoods.

The results showed that all three examined network tariff structures significantly reduce the maximum peak load when EV penetration is high. In all four neighbourhoods, implementing a capacity based tariff structure reduced the total network peak in comparison with the total network peak under the current tariff structure. The results also showed that the capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW outperformed the other two examined tariff structures. This also suggests that this network tariff structure is the ablest to postpone future infrastructural investments.

13.1.4 Sub-question 4: financial effect on consumer groups

What are the financial effects of different distribution network tariff structures on consumers?

Chapter 10 discussed the financial effect of the examined tariff structures on consumers. The results showed that, with the assumptions made in Section 7.1.1, the expected network charge was the lowest for the capacity bandwidth tariff with a smallest bandwidth of 2 kW and the highest for the other configuration of a capacity bandwidth tariff. However, it was acknowledged that the results are highly influenced by the made assumptions.

Furthermore, the results showed that for all three examined capacity based network tariff structures, active consumers are going to be paying more than passive consumers. Active consumers are consumers that either have an EV or produce electricity through PV. This can be seen as positive, considering that the increase of active consumers is partly causing the increasing challenges for the distribution network (Mahmud & Zahedi, 2016; Moraga-González & Mulder, 2018).

13.1.5 Sub-question 5: relating tariff structures to the regulatory principles

How do different distribution network tariff structures relate to the regulatory principles that they must adhere to?

In Chapter 11, it was determined that all three examined network tariff structures are non-discriminatory and transparent.

For the principle of cost-recovery, it was not possible to draw conclusions within the scope of this research since it cannot be assumed that the data set is an actual representation of the service area of Stedin or the Netherlands.

Concerning the regulatory principles of cost-reflectiveness and promoting efficiency, the results showed that the capacity bandwidth tariff with a bandwidth of 2, 4, 8 and 17 kW outperformed the other two tariff structures. Although in some situations, the personal peak charge was found to be more cost-reflective.

13.2 Answer to the main research question

What are the effects of different capacity based distribution network tariff structures on electricity demand, expected network charges and network peak load in the service area of Stedin?

In this thesis three different network tariff structures were examined, two different configurations of a capacity bandwidth tariff and a personal peak charge. The results showed that all three examined network tariff structures significantly reduce the maximum load and maximum daily load of consumers with an EV.

The network peak load for high EV penetration scenarios was significantly reduced when consumers were subject to one of the three examined network tariff structures, also suggesting that future network expansion can be postponed when another tariff structure is in place.

The expected average network charge of the three examined network tariff structures is highly dependent on the chosen tariff for each bandwidth or respectively the price per kW in the personal peak charge model. The results showed that active consumers are going to be paying more than passive consumers under all three examined options.

The capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW outperformed the other two examined options based on the expected effects on the electricity demand and the network peak load. The results also showed that based on the key regulatory principles the capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW scored better than the other two examined network tariff structures.

13.3 Recommendations for future research

Based on the results of this research and the discussed impacts of the made assumptions and the limitations in Chapter 12, recommendations for future research are made.

First, it is recommended to reanalyse the effects of different capacity based network tariff structures on the maximum network peak when data from a whole year is available. Since the allocation of the most applicable bandwidths should be based on the electricity pattern of a whole year. It is expected that the results of the examined network tariff structures, in reality, are more comparable than is currently depicted.

Second, the behaviour of consumers, when subject to a capacity based tariff, should be more closely examined to be able to more accurately model the impact of a capacity based network tariff structure. In this research, it was assumed that all consumers minimise their network costs, which might not always be the case. This might also result in clearer differences between the effects of a capacity bandwidth tariff and a personal peak charge.

Third, additional research should be done to more accurately describe the charging behaviour of consumers, to be able to analyse the effects of a capacity based network tariff structure more accurately. This research assumed that consumers either all charge upon arrival or individually optimise based on the wholesale prices. The results showed large differences in the effects of these two charging strategies.

Fourth, the impact of the examined network tariff structures on the cost-recovery of all Dutch DSOs should be analysed. It was acknowledged that the principle of cost-recovery might play an important role in the selection of the most suitable network tariff structure. Within the scope of this thesis, it was not possible to draw conclusions concerning the ability to recover the efficient costs of all Dutch DSOs. When a data set that accurately represents the service area of a DSO or the Netherlands, the cost-recovery problem can be investigated as a non-cooperative game between consumers and a regulator. This will result in heights of tariffs that make it possible for DSOs to recover their efficient costs. Based on these tariffs the expected effects of different network tariff structures can be examined and these network tariff structures can be more adequately compared.

Fifth, the preference of consumers should be more extensively investigated, for example with a simple questionnaire. Since the effects of the different tariff structures were comparable, the preference of consumers might be decisive.

Sixth, the possibility to implement an aggregated bandwidth tariff should be investigated. Under an aggregator bandwidth tariff, an aggregator allocates the flexibility of the consumers to not exceed their combined bandwidth. The aggregator is allowed to schedule the flexible demand of connected consumers. Aggregating the flexible load of multiple consumers creates a higher peak shaving capacity than a normal capacity bandwidth tariff (O'Connell et al., 2012; Voulis et al., 2017).

Last, the impact of different network tariff structures on line overloading should be investigated. The simulation model should be expanded to include the actual neighbourhood layout and line capacities to investigate the effect of different tariff structures on the maximum used line capacity. The full neighbourhood layouts, including the line capacities, are presented in Appendix C.

13.4 Policy advise

The objective of this research was to be able to compare different network tariff structures with each other, to be able to give policy advice considering the most applicable network tariff structure in the Netherlands. In this thesis, the effects of two different capacity bandwidth tariff structures and a personal peak charge were investigated. Based on the results, the following recommendations are made:

First, all three examined capacity based network tariff structures show significant potential to promote more efficient electricity use, when compared with the current tariff structure. Furthermore, all examined capacity based network tariff structures appear to be more cost-reflective than the current tariffs structure. Therefore it is recommended to implement a capacity based network tariff structure in the Netherlands in the near future.

Second, the results showed that the three examined capacity based network tariff structures are comparable. Although, the capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW showed the most potential. However, it is acknowledged that the principle of cost-recovery plays an important part in the preference of the Dutch DSOs. Therefore, it is recommended to implement a capacity based network tariff structure that adheres to the principle of cost-recovery for all Dutch DSOs.

Ideally, it is recommended to try to create different data sets that accurately describes the service area of the Dutch DSOs. Thereafter, the cost-recovery problem can be simulated as a non-cooperative game between the consumers and each DSO, which should lead to cost-reflective tariffs for each DSO individually. By comparing the heights of these cost-reflective tariffs it should be possible to be able to choose the preferred configuration of the capacity bandwidth tariff. However, the expected effects of a capacity bandwidth tariff are still expected to be very comparable to the personal peak charge model.

14 Academic and social relevance

This chapter discusses the academic and social relevance of the research. The academic relevance is analysed in the first section. The second section discusses the social relevance. The second section also discusses the relevance within the CoSEM programme.

14.1 Academic relevance

The results of this thesis confirmed the results of Nijhuis et al. (2017), Ren et al. (2016) and Simhauser (2016) which stated that capacity based tariff structures are more cost-reflective and efficient than a fixed tariff. Furthermore, also the results from Brown, Farqui and Grausz, stating that no single best network tariff design exists, were confirmed (2015).

This thesis builds on the existing literature by expanding on a case study in the Netherlands and by further reflection upon the key regulatory principles. This results in a more extensive and broader comparative analysis of different network tariff structures than previously encountered in literature. However, the analysis of the principle of cost-recovery showed that there still are aspects on which the analysis can be expanded. Furthermore, it was shown that the results are highly influenced by the made assumptions, which gives room for improvement.

The results of the thesis also showed that active consumers are expected to be paying more than passive consumers when a capacity based tariff structure is implemented. This confirms the conclusions drawn of Haapaniemi et al. (2017) and Hoarau and Perez (2019). When a volumetric tariff structure would be implemented, passive consumer would be paying more. Which is in accordance with the results of Schittekatte and Meeus (2018b). It can be considered fair if active consumers are paying more than passive consumers (Schittekatte & Meeus, 2018b).

The notion of fairness in network tariffs within this thesis was encapsulated by the five key regulatory principles. By defining these principles clearly, part of the complexity of designing network tariffs was reduced. It was found that in existing literature these principles are often not defined or related to, while in this thesis the added value of clearly defining these principles beforehand was shown. Although it must be said that some relevant trade-offs were not encapsulated by the definitions used in this research.

Lastly, four Dutch neighbourhoods were recreated and validated. These neighbourhoods and their layouts, which are shown in Appendix C, can be used to perform similar analyses as done in this research. Appendix C also shows the layout of a fifth neighbourhood, which was not used in the analysis. The anonymised electricity pattern of the consumers of a part of the data set is also published with this thesis, which also can be used for future research. This data set also shows which consumers are used to recreate the four neighbourhoods.

14.2 Societal relevance

In 2018, a committee with representatives of a lot of large stakeholders published a report investigating the obstacles regarding network tariffs in the Netherlands. The Dutch DSOs aim to come forward with a proposal regarding their advice for the implementation of a new network tariff structure in the Netherlands, which is to be implemented in the new regulating period starting January 1st 2022 (Droste et al., 2018). Although the ACM, and not the Dutch DSOs, decide what the new network tariff structure will be.

The results of this thesis aim to contribute to the preliminary proposal of the Dutch DSOs and the current discussion between the Dutch DSOs leading up to this preliminary proposal. In the Netherlands, a capacity bandwidth tariff is mostly discussed, but the results of this thesis showed that also the implementation of a personal peak charge significantly incentives efficient network usage and reduces network peak load. Furthermore, since the results from all three examined network tariff structures were very promising, it is emphasised that a new network tariff structure must enable all Dutch DSOs to recovery their efficient costs.

14.2.1 Relevance within the CoSEM programme

This research subject fits well within the Complex Systems Engineering and Management (CoSEM) programme. A CoSEM thesis is characterised by design, engineering and technology components and has interfaces with both the public and private domain.

The subject has clear design components since it investigates different design options for a new distribution network tariff structure. These design options are bounded by what is technologically and legally possible. Furthermore, network tariffs allocate costs between DSOs and consumers. DSOs operate on the intersection of the public and private domain. The aforementioned characteristics all can be found within the topic of this thesis and therefore this research fits well within the CoSEM programme.

References

Ackeby, S., Ohlsson, L., & Etherden, N. (2013). Regulatory aspects of energy storage in sweden.

Aldrich, J. O. (2018). *Using ibm spss statistics: An interactive hands-on approach*. Sage Publications.

ArcGis.com. (n.d.). Woningtypering: Kaart met de classificatie van woningtypes op basis van de bag [https://www.arcgis.com/home/item.html?id=283f14dcd39448bd929461d2725be5cb, Accessed on 20 October 2020].

Authoriteit Consument & Markt. (2016). Methodebesluit regionale netbeheerders elektriciteit 2017 – 2021 [https://www.acm.nl/sites/default/files/old_publication/publicaties/16174_methodebesluit-regionale-netbeheerders-elektriciteit-2017-2021.pdf].

Autoriteit Consument & Markt. (2020). Tarievenbesluit stedin netbeheer b.v. elektriciteit 2020 [https://www.acm.nl/sites/default/files/documents/2019-11/tarievenbesluit-elektriciteit-2020-stedin.pdf].

Azarova, V., Engel, D., Ferner, C., Kollmann, A., & Reichl, J. (2018). Exploring the impact of network tariffs on household electricity expenditures using load profiles and socio-economic characteristics. *Nature Energy*, *3*(4), 317–325.

Bhattacharyya, S., Wang, Z., Cobben, J., Myrzik, J., & Kling, W. (2008). Analysis of power quality performance of the dutch medium and low voltage grids. *2008 13th International Conference on Harmonics and Quality of Power*, 1–6.

Bjelland Eriksen, A., & Mook, V. (2020). Proposed changes to the design of network tariffs for low voltage grid users in norway.

Blank, L., & Gegax, D. (2014). Residential winners and losers behind the energy versus customer charge debate. *The Electricity Journal*, *27*(4), 31–39.

Box, G. E. (1976). Science and statistics. *Journal of the American Statistical Association*, *71*(356), 791–799.

Brown, T., Faruqui, A., & Grausz, L. (2015). Efficient tariff structures for distribution network services. *Economic Analysis and Policy*, *48*, 139–149.

Brugel. (n.d.). Brugel keurt de tarieven voor de distributie van elektriciteit en gas van sibelga voor de periode 2020-2024 goed [https://www.brugel.brussels/nl_BE/actualites/brugel-keurt-de-tarieven-voor-de-distributie-van-elektriciteit-en-gas-van-sibelga-voor-de-periode-2020-2024-goed-364].

CEER. (2017). Electricity distribution network tariffs, ceer guidelines of good practice.

CEER. (2020). CEER paper on electricity distribution tariffs supporting the energy transition.

Centraal Bureau voor de Statistiek. (2019). Share of renewable energy up to 7.4 percent [https://www.cbs.nl/en-gb/news/2019/22/share-of-renewable-energy-up-to-7-4-percent].

Centraal Bureau voor de Statistiek. (2020). Energieverbruik particuliere woningen; woningtype en regio's [https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?fromstatweb].

D-Cision. (2019). Verkenning naar de mogelijkheden van flexibilisering van nettarieven.

Dewkali, S., & Bogaert, T. (2019). Betrouwbaarheid van elektriciteitsnetten in nederland [https://www.netbeheernederland.nl/_upload/Files/Betrouwbaarheid_van_elektriciteitsnetten_in_Nederland_-_Resultaten_2019_178.pdf].

Droste, E., Vrolijk, R., Dreessen, G., Bakker, M., Nienhuis, P., Bodewes, H., Poot, J., Oskpa, H.-P., Ramaker, A., Waltmans, N., Gremmen, Y., van der Velde, F., Kloppenborg, E., de Joode, J., & Spee, L. (2018). Belemmeringen in nettarieven [https://www.energie-nederland.nl/app/uploads/2018/06/OTE_-Belemmeringen-in-nettarieven.pdf]. *Overlegtafel Energievoorziening (OTE)*.

ENTSO-E Transparency Platform. (n.d.). Day-ahead prices [https://transparency.entsoe.eu / transmission - domain / r2 / dayAheadPrices / show, Accessed on 7 October 2020].

Etherden, N., & Bollen, M. H. (2014). Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy–some illustrative case studies. *Electric Power Systems Research*, *114*, 39–48.

European Commission. (2015). Study on tariff design for distribution systems.

European Commission. (2019). *Going climate-neutral by 2050: A strategic long-term vision for a prosperous, modern, competitive and climate-neutral eu economy*. Publications Office of the European Union.

EV-database.nl. (n.d.). Tesla model 3 standard range plus [https://ev-database.nl/auto/1177/Tesla-Model-3-Standard-Range-Plus, Accessed on 14 October 2020].

GNU.org. (n.d.). Glpk (gnu linear programming kit) [https://www.gnu.org/software/glpk/, Accessed on 21 September 2020].

Haapaniemi, J., Narayanan, A., Tikka, V., Haakana, J., Honkapuro, S., Lassila, J., Kaipia, T., & Partanen, J. (2017). Effects of major tariff changes by distribution system operators on profitability of photovoltaic systems. *2017 14th International Conference on the European Energy Market (EEM)*, 1–6.

Hage, J. (2019). Hoe zit mijn energierekening in elkaar? [https://www.consumentenbond.nl/energie-vergelijken/energierekening, Accessed on 12 September 2020].

Hall, N. L., Jeanneret, T. D., & Rai, A. (2016). Cost-reflective electricity pricing: Consumer preferences and perceptions. *Energy Policy*, *95*, 62–72.

Hennig, R., Jonker, M., Tindemans, S., & De Vries, L. (2020). Capacity subscription tariffs for electricity distribution networks: Design choices and congestion management. *2020 17th International Conference on the European Energy Market (EEM)*, 1–6.

Hinton, P. R., McMurray, I., & Brownlow, C. (2014). *Spss explained*. Routledge.

Hinz, F., Schmidt, M., & Möst, D. (2018). Regional distribution effects of different electricity network tariff designs with a distributed generation structure: The case of germany. *Energy Policy*, *113*, 97–111.

Hoarau, Q., & Perez, Y. (2019). Network tariff design with prosumers and electromobility: Who wins, who loses? *Energy Economics*, *83*, 26–39.

Hylkema, W. (2020). Vlaams capaciteitstarief kan pas na invoering energiewet in nederland navolging krijgen [https://energeia.nl/energeia-artikel/40089420/gelezen-vlaams-capaciteitstarief, Accessed on 24 August 2020]. *Energeia*.

Jedlix.nl. (n.d.). Hoe werkt jedlix [https://www.jedlix.com/nl/hoe-werkt-jedlix/, Accessed on 6 December 2020].

Lu, L., & Waddams Price, C. (2018). Designing distribution network tariffs that are fair for different consumer groups.

Mahmud, N., & Zahedi, A. (2016). Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation. *Renewable and Sustainable Energy Reviews*, *64*, 582–595.

Meeus, L., Govaerts, N., & Schittekatte, T. (2020). Cost-reflective network tariffs: Experiences with forward looking cost models to design electricity distribution charges.

Milieucentraal.nl. (n.d.). Gemiddeld energieverbruik [https://www.milieucentraal.nl/energie-besparen/inzicht-in-je-energierekening/gemiddeld-energieverbruik, Accessed on 4 JanuarY 2021].

Milis, K., Peremans, H., Springael, J., & Van Passel, S. (2019). Win-win possibilities through capacity tariffs and battery storage in microgrids. *Renewable and Sustainable Energy Reviews*, *113*, 109238.

Ministerie van Economische Zaken. (2016). Energierapport transitie naar duurzaam.

Momber, I., Wogrin, S., & San Román, T. G. (2015). Retail pricing: A bilevel program for pev aggregator decisions using indirect load control. *IEEE Transactions on Power Systems*, *31*(1), 464–473.

Moraga-González, J. L., & Mulder, M. (2018). Electrification of heating and transport: A scenario analysis for the netherlands up to 2050. *Electrification of heating and transport*.

Narayanan, A., Haapaniemi, J., Kaipia, T., & Partanen, J. (2018). Economic impacts of power-based tariffs on peer-to-peer electricity exchange in community microgrids. *2018 15th International Conference on the European Energy Market (EEM)*, 1–5.

NEDU. (n.d.). Verbruiksprofielen 2020 [https://www.nedu.nl/documenten/verbruiksprofielen/, Accessed on 8 December 2020].

Neuteleers, S., Mulder, M., & Hindriks, F. (2017). Assessing fairness of dynamic grid tariffs. *Energy Policy*, *108*, 111–120.

Nijhuis, M., Gibescu, M., & Cobben, J. (2017). Analysis of reflectivity & predictability of electricity network tariff structures for household consumers. *Energy Policy*, *109*, 631–641.

Nikolic, I., Lukszo, Z., Chappin, E., Warnier, M., Kwakkel, J., Bots, P., & Brazier, F. (2019). Guide for good modelling practice in policy support.

O'Connell, N., Wu, Q., Østergaard, J., Nielsen, A. H., Cha, S. T., & Ding, Y. (2012). Day-ahead tariffs for the alleviation of distribution grid congestion from electric vehicles. *Electric Power Systems Research*, *92*, 106–114.

Ortega, M. P. R., Pérez-Arriaga, J. I., Abbad, J. R., & González, J. P. (2008). Distribution network tariffs: A closed question? *Energy Policy*, *36*(5), 1712–1725.

Passey, R., Haghdadi, N., Bruce, A., & MacGill, I. (2017). Designing more cost reflective electricity network tariffs with demand charges. *Energy Policy*, *109*, 642–649.

Picciariello, A., Reneses, J., Frias, P., & Söder, L. (2015). Distributed generation and distribution pricing: Why do we need new tariff design methodologies? *Electric Power Systems Research*, *119*, 370–376.

Pyomo.com. (n.d.). About pyomo [http://www.pyomo.org/about, Accessed on 21 September 2020].

Ren, Z., Grozev, G., & Higgins, A. (2016). Modelling impact of pv battery systems on energy consumption and bill savings of australian houses under alternative tariff structures. *Renewable Energy*, *89*, 317–330.

Reneses, J., & Ortega, M. P. R. (2014). Distribution pricing: Theoretical principles and practical approaches. *IET Generation, Transmission & Distribution*, *8*(10), 1645–1655.

Rijksdienst voor Ondernemend Nederland. (n.d.). Cijfers elektrisch vervoer [https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-en-milieu-innovaties/elektrisch-rijden/stand-van-zaken/cijfers, Accessed on 14 October 2020].

Ruppert, M., Hayn, M., Bertsch, V., & Fichtner, W. (2016). Impact of residential electricity tariffs with variable energy prices on low voltage grids with photovoltaic generation. *International Journal of Electrical Power & Energy Systems*, *79*, 161–171.

Saguan, M., & Meeus, L. (2014). Impact of the regulatory framework for transmission investments on the cost of renewable energy in the eu. *Energy Economics*, *43*, 185–194.

Schittekatte, T., & Meeus, L. (2018a). Least-cost distribution network tariff design in theory and practice. *Robert Schuman Centre for Advanced Studies Research Paper No. RSCAS*, *19*.

Schittekatte, T., & Meeus, L. (2018b). Limits of traditional distribution network tariff design and options to move beyond.

Schittekatte, T., Momber, I., & Meeus, L. (2018). Future-proof tariff design: Recovering sunk grid costs in a world where consumers are pushing back. *Energy economics*, *70*, 484–498.

Simshauser, P. (2016). Distribution network prices and solar pv: Resolving rate instability and wealth transfers through demand tariffs. *Energy Economics*, *54*, 108–122.

Solarmagazine.nl. (n.d.-a). Klimaat- en energieverkenning 2019: 9 gigawattpiek zonnepanelen in 2020 [https://solarmagazine.nl/nieuws-zonne-energie/i19808/klimaat-en-energieverkenning-2019-9-gigawattpiek-zonnepanelen-in-2020, Accessed on 5 November 2020].

Solarmagazine.nl. (n.d.-b). Woononderzoek nederland: 13 procent eengezinswoningen heeft zonnepanelen [https://solarmagazine.nl/nieuws-zonne-energie/i18269/woononderzoek-nederland-13-procent-eengezinswoningen-heeft-zonnepanelen, Accessed on 4 November 2020].

Stedin. (2020). Elektriciteit tarieven 2020 [https://www.stedin.net/-/media/project/online/files/tarieven/stedin-2020-tarieven-kv-elektriciteit.pdf].

Steen, D., Carlson, O., & Tuan, L. A. (2015). Effects of network tariffs on residential distribution systems and price-responsive customers under hourly electricity pricing. *IEEE Transactions on Smart Grid*, *7*(2), 617–626.

Strielkowski, W., Štreimikienė, D., & Bilan, Y. (2017). Network charging and residential tariffs: A case of household photovoltaics in the united kingdom. *Renewable and Sustainable Energy Reviews*, *77*, 461–473.

Van Cappellen, L. (2019). *Variable network tariffss in the lv-network* (Master's thesis). Technische Universiteit Eindhoven. the Netherlands.

Van Oirsouw, P. (2011). *Netten voor distributie van elektriciteit*. Phase to Phase.

Verzijlbergh, R. (2013). The power of electric vehicles, exploring the value of flexible electricity demand in a multi-actor context.

Vogelsang, I. (2006). Electricity transmission pricing and performance-based regulation. *The Energy Journal*, *27*(4).

Voulis, N., Warnier, M., & Brazier, F. M. (2017). Storage coordination and peak-shaving operation in urban areas with high renewable penetration. *2017 IEEE 14th International Conference on Networking, Sensing and Control (ICNSC)*, 531–536.

VREG. (2020a). Tariefmethodologie 21-24: Nieuwe tariefstructuur vanaf 2022.

VREG. (2020b). Verslag over consultatie cons-2019-02 met betrekking tot de vaststelling van de tariefstructuur periodieke distributienettarieven elektriciteit voor klanten met een kleinverbruiksmeetinrichting.

Young, S., Bruce, A., & MacGill, I. (2019). Potential impacts of residential pv and battery storage on australia's electricity networks under different tariffs. *Energy policy*, *128*, 616–627.

Zugno, M., Morales, J. M., Pinson, P., & Madsen, H. (2013). A bilevel model for electricity retailers' participation in a demand response market environment. *Energy Economics*, *36*, 182–197.

Appendices

A Literature review

A.1 Methodology

This literature review focused on studies regarding the effects of distribution network tariff design. The literature to be reviewed was selected using Web of Science. The search was limited to peer-reviewed English articles published from 2010 onward. The used search query can be found in Table 32 below.

Outer operator	**Keyword**	**Inner operator**
Title	((Distribu*	OR
	Network*	OR
	Tariff)	AND
	(Tariff*	OR
	Design	OR
	Scheme))	OR
AND Topic	(Distribu*	AND
	Tariff*	AND
	Electric*	AND
	Network*	AND
	(RES	OR
	Renew*	OR
	Solar	OR
	Wind))	

Table 32: Full search string used for literature research

This search query yielded a total of 36 results. After reading the titles and abstracts of these articles, these results were narrowed down to 12. The primary reason being that the subject of these articles were price-mechanisms of electricity in general, instead of network tariffs. Hereafter, with the use of snowballing two more articles were selected. This resulted in a list of 14 articles to be reviewed in this chapter.

A.2 Overview of results

The full list of the selected literature can be found in Table 33 below. The reviewed literature is categorised by their theme, the used tariff scheme and the discussed interaction with RES.

Reference	**Theme**	**Tariff scheme**	**RES interaction**
(Azarova et al., 2018)	Effects of 11 network tariff scenarios on household budgets	Fixed, volumetric & capacity	None
(Blank & Gegax, 2014)	Comparison of energy charge and demand charge	Volumetric & capacity	None
(Brown et al., 2015)	Methods for ensuring economic efficiency when devising tariffs for distribution network	Volumetric & capacity	None
(Haapaniemi et al., 2017)	Effect of DSO tariff structures on PV profitability	Fixed & Capacity	PV
(Hoarau & Perez, 2019)	Effect of DERs and EVs on grid cost recovery under different tariffs	Volumetric & capacity	PV & BES (EV)
(Narayanan et al., 2018)	Economic impacts of revising the tariff structure on customers with PV installations	Capacity	PV
(Nijhuis et al., 2017)	Assesment of different tariff structures	Fixed, volumetric & capacity	PV
(Ren et al., 2016)	Impact of PV battery systems on demand and energy consumption under different tariffs	Fixed, volumetric & capacity	PV & BES
(Ruppert et al., 2016)	Impact of different tariffs on LV grid stability	Fixed, wholesale & Sales-driven	PV
(Schittekatte et al., 2018)	PV and battery interaction with tariff stuctures on grid recovery	Volumetric & capacity	PV & BES
(Simshauser, 2016)	Tariff structures under high penetration of solar PV	Fixed, volumetric & capacity	PV
(Steen et al., 2015)	Effect of network tariffs on distribution system and customers behaviour	Volumetric & capacity	BES (EV)
(Strielkowski et al., 2017)	Effect of PV integration on wealth distribution with different tariffs	Fixed, volumetric & capacity	PV
(Young et al., 2019)	Economic impacts of residential PV and BES on electricity network businesses	Fixed, time-of-use & seasonal	PV & BES

Table 33: Overview of literature

B Results of statistical analysis

B.1 Housing type

ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
TotAvgLoad * HousingType	Between Groups	(Combined)	,281	4	,070	1,086	,363
	Within Groups		24,132	373	,065		
	Total		24,413	377			
TotMaxLoad * HousingType	Between Groups	(Combined)	89,764	4	22,441	8,559	,000
	Within Groups		978,005	373	2,622		
	Total		1067,770	377			
AvgMaxLoad * HousingType	Between Groups	(Combined)	44,054	4	11,014	19,954	,000
	Within Groups		205,878	373	,552		
	Total		249,932	377			
PercentInPeak * HousingType	Between Groups	(Combined)	,032	4	,008	1,989	,096
	Within Groups		1,514	373	,004		
	Total		1,547	377			
LargerThan4kW * HousingType	Between Groups	(Combined)	57,120	4	14,280	8,688	,000
	Within Groups		613,059	373	1,644		
	Total		670,178	377			

Figure 26: ANOVA table for housing type

B.2 Presence of PV

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
AvgLoad	Equal variances assumed	11,724	,001	16,086	376	,000	,34037	,02116	,29876	,38197
	Equal variances not assumed			14,669	207,663	,000	,34037	,02320	,29462	,38611
MaxLoad	Equal variances assumed	,037	,847	-2,126	376	,034	-,38429	,18073	-,73967	-,02892
	Equal variances not assumed			-2,132	270,013	,034	-,38429	,18027	-,73921	-,02938
AvgMaxLoad	Equal variances assumed	,014	,906	-7,236	376	,000	-,59637	,08241	-,75842	-,43432
	Equal variances not assumed			-7,138	257,797	,000	-,59637	,08355	-,76089	-,43185
Larger4KW	Equal variances assumed	37,541	,000	-3,118	376	,002	-,44346	,14222	-,72310	-,16382
	Equal variances not assumed			-2,529	158,089	,012	-,44346	,17532	-,78972	-,09719
PercentInPeak	Equal variances assumed	54,965	,000	-8,940	376	,000	-,05618	,00628	-,06854	-,04382
	Equal variances not assumed			-7,561	172,888	,000	-,05618	,00743	-,07085	-,04151

Figure 27: Report of the SPSS analysis for the presence of PV

B.3 Presence of an EV

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
AvgLoad	Equal variances assumed	11,724	,001	16,086	376	,000	,34037	,02116	,29876	,38197
	Equal variances not assumed			14,669	207,663	,000	,34037	,02320	,29462	,38611
MaxLoad	Equal variances assumed	,037	,847	-2,126	376	,034	-,38429	,18073	-,73967	-,02892
	Equal variances not assumed			-2,132	270,013	,034	-,38429	,18027	-,73921	-,02938
AvgMaxLoad	Equal variances assumed	,014	,906	-7,236	376	,000	-,59637	,08241	-,75842	-,43432
	Equal variances not assumed			-7,138	257,797	,000	-,59637	,08355	-,76089	-,43185
Larger4KW	Equal variances assumed	37,541	,000	-3,118	376	,002	-,44346	,14222	-,72310	-,16382
	Equal variances not assumed			-2,529	158,089	,012	-,44346	,17532	-,78972	-,09719
PercentInPeak	Equal variances assumed	54,965	,000	-8,940	376	,000	-,05618	,00628	-,06854	-,04382
	Equal variances not assumed			-7,561	172,888	,000	-,05618	,00743	-,07085	-,04151

Figure 28: Report of the SPSS analysis for the presence of EV

B.4 Expected network charges of active and passive consumers

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
BW1	Equal variances assumed	37,678	,000	3,907	376	,000	28,67553	7,34002	14,24290	43,10816
	Equal variances not assumed			3,233	166,126	,001	28,67553	8,86882	11,16541	46,18564
BW2	Equal variances assumed	57,434	,000	3,856	376	,000	16,16864	4,19318	7,92363	24,41366
	Equal variances not assumed			3,203	167,692	,002	16,16864	5,04785	6,20313	26,13416
MC	Equal variances assumed	12,543	,000	4,458	376	,000	25,39568	5,69680	14,19410	36,59725
	Equal variances not assumed			3,981	204,672	,000	25,39568	6,37938	12,81795	37,97340

Figure 29: Report of the SPSS analysis for the expected network charges of active and passive consumers

C Neighbourhood layout and capacities

C.1 1: Small neighbourhood consisting of townhouses and corner houses

Transformer	Cable	Subcable	Apartment	Townhouse	C. house	Semidetached	Detached
200 kW	152,4 kW			11	3		
		152,4 kW		7	3		
		86,8 kW		8	2		
	152,4 kW			10	2		
		36,0 kW		3	2		

Table 34: The representation of the layout of the first neighbourhood

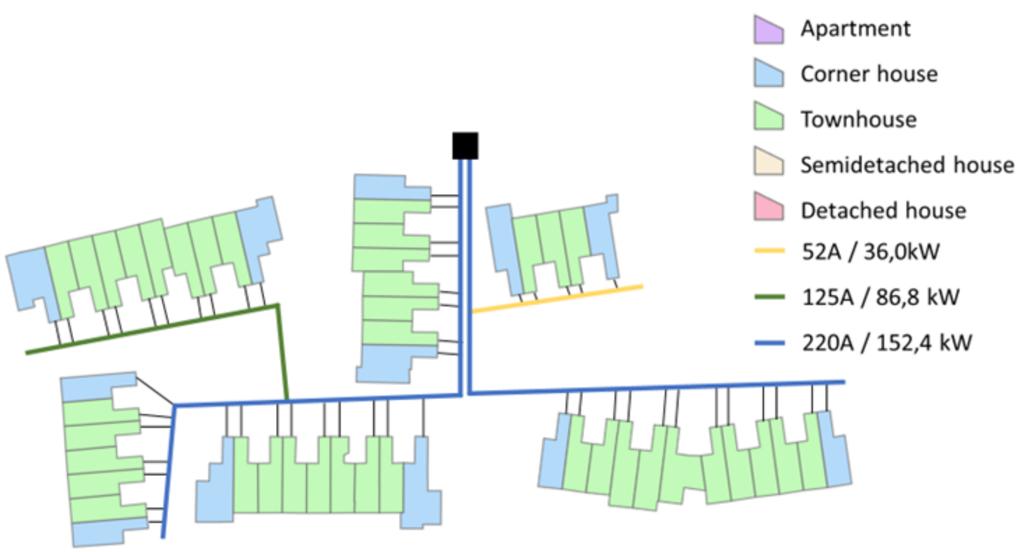


Figure 30: The representation of the layout of the first neighbourhood

C.2 2: Medium size neighbourhood with predominantly small houses

Transformer	Cable	Subcable	Apartment	Townhouse	C. house	Semidetached	Detached
400 kW	86,8 kW			3	6		
	138,6 kW		1	1	2	16	3
	180,1 kW		49				
	180,1 kW			12	4		

Table 35: The representation of the layout of the second neighbourhood

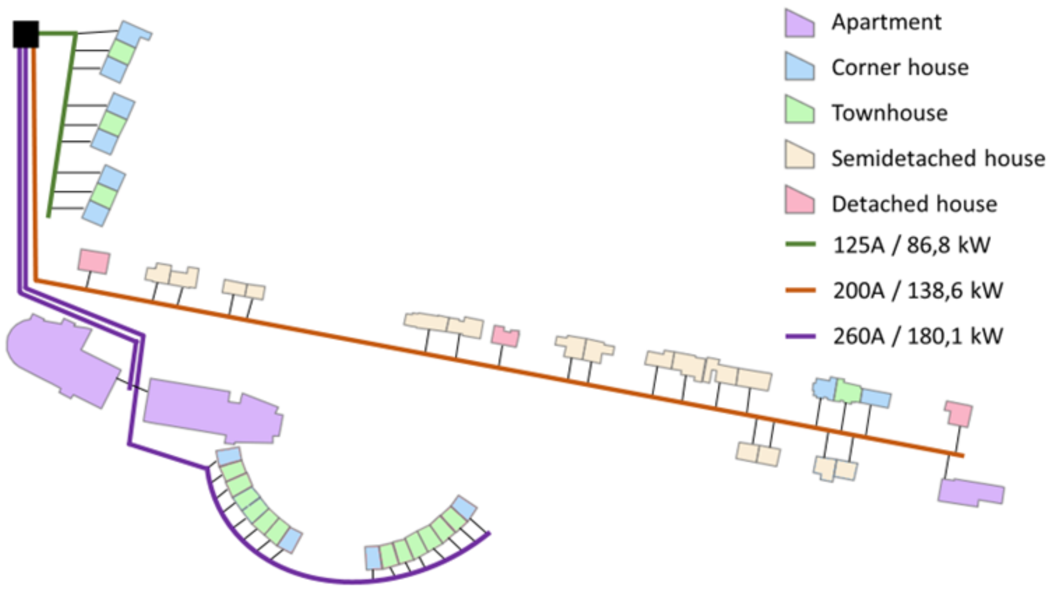


Figure 31: The representation of the layout of the second neighbourhood

C.3 3: Medium size neighbourhood with predominantly large houses

Transformer	Cable	Subcable	Apartment	Townhouse	C. house	Semidetached	Detached
400 kW	183,6 kW						3
		36,0 kW					1
	121,2 kW			10	3		10
	121,2 kW			8	6		
	121,2 kW						28
	121,2 kW						16
		121,2 kW					7

Table 36: The representation of the layout of the third neighbourhood

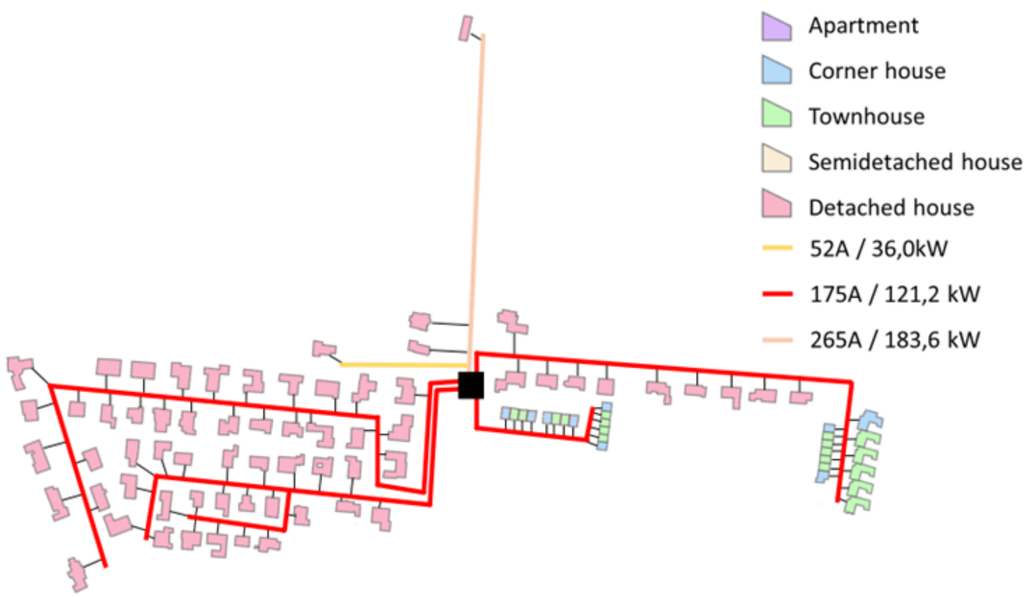


Figure 32: The representation of the layout of the third neighbourhood

C.4 4: Large neighbourhood consisting of small houses

Transformer	Cable	Subcable	Apartment	Townhouse	C. house	Semidetached	Detached
300 kW	138,6 kW			18	6		
		138,6 kW		10	6		
	138,6 kW			15	5		
		138,6 kW		3	2		
		138,6 kW	12				
	138,6 kW		32	29	4		
		138,6 kW		7	1		
	138,6 kW		6	24	4		
		138,6 kW		8	2		
		138,6 kW		2	1		

Table 37: The representation of the layout of the fourth neighbourhood

Figure 33: The representation of the layout of the fourth neighbourhood

C.5 5: Large neighbourhood consisting of all types of houses

Transformer	Cable	Subcable	Apartment	Townhouse	Corner	Semidetached	Detached
630 kW							
	180,1 kW		32	5	2		
		180,1 kW		3	1		
	180,1 kW			4	2	2	1
	138,6 kW			12	12	8	
		138,6 kW		2	2		
	138,6 kW		14	10	4	8	
	138,6 kW			14	2	14	
		138,6 kW		8	2		
		138,6 kW		2	1		

Table 38: The representation of the layout of the fifth neighbourhood

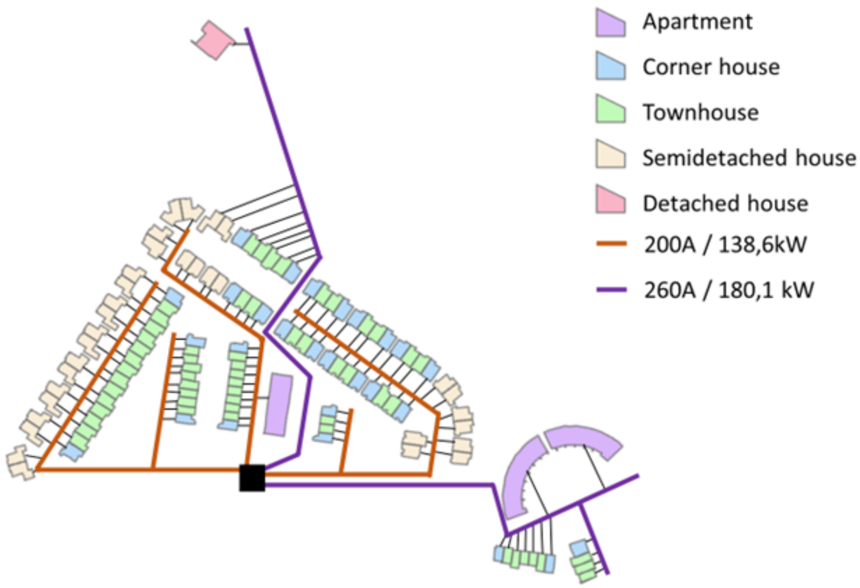


Figure 34: The representation of the layout of the fifth neighbourhood

D Model input EVs

D.1 Verzijlbergh's synthetic driving profiles

Driver	Departure time	Arrival time	Distance (km)
1	10:11	13:12	3,1
2	09:26	18:34	35,2
3	09:31	15:21	14,5
4	08:41	14:26	7,8
5	11:21	18:54	16,8
6	09:13	15:27	10,9
7	09:16	16:50	24,8
8	10:27	15:20	5,7
9	09:06	18:33	50,8
10	11:07	18:58	21,7
11	11:31	19:11	28,2
12	09:26	19:25	109,2
13	13:21	18:26	11,8
14	09:16	18:45	58,8
15	09:07	17:17	31,0
16	15:04	19:22	3,2
17	09:13	18:25	40,1
18	09:11	18:59	77,0
19	10:11	18:46	45,2
20	09:40	19:22	65,9
21	07:38	17:58	4,3
22	08:38	22:17	4,5
23	09:08	16:01	19,5
24	09:09	19:24	91,8
25	15:09	19:48	7,9

Table 39: Synthetic driving profiles, retrieved from (Verzijlbergh, 2013)

D.2 Finalised model inputs for EVs

EV	Start Time Mean	Start Time Std [h]	Target Time	Start SoC Mean [%]	Start SoC Std [%]	Target SoC [%]	Battery size [kWh]	Max charge rate [kW]	Charge η [%]	Daily demand Mean [kWh]	Daily demand Std [kWh]
1	13:12	1	10:11	40	0.0	0.26	60	11	0.9	0.47	0.09
2	18:34	1	09:26	40	0.0	0.34	60	11	0.9	5.39	1.08
3	15:21	1	09:31	40	0.0	0.29	60	11	0.9	2.22	0.44
4	14:26	1	08:41	40	0.0	0.27	60	11	0.9	1.19	0.24
5	18:54	1	11:21	40	0.0	0.29	60	11	0.9	2.57	0.51
6	15:27	1	09:13	40	0.0	0.28	60	11	0.9	1.67	0.33
7	16:50	1	09:16	40	0.0	0.31	60	11	0.9	3.79	0.76
8	15:20	1	10:27	40	0.0	0.26	60	11	0.9	0.87	0.17
9	18:33	1	09:06	40	0.0	0.38	60	11	0.9	7.77	1.55
10	18:58	1	11:07	40	0.0	0.31	60	11	0.9	3.32	0.66
11	19:11	1	11:31	40	0.0	0.32	60	11	0.9	4.31	0.86
12	19:25	1	09:26	40	0.0	0.53	60	11	0.9	16.71	3.34
13	18:26	1	13:21	40	0.0	0.28	60	11	0.9	1.81	0.36
14	18:45	1	09:16	40	0.0	0.40	60	11	0.9	9.00	1.80
15	17:17	1	09:07	40	0.0	0.33	60	11	0.9	4.74	0.95
16	19:22	1	15:04	40	0.0	0.26	60	11	0.9	0.49	0.10
17	18:25	1	09:13	40	0.0	0.35	60	11	0.9	6.14	1.23
18	18:59	1	09:11	40	0.0	0.45	60	11	0.9	11.78	2.36
19	18:46	1	10:11	40	0.0	0.37	60	11	0.9	6.92	1.38
20	19:22	1	09:40	40	0.0	0.42	60	11	0.9	10.08	2.02
21	17:58	1	07:38	40	0.0	0.26	60	11	0.9	0.66	0.13
22	22:17	1	08:38	40	0.0	0.26	60	11	0.9	0.69	0.14
23	16:01	1	09:08	40	0.0	0.30	60	11	0.9	2.98	0.60
24	19:24	1	09:09	40	0.0	0.48	60	11	0.9	14.05	2.81
25	19:48	1	15:09	40	0.0	0.27	60	11	0.9	1.21	0.24

Table 40: Finalised EV model inputs

D.3 Finalised model inputs for EV validation

EV	Start Time Mean	Start Time Std [h]	Target Time	Start SoC Mean [%]	Start SoC Std [%]	Target SoC [%]	Battery size [kWh]	Max charge rate [kW]	Charge η [%]	Daily demand Mean [kWh]	Daily demand Std [kWh]
1	13:12	1	10:11	40	0.0	0.26	60	3.7	0.9	0.47	0.09
2	18:34	1	09:26	40	0.0	0.34	60	3.7	0.9	5.39	1.08
3	15:21	1	09:31	40	0.0	0.29	60	3.7	0.9	2.22	0.44
4	14:26	1	08:41	40	0.0	0.27	60	3.7	0.9	1.19	0.24
5	18:54	1	11:21	40	0.0	0.29	60	3.7	0.9	2.57	0.51
6	15:27	1	09:13	40	0.0	0.28	60	3.7	0.9	1.67	0.33
7	16:50	1	09:16	40	0.0	0.31	60	3.7	0.9	3.79	0.76
8	15:20	1	10:27	40	0.0	0.26	60	3.7	0.9	0.87	0.17
9	18:33	1	09:06	40	0.0	0.38	60	3.7	0.9	7.77	1.55
10	18:58	1	11:07	40	0.0	0.31	60	3.7	0.9	3.32	0.66
11	19:11	1	11:31	40	0.0	0.32	60	3.7	0.9	4.31	0.86
12	19:25	1	09:26	40	0.0	0.53	60	3.7	0.9	16.71	3.34
13	18:26	1	13:21	40	0.0	0.28	60	3.7	0.9	1.81	0.36
14	18:45	1	09:16	40	0.0	0.40	60	3.7	0.9	9.00	1.80
15	17:17	1	09:07	40	0.0	0.33	60	3.7	0.9	4.74	0.95
16	19:22	1	15:04	40	0.0	0.26	60	3.7	0.9	0.49	0.10
17	18:25	1	09:13	40	0.0	0.35	60	3.7	0.9	6.14	1.23
18	18:59	1	09:11	40	0.0	0.45	60	3.7	0.9	11.78	2.36
19	18:46	1	10:11	40	0.0	0.37	60	7.2	0.9	6.92	1.38
20	19:22	1	09:40	40	0.0	0.42	60	7.2	0.9	10.08	2.02
21	17:58	1	07:38	40	0.0	0.26	60	7.2	0.9	0.66	0.13
22	22:17	1	08:38	40	0.0	0.26	60	7.2	0.9	0.69	0.14
23	16:01	1	09:08	40	0.0	0.30	60	7.2	0.9	2.98	0.60
24	19:24	1	09:09	40	0.0	0.48	60	7.2	0.9	14.05	2.81
25	19:48	1	15:09	40	0.0	0.27	60	7.2	0.9	1.21	0.24

Table 41: EV model inputs that are used for the validation