Highlights

Designing future-proof electricity distribution network tariffs in the Netherlands

R.M.W. van Rossum

- Regulatory principles are defined to compare network tariff structures
- Capacity based tariff structures significantly reduce network peak load
- Active consumers are paying more when a capacity based tariff is implemented
- Capacity based tariff structures are more cost-reflective and efficient

Designing future-proof electricity distribution network tariffs in the Netherlands

R.M.W. van Rossum[a,*]

[a] Faculty of Technology Policy and Management, Delft University of Technology, Jaffalaan 5 2628BX Delft, The Netherlands

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ABSTRACT

With the fast-growing electricity demand, challenges arise affecting the reliability and the quality of the distribution network. The Dutch DSOs could expand the network capacity, but it is not sure if the network can be expanded fast enough. Network expansion will result in higher total consumer costs and if the network expansion rate is too low, the reliability of the distribution network would be highly affected.

Currently, the distribution network tariff in the Netherlands for residential consumers is only based on the connection type. Changing the network tariff structure to stimulate demand response is an option to deal with these challenges.

The effects of different network tariff structures in the Netherlands are still unknown. This paper investigates the effects of two configurations of a capacity bandwidth tariff and a personal peak charge on the maximum network peak and the expected consumer charge. This is done by using the model of Hennig et al. (2020) that simulates the allocation of flexible demand of consumers under different network tariff structures.

To be able to compare the different network tariff structures, the five key regulatory principles are used. Since these regulatory principles are often ill-defined and unclear, we first propose a set of normative criteria which can be used to quantify if a tariff structure adheres to these principles.

The results show that all examined network tariff structures significantly reduce the overall network peak. Furthermore, the examined tariff structures are more efficient and cost-reflective than the current fixed tariff. A capacity bandwidth tariff with bandwidths of 2, 4, 8 and 17 kW seems the best option for a future-proof network tariff structure in the Netherlands.

1. Introduction

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 and Zahedi, 2016). Voltage drops and thermal overloading are two of these problems and these can be prevented in multiple ways (Mahmud and Zahedi, 2016; Etherden and Bollen, 2014). The Dutch 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 (Schittekatte et al., 2018; Ortega et al., 2008). Moreover, it is assumed that the electricity demand will grow faster than network expansion can cope with.

Since the electricity distribution network is dimensioned for the peak load (Schittekatte et al., 2018), another way to prevent these problems is to change the way congestion is priced and try to incentivise demand response to reduce the peak load of the network. Demand response can be incentivised by changing the current network tariff structure.

The two main categories of distribution network tariff structures are volumetric tariffs and capacity based tariffs (Schittekatte et al., 2018; Ortega et al., 2008). However, within these two categories, there are still many variants. Currently, the network tariff for residential consumers in the Netherlands is a fixed tariff, only based on the size of the connection (European Commission, 2015; Lu and Waddams Price, 2018). In the Netherlands, capacity based tariffs are discussed and examined as potential future network tariff options (Droste et al., 2018; D-Cision, 2019).

The possibilities that the Netherlands has to change the network tariff structure is bounded by Dutch and European law and regulation. The legal framework includes so-called regulatory principles to which a network tariff structure must adhere (Ortega et al., 2008). A network tariff structure must adhere to the following five principles: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency (European Commission, 2015; Droste et al., 2018; CEER, 2017).

The current network tariff structure in most countries has become unfit as the network tariffs are not cost-reflective anymore (Strielkowski et al., 2017). The regulatory principle of cost-reflectiveness states that costs are allocated to those who impose costs on the network (CEER, 2017). This 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 (Ren et al., 2016; Simshauser, 2016; Nijhuis et al., 2017). Furthermore, the potential network cost reduction capacity of a capacity based network tariffs would be significant (Ren et al., 2016; Steen et al., 2015; Young et al., 2019). However, capacity based tariffs come in different forms (Simshauser, 2016; Young et al., 2019; Narayanan et al., 2018) and Brown et al. (2015) even concluded that there is no single best network tariff design.

Currently, in the Netherlands, multiple capacity based network tariff structures are examined. A capacity bandwidth tariff, where consumers contract a certain bandwidth

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*Corresponding author.
E-mail address: *R.M.W.vanRossum@student.tudelft.nl*

in which they are free to consume electricity, and a personal peak charge, where consumers pay for the maximum amount of capacity required each month are two most prevalent options (Droste et al., 2018). In this paper, we aim to aid the current discussion concerning the most suitable network tariff structure in the Netherlands. This will be done by comparing different capacity based network tariff structures based on their ability to reduce network peak load, their expected consumer charge, and how they adhere to the regulatory principles of network tariff design. A simulation model is used to analyse the effects of a network tariff structure by simulating the expected demand of consumers when subject to that tariff structure. Furthermore, since these regulatory principles are often ill-defined and unclear, we first propose a set of normative criteria which can be used to quantify if, and if applicable to what extent, a tariff structure adheres to these principles.

This paper is structured as follows. Section 2 discusses the method used to simulate the expected demand of consumers when subject to different network tariff structures. Section 3 presents the proposed set of normative criteria used to quantify the regulatory principles. Section 4 outlines the generated results, which are subsequently discussed in Section 5. Followed by some conclusions and policy implications in Section 6.

2. Methods

An optimisation model is used to simulate the expected electricity demand of consumers and the corresponding network peaks. Similar mathematical models have already been used before, where the behaviour of consumers is simulated with the use of optimisation models (Zugno et al., 2013; Momber et al., 2015; Saguan and Meeus, 2014). Schittekatte et al. (2018) also used an optimisation model to simulate the electricity demand of consumers when subject to different network tariff structures. These optimisation models assume that consumers change their behaviour to minimise their overall (network) costs. The main limitation of these optimisation models is that a very complex phenomenon, the behaviour of consumers, is modelled through a very simple and straightforward assumption.

2.1. 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 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.

2.2. Data

The used data consists of the measured electricity consumption for every fifteen minutes of 396 households in the service area of Stedin. The data set also includes information about the housing type, the presence of PV and EV of the consumers. It contains data from the 2nd of July till the 30th of September of 2020, which accumulates to a total of 91 days. Because the data originates from three summer months the average loads are relatively low. The data is provided by Stedin, is processed in Excel and analysed using SPSS. The descriptive statistics of the data set are shown in Table 1.

	Min	Max	Mean	St. dev
Average load [kW]	-0,90	1,30	0,199	0,254
Max load [kW]	0,51	14,9	4,351	1,683
Avg. max. load [kW]	0,02	6,97	2,037	0,814
% in peak	0,14	0,58	0,352	0,064

Table 1
Descriptive statistics of whole data set with 378 consumers. Average maximum load represents the average daily maximum peak of consumers, % in peak is the percentage of electricity used between 17:00 and 23:00.

2.3. Recreation of neighbourhoods

This data set is used to recreate four different Dutch neighbourhoods. Based on the housing type, consumers are drawn from the data set to form a neighbourhood. These neighbourhoods are validated by comparing the load-duration curves of the actual neighbourhoods and the recreated neighbourhoods. The recreated neighbourhoods are combined with the LV-transformer characteristics to be able to analyse the effects of tariff structures on the transformer load.

2.4. Network tariff structures

The initial electricity demand is assumed to be inflexible. Consumers do not change this part of their demand and therefore this part of their 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. The network tariff structures that are examined are the current fixed tariff, two configurations of a capacity bandwidth tariff and a personal peak charge.

2.4.1. Current fixed tariff

When consumers are subject to the current fixed tariff they have no incentive to change their behaviour to minimise their network costs. The capacity rate of this tariff structure is approximately €160. It is assumed that the other components, the standing charge, the measurement rate and the periodic connection fee, remain constant.

2.4.2. Capacity bandwidth tariff

The second 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 to a minimum bandwidth of 4 kW, both of these options are examined. The characteristics of these two models can be found in Table 2. The exceedance fee in both options is 0,50 €/kWh, which is following Hennig et al. (2020). The prices shown in Table 2 are the prices for the capacity rate only. It is assumed that when subject to a capacity bandwidth tariff, a consumer will never exceed their bandwidth limit by charging their EV.

Table 2
The two configurations of the examined capacity bandwidth tariffs and their characteristics, prices in €.

CBT min 2kW		CBT 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

2.4.3. Personal peak charge

The third investigated tariff structure is a personal peak charge. In this case, the network charge of consumers is dependent on the average maximum capacity they use each month. The charge per needed kW of capacity is kept proportionally to the charge under the current tariff. 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. It is assumed that when subject to the personal peak charge, a consumer will never exceed the maximum capacity limit of the personal peak charge by charging their EV.

2.5. 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. Indicating that consumers will schedule the charging of their EV to minimise network costs.

2.6. Examined charging strategies

The charging demand is allocated based on two different charging strategies. These charging strategies are: charging on arrival and individual optimisation (Hennig et al., 2020).

2.6.1. Charge on arrival

With the charging on arrival strategy, consumers charge their EV as soon as they get home. The EV then starts charging as fast as possible while keeping the capacity under the maximum allowed limit.

2.6.2. Individual optimisation

With the individual optimisation strategy, all consumers charge when the wholesale electricity prices are the lowest. In reality, future wholesale prices are not known, and therefore it is not possible to optimise the EV charging perfectly. This results in the situation that all consumers charge at the same time. Furthermore, it is expected that when a large amount of EVs all start charging simultaneously this affects the wholesale price. However, this interaction between the change in electricity demand and the wholesale price is not included in the model.

3. Defining the regulatory principles

The five key regulatory principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency. The regulatory principles originate from Article 18 of European Regulation 2019/943 and can also be found in Article 36 of the Dutch electricity law.

3.1. Non-discriminatory

Non-discriminatory cost allocation entails that consumers are handled equally in equal circumstances (Droste et al., 2018). 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.

3.2. Cost-recovery

If a network tariff structure enables a DSO to recoup all their efficient costs, it adheres to the principle of cost-recovery (Droste et al., 2018).

The Dutch regulator determines the maximum height of the tariffs that any DSO is allowed to charge consumers (Autoriteit Consument & Markt, 2020). The regulator 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).

Indicating that the heights of the current tariffs are set in a way that all efficient costs are recouped through the network charges. Implying that for another network tariff structure to adhere to the principle of cost-recovery, the sum of total network charges of all consumers in the service area of that DSO should stay the same. Since all DSOs play a key role in maintaining and monitoring the critical infrastructure that is the electricity network, this should be the case for all DSOs separately.

3.3. Cost-reflectiveness

The principle of cost-reflectiveness states that costs are allocated to those who impose costs on the network (CEER, 2017). 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 and Ortega, 2014).

Because a network tariff structure will never be fully cost-reflective, 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. We adopt the definition of Passey et al. (2017).

Passey et al. (2017) analysed the cost-reflectiveness of different capacity based network charges. 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 coincidental network peak of that month (Passey et al., 2017).

3.4. Transparency

Transparency in network tariffs entails 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 and Ortega, 2014). Although transparency is one of the key regulatory principles and is mentioned in both European and Dutch law and regulation, existing literature is not clear about what a transparent network tariff structure exactly entails and what criteria could be used to determine this.

We use the following question to determine if a network tariff structure is transparent: *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.

3.5. Promoting efficiency

Network tariffs should promote efficient network usage (Droste et al., 2018). 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 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.

4. Results

4.1. Effect on maximum network peak

The four recreated neighbourhoods are used to examine the effects of different capacity based network tariff structures on the maximum network peak. The effect on the maximum network peak is examined by looking at the maximum transformer loading for an increasing number of consumers that charge an EV. The results of all four neighbourhoods are very comparable, therefore only the results of one of the four neighbourhoods are shown. This neighbourhood has a total of 97 consumers and the LV-transformer has a capacity of 400 kW. The initial maximum transformer loading of this neighbourhood is relatively low, at only 20 percent. The results are averaged over 40 simulations for each combination of tariff structure and charging strategy.

4.1.1. Current fixed tariff

Figure 1 shows the maximum transformer capacity as a function of the amount of EVs for the simulated neighbourhood. From the results of Figure 1, it can be seen that transformer overloading occurs before 100 percent EV penetration. Furthermore, 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 coincidental in the individual optimisation charging strategy. Since not everyone arrives home at the same time, the coincidence

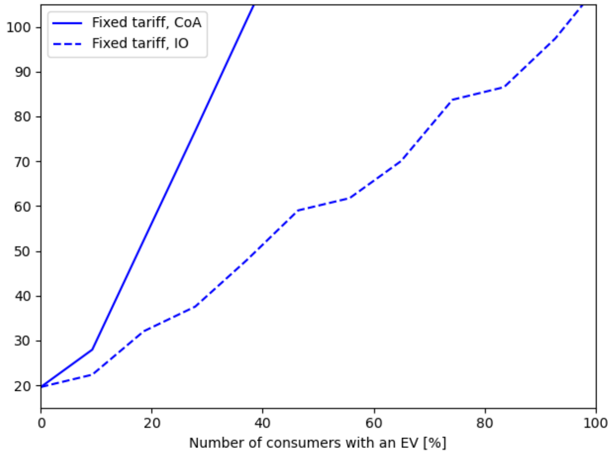

Figure 1: The maximum transformer capacity as a function of the percentage of consumers in the neighbourhood that have an EV under the current network tariff structure. 'CoA' denotes the Charge on arrival strategy, 'IO' denotes the individual optimisation strategy.

factor is a lot lower when this charging strategy is used. Under 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.

4.1.2. Capacity bandwidth tariff

In Figure 2, the results of the simulations of the two different configurations of a capacity bandwidth tariff are added to the results of the fixed tariff. The results clearly show that the maximum transformer loading is a lot lower than without the introduction of the capacity bandwidth tariff. The amount of EV penetration could be as high as 100 percent before transformer overloading occurs under a capacity bandwidth tariff structure.

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

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, it is seen that with low amounts of EV penetration the individual optimisation strategy outperforms the charging on arrival strategy. However, this is not true for high amounts of EV penetration. This is because with the individual optimisation strategy consumers charge outside of the already existing network peak. Therefore, at low amounts of EV penetration, the total network peak is not that high. But as the amount of EV penetration increases, and because of the high coincidence factor under this charging strategy, with higher amounts of EV penetration, the network peak is primarily caused by the coincident charging of all consumers.

4.1.3. Personal peak charge

In Figure 3, the results of the simulation when consumers were subject to the personal peak charge are added to the already existing results from Figure 2. The results in Figure 3 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.

4.2. Expected network charge

The model is used to calculate the expected network charges for every consumer in the data set. The expected network charge for the current fixed tariff is constant at €160.

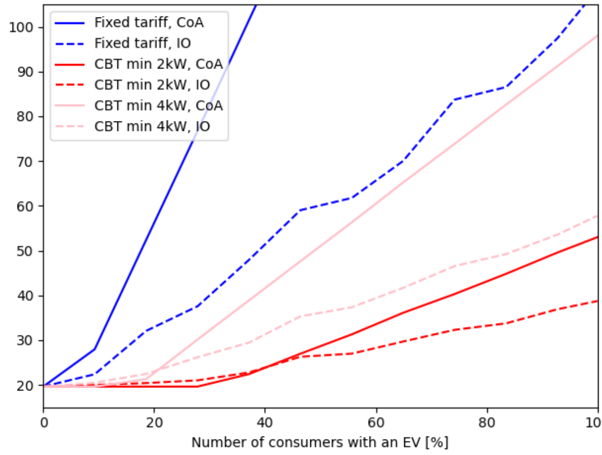

Figure 2: The maximum transformer capacity as a function of the amount of added EVs under a capacity bandwidth tariff. 'CoA' denotes the Charge on arrival strategy, 'IO' denotes the individual optimisation strategy.

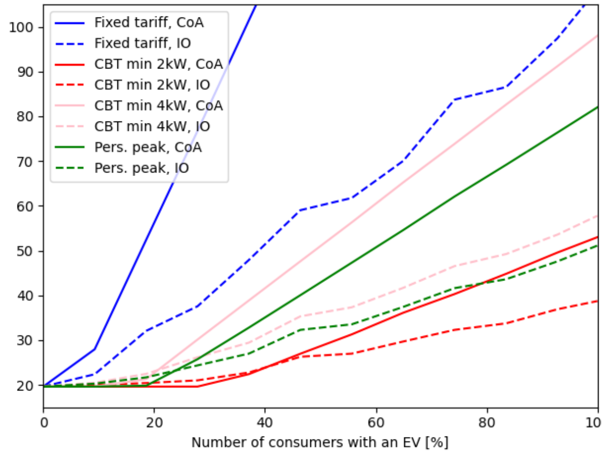

Figure 3: The maximum transformer capacity as a function of the amount of added EVs under all examined tariff structures. 'CoA' denotes the Charge on arrival strategy, 'IO' denotes the individual optimisation strategy.

4.2.1. Expected network charge for the consumers in the data set

Table 3 shows the descriptive statistics of the expected charges for all consumers in the data set.

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 assumed heights of the tariffs of Table 2

Table 3
Descriptive statistics of the expected network charges of the consumers in the data set for different network tariff structures, all prices in euro (€).

	Min	Mean	Max	St. dev
Fixed tariff	160,00	160,00	160,00	0,00
CBT min 2kW	90,00	127,17	765,00	70,11
CBT min 4kW	160,00	169,00	484,06	40,03
Personal peak	14,32	150,72	501,64	54,74

Table 4
Descriptive statistics of the expected charges of the data set based on the division in active and passive consumers.

	CBT min 2kW	CBT min 4kW	Pers. peak
Active	€145,23	€179,19	€166,71
Passive	€116,55	€163,02	€141,32

Table 5
The results of the independent t-test for the expected network charges for the division in active and passive consumers.

	CBT min 2kW	CBT min 4kW	Pers. peak
Sig.	0,001	0, 002	0,000
$\Delta Mean$	€28,68	€16,17	€25,40

4.2.2. Difference between active and passive consumers

The financial effects of different tariff structures on two different groups of consumers, active and passive consumers, are also analysed. 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 4.

The differences in expected network charges show that for all three tariff structures, active consumers are expected to pay more than passive consumers. To test if the differences in Table 4 are significant an independent t-test is performed. A summary of the results of this t-test is shown in Table 5.

The results from Table 5 show that the network charges for active consumers are significantly higher for all three network tariff structures. Indicating that under a capacity based tariff structure, active consumers are going to be paying more than passive consumers. 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 and Zahedi, 2016; Moraga-González and Mulder, 2018), the fact that active consumers are expected to be paying more under a capacity based tariff structure can be seen as positive.

4.3. Reflection on regulatory principles

In Section 3 normative criteria to define the key regulatory principles are proposed. These five key principles are: non-discriminatory, cost-recovery, cost-reflectiveness, transparency and promoting efficiency.

4.3.1. Non-discriminatory

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.

4.3.2. Cost-recovery

For a 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. The expected network charges in Table 3 show that only the average expected network charge of a capacity bandwidth tariff where the smallest bandwidth is 4 kW is higher than that of the current fixed tariff.

However, it can not be assumed that the used data set is an actual representation of the consumers 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.

Therefore, with the limited amount of data, nothing can be concluded 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. When n accurate representation of a service area of a DSO or the Netherlands is available. 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 and Perez, 2019; Schittekatte et al., 2018; Schittekatte and Meeus, 2018)

A capacity based network tariff results is 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. A tariff structure that minimises these risks could be preferred by DSOs.

4.3.3. Cost-reflectiveness

The regulatory principle of cost-reflectiveness states that costs must be allocated to those who impose costs on the network (CEER, 2017). Cost-reflectiveness is defined by the definition of Passey et al. (2017). Passey et al. (2017) de-

Table 6
The Pearson's correlation coefficients between expected network charge and average applicable peak demand, highest correlation in each calculation in bold

	CBT min 2kW	CBT min 4kW	Pers. 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**

fined cost-reflectiveness as the linear Pearson's correlation between the network charge and the average of the applicable peak demand over each month. In which the applicable peak demand is the share of the total coincidental network peak of that month.

To calculate this correlation, the average of the applicable peak demand over each month is calculated for each consumer in the data set. Because the cost-reflectiveness is depended on the network peak, the cost-reflectiveness is different for each network. Therefore, the cost-reflectiveness is calculated for each neighbourhood separately, as well as 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 6.

The results in Table 6 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 a 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 already show that for these five different options, no single tariff structure is the most cost-reflective in each case. This shows the difficulty in calculating the cost-reflectiveness of a network tariff structure and the difficulty of designing cost-reflective tariffs. Because 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.

4.3.4. 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 that the methodology to calculate the height of the tariffs should be transparent (CEER, 2017; Reneses and Ortega, 2014). The current methodology for calculating the current 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 methodology to calculate the tariffs for the examined network tariff structures is transparent. 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.

4.3.5. Promoting efficiency

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 4 shows the load factor of the neighbourhood as a function of the percentage of consumers that have an EV.

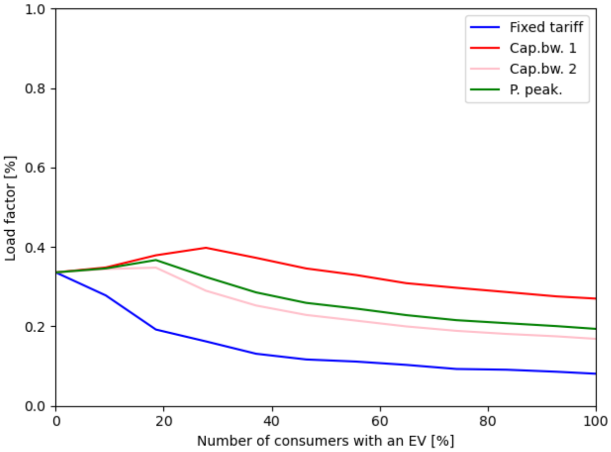

Figure 4: The load factor as a function of the amount of added EVs under all examined tariff structures.

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 promotes efficiency the best, followed by the personal peak charge tariff, and lastly the capacity bandwidth tariff with a smallest bandwidth of 4 kW.

5. Discussion

The results show that the examined capacity based tariffs are more cost-reflective and efficient. Which confirms the findings by Nijhuis et al. (2017), Ren et al. (2016) and Simshauser (2016). Moreover, the results showed that implementing a capacity based network tariff would result in significant reductions of the maximum network peak, in comparison with the current network tariff structure. Lastly, the results showed that the effects are the most significant for a capacity bandwidth tariff with possible bandwidths of 2, 4, 8 and 17 kW.

Some important limitations have to be recognised and the impact of different assumptions must be assessed. The first limitation is the fact that the used data originates from summer months. Hereafter we discuss the effect of the most important assumptions. Lastly, the simplifications made by quantifying the regulatory principles are discussed.

5.1. 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.

Since all bandwidths are allocated to the consumers based on the electricity pattern of these three summer months, it can be disputed if the generated results are realistic. It could be the case that the allocation of bandwidths to consumers would be done differently if it was 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) the months 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). 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 CBSverbruik.

Based on this changed electricity pattern, the simulation is run for the neighbourhood. Figure 5 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 the newly generated average month.

Figure 5 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 difference in the results would be smaller than suggested in Section 4.

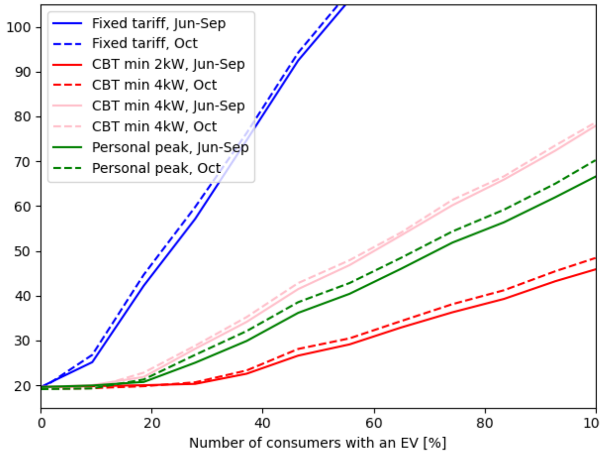

Figure 5: The maximum transformer capacity as a function of the percentage of consumers that have an EV for all examined tariff structures.

5.2. Impact of assumptions on results

To be able to simulate the expected electricity demand of consumers when subject to different network tariff structures, important assumptions were made. The first paragraph discusses the assumption that consumers minimise their network costs, the second paragraph discusses the assumptions that consumers either charge upon arrival or individually optimise. The third paragraph shortly discusses the interaction between the assumed tariff heights and the results.

5.2.1. 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.

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.

5.2.2. Consumers charge upon arrival or individually optimise

Secondly, it was assumed that consumers either all charge upon arrival or all 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.

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.

5.2.3. Interaction between tariff height and results

Changing the heights of the tariffs does not only result in other expected charges for consumers, but it also influences other results since there exists an interaction between the heights of the tariffs and the results of the capacity bandwidth tariffs.

The heights of the tariffs influences which bandwidth gets allocated a consumer. If the difference in price between two bandwidths is larger, consumers are more likely to get allocated a smaller bandwidth. The opposite is true for the exceedance fee. A larger exceedance fee would result in more consumers choosing a higher bandwidth. Therefore, a sensitivity analysis is performed. Since it was found that the sum of all bandwidths of all consumers is a good indicator for the expected effects of that 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.

Figure 6 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.

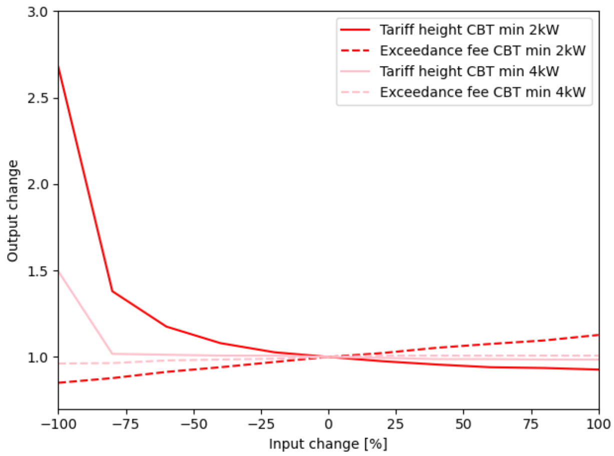

Figure 6: Results of the sensitivity analysis for the height of the tariffs and the exceedance fee for both configurations of the capacity bandwidth tariff

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 the current assumptions, the relation 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.

5.3. Quantifying the regulatory principles

The five key principles were defined in Section 3. By doing so, 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 paper.

First, as already briefly touched upon, the cost-recovery problem of the DSOs is not fully taken into account within the scope of this paper. Due to the fact that the available data is no accurate representation of the service area of a DSO or the Netherlands. This paper 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 and Perez, 2019; Schittekatte et al., 2018; Schittekatte and Meeus, 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 paper, 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 paper, the definition of Passey et al. (2017). was used.

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 Reneses and Ortega (2014), a tariff structure is cost-reflective when prices are close to marginal costs.

Third, the trade-off between the cost-reflectiveness and cost-recovery was not accurately represented. By defining cost-reflectiveness with the definition of Passey et al. (2017), cost-reflective charges do not represent the marginal cost of consumers. The trade-off between cost-reflectiveness and cost-recovery 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 paper. Although these principles do not directly originate from European or Dutch law and regulation they are identified as important by CEER (2017). These principles were not taken into account in the scope of this paper.

6. Conclusions and policy implications

6.1. General conclusions

The results showed that all three examined network tariff structures significantly reduced the network peak load when consumers were subject to one of the three examined network tariff structures. The expected average network charge of the three examined network tariff structures is highly dependent on the chosen heights 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.

6.2. Recommendations for future research

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).

6.3. Policy advise

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.

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References

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`.

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

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

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

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. Overlegtafel Energievoorziening (OTE) `https://www.energie-nederland.nl/app/uploads/2018/06/OTE_-Belemmeringen-in-nettarieven.pdf`.

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 .

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

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

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.

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, 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, in: 2018 15th International Conference on the European Energy Market (EEM), IEEE. pp. 1–5.

NEDU, . Verbruiksprofielen 2020 `https://www.nedu.nl/documenten/verbruiksprofielen/`, Accessed on 8 December 2020.

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

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

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.

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

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, 1645–1655.

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., 2018. Least-cost distribution network tariff design in theory and practice. Robert Schuman Centre for Advanced Studies Research Paper No. RSCAS 19.

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.

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, 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.

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.

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

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.