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Analysis of reflectivity & predictability of electricity network tariff structures for household consumers

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\begin{abstract}
Distribution network operators charge household consumers with a network tariff, so they can recover their network investment and operational costs. With the transition towards a sustainable energy system, the household load is changing, through the introduction of photovoltaics and electric vehicles. The tariff structures which are currently employed in the EU are either capacity and/or energy consumption based. In light of the changes in the household load the question whether these tariff structures are the most suitable merits renewed attention. In this work, the cost-reflectivity of various tariff structures has been computed based on a distribution network planning approach. Next to this, the predictability of a network tariff, i.e. how much change would a household experience in network charges in two consecutive years has also been computed to gain insight into how well users will be able to react to the tariff. The results show that a peak load based network tariffs score best on the reflectivity while having an acceptable level of predictability. The switch from an energy consumption based network tariff, which is now most often applied, towards a peak load based network tariff should therefore, be considered.
\end{abstract}

\section{Introduction}
Access to electricity is seen as a public good, not only because of the capital intensive nature of electricity network investments but also because electricity is seen as a primary good. The distribution network operator (DNO) is responsible for the electricity network that connects the residential consumers to the power system. The DNO is therefore often operating in a regulated monopoly environment. This is different from the generation and wholesale of electricity which often takes place in a deregulated market environment. In these unbundled markets the end-user pays a separate tariff for the energy he consumes and for his connection to the network which transports this energy. For the regulated environment in which the DNOs operate, the regulator is charged with setting the maximum income level of a DNO. Depending on the regulations, the method by which the DNO can charge the consumers to generate this income is up to the DNO to decide or fixed by the regulator. The employed tariff structure is dependent on the policy goals one tries to achieve. Ensuring affordable access to electricity, reducing greenhouse gas emissions, and the ease of understanding of the tariff, among others, play a role in the determination of the residential network tariff structure. In most European countries the tariff structure is primarily dependent on the amount of energy a consumer has used.

Only Sweden, Spain, and the Netherlands employ a tariff structure which (also) has a capacity component and in Italy, one is being introduced. In these countries, the capacity component in the case of household consumers, is however, a fixed component (AF - Mercados EMI, 2015). The problem with the cost-reflectivity of the grid tariff has already been noted in research by Picciariello et al. (2015), Eid et al. (2014) among others. The need for further research is motivated by the changes in the energy use of residential consumers due to the transition to a sustainable energy system. With rooftop PV, residential consumers are also becoming producers and can feed energy back into the grid. The rise in PV generates additional problems for the operation of the grid. An energy-based grid tariff, for instance, lets the consumers with PV actually pay a lower contribution to the DNO, while in fact, they increase the cost for the network operator. On the other hand, the introduction of electric vehicles (EVs) or heat pumps can double the peak usage of a single household (Nijhuis et al., 2015). These changes give rise to the question whether the current grid tariffs structure employed by DNOs is still tenable or if changes to the tariff structure would be required, see e.g. Cassent et al. (2009) for the effects of distributed generation and O'Connell et al., 2012b, 2012a) for tariff based congestion prevention in the case of EVs.

The network tariffs should cover the cost of the DNO. DNOs have

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\end{footnotesize}
next to the general cost of doing business (overhead, cost of capital, etc.) expenses related to network investments and energy losses within the network. The regulator generally sets the maximum income level the DNO may achieve to cover all these costs. The question of the network tariff is: which part of this cost each of the individual consumers should pay according to their contribution to the energy losses and network investments. The challenge with the creation of a cost-reflective grid tariffs for the residential consumers is the dependency of both these cost components on the other residential consumers. The required strength of a residential low voltage network is based on the combined peak load of the connected consumers (Koliou et al., 2015). The loading of an individual consumer is however volatile and has a low correlation with the load of other individual consumers (Nijhuis et al., 2017a), meaning the peak load of a single consumer is not directly related to the peak load of the network. The losses within the network have a quadratic relationship with the loading of the network, so no simple linear relationship exists between the load profile of a single consumer and the losses within the network. For non-residential consumers, the relationship between the costs and a specific user is more apparent as dedicated network investments are often needed. The available network capacity can be used more easily as a guide for the network tariff for these types of users (Sotkiewicz and Vignolo, 2007; Li and Tolley, 2007; Li et al., 2010). For residential consumers, this is however not the case.

With the introduction of an advanced metering infrastructure, other tariff structures become possible for residential consumers. To make full use of the additional capabilities of the smart meters more dynamic network tariffs have been proposed, for instance, based on generating a multiple tier time of use tariff (Wang and Li, 2011; Sigaude et al., 2013; De Oliveira-De Jesús et al., 2005). For these dynamic tariffs to induce a reduction in the peak demand, the tariff should be implemented via automation of smart appliances (Newham and Bowker, 2010) or the tariff should consist of an auction-based pricing structure (Verzijlbergh et al., 2014; Weckx et al., 2013). The reactions (behavioural changes) of users to these more dynamic tariffs have also been investigated (Schreiber and Hochloff, 2013; Stokke et al., 2010; Bartusch et al., 2011; Kobus et al., 2015; Faruqui et al., 2015). These tariff structures can become opaque for the consumer due to their complexity and often require autonomously operating appliances. Next to this, the influence of a single user on the loading of the residential low voltage (LV) network can be large, making more dynamic network tariff structures hard to implement. More simple network tariffs structures, like capacity based tariffs, should therefore still be considered.

The use of a capacity tariff for residential consumers to generate a higher cost-reflectivity has been proposed throughout the years (Berg and Sawvides, 1983; Hledík, 2014; Dupont et al., 2014; Jargstorf and Belmans, 2015; Tuunanen et al., 2016). A quantitative assessment of the reflectivity of the network tariff is however often missing. In all of the aforementioned studies the cost-reflectivity is only addressed in the form of the effect on the loading of the network for a single group of consumers, not taking into account the large diversity in the number of consumers connected to a single MV/LV transformer (less than 20 consumers for rural areas, while over 200 consumers for urban areas). In Jargstorf and Belmans (2015) the network cost is assumed to scale with the peak contribution of the user and in Jargstorf et al. (2015) the network reinforcement cost are taken into account. Both of these approaches do not fully assess the investment cost for a DNO based on the contribution of a single user. Therefore an approach in which the influence of a single consumer on the network cost is determined has to be developed.

In this paper, the reflectivity of different network tariff structures for residential consumers will be assessed. The assessment of these different tariff structures will be done based on the part of the network cost which can be contributed to a single consumer. In order to do this a characterisation of the household load which allows for the assessment of the impact on the network of each individual consumer is proposed. Through the use of reference network models, the reflectivity of the network tariff for individual consumers can be determined. Different tariff structures are subsequently assessed in terms of reflectivity and predictability. To get a better idea on the appropriateness of different tariff structures first a small introduction into network tariffs is given in Section 2. The different tariff structures which are assessed are also discussed in Section 2. The approach to the evaluation of the different policies with respect to the tariff structure and the metrics which are used to evaluate the tariffs are discussed in Section 3. The results for the case of the Dutch network are shown in Section 4, after which the conclusions and the implications for the network tariff policy are discussed.

2. Network tariff structures

To start the discussion on the network tariffs, first of all, the goals of a network tariff will be discussed. After the goals are discussed, the current tariff structure in the EU will be examined, followed by a discussion on the household load and the distribution network cost. Based on the characteristics of the household load, different tariffs structures are defined in the Sections 2.5–2.9.

2.1. Network tariff goals

In the determination of the network tariff, the first thing the regulator is concerned with is setting an adequate revenue allowance for the DNO, i.e. the maximum income of the DNO. Multiple options exist for setting the total level of income a DNO can obtain. If multiple DNOs exist in one country, yardstick regulation can be employed. If this is not the case, the revenue allowance can be based on an estimation of the marginal cost of the DNO. Both these methods have been discussed in the literature. Nonetheless, when a certain revenue allowance is set, the question still remains how much each end-user should contribute to this allowed revenue. To distribute the cost among the users, the DNO should determine the tariff structure. The policy goals with respect to the network tariff structure (Pérez-Ariaga et al., 2013; Vivek and Parsons, 2010) are discussed in the next subsections.

2.1.1. Cost-reflectivity

The cost-reflectivity, i.e. the amount of tariff a user pays versus the cost the DNO incurred due to the use of its network, is often the main tariff goal. This can be a combination of two subgoals: cost-causality and equity. These two measures should respectively ensure that a tariff reflects the contribution of each network user to the cost of the network, as well as that the tariff does not discriminate between users. If the cost-reflectivity of the network tariff is not adequate, the user will not face a lower tariff if their network usage is reduced, as the relationship between the network usage and the tariff paid is lacking.

2.1.2. Allocative efficiency

Different consumers have different valuations of energy; in order to achieve a maximum utility, the tariff and the supplied service level should be matched with how much a consumer values the service.

2.1.3. Accessibility to electricity

Access to energy in general and electricity, in particular, is seen as a necessary good. Every user should, therefore, be able to have access to the network irrespective whether it is economically profitable for the DNO or not.

2.1.4. Transparency

How each of the consumers is charged for their network usage should be clear.

2.1.5. Simplicity

The network tariffs should be easy enough to understand for all
consumers. If a tariff structure is employed, which is cost-reflective but too difficult for the general consumer to understand, part of the cost-reflectivity is lost. No longer is everyone able to discern whether the tariff is, in fact, cost-reflective or not.

2.1.6. Predictability

The network tariff should be such that a consumer can make an accurate estimate of the amount he/she has to pay. If the user wants to act on the network tariff, he/she needs to be able to make a prediction on how taking a certain action, like applying energy saving lighting, would impact their tariff. If this is not the case, the user would have no incentive to minimise their network usage even if the cost-reflectivity is high.

2.1.7. Robustness

With the transition towards an energy system dominated by renewable energy, the network tariff should be able to handle the accompanying load changes. This transition will almost certainly not be homogeneous over the country, while the network tariff generally is, therefore the tariff should be able to handle both users with a net consumption of electricity and a net production of electricity. 1em

These policy goals the regulator has with respect to the regulation of the electricity distribution sector are generally met in different ways. The accessibility to electricity is usually only considered in relation to new connections. The costs associated with a new residential connection are therefore often partly socialised by only applying shallow connection cost. In the case of shallow connection costs, only part of the costs of connecting a new consumer is assigned to the consumer itself, the cost of laying the network from the public road to the household, for instance, are socialised among all the other users (Frias et al., 2009). For the initial connection charge, the affordable access to energy is often the main policy driver, while for the recurring network tariffs the other policy goals become more relevant. These initial connection charges and how they can best be levied are not taken into account in this paper, only the reoccurring network tariffs are taken into account.

2.2. Current tariff

Now that the policy goals of the regulator have been established, a closer look can be taken at the different types of distribution network tariffs. To gain more insight into how these policy goals have shaped the tariff structure in Europe a short overview of the current electricity network tariff structure in Europe is given. The distribution network tariffs employed in the EU in 2015 are generally a combination of a fixed charge, an energy usage charge and a capacity charge. An overview of the applied tariffs components is given in Table 1.

From the table, it can be seen that the energy usage related charge is the most popular with 92% of countries having implemented an energy usage based tariff component, while also the largest share of the income of the DNO comes from this tariff component. If a closer look is taken at some of the tariff structures a trend of moving further away from capacity-based tariffs becomes visible. In The Netherlands, for instance, the EU reports the use of a combined capacity and fixed tariff for household consumers. The capacity part of the distribution network tariff is based on the value of the protection device which limits the amount of current a household can draw. In Fig. 1 an overview of the ratings of the instillation protection devices at the household level in the Dutch LV-network is given. In the same figure, the peak load of household consumers based on smart meter measurements is also indicated. It can be seen that the lowest capacity value, 5.75 kW, is high enough for about 60% of the household consumers, while almost none seem to require a capacity of more than 17.25 kW. In the Dutch capacity tariff system, there is no cost difference between a 17.25 kW and a 5.75 kW connection. For larger connections, there is a price difference. In practice, almost all of the household consumers pay the same price based on the capacity tariff, effectively generating a fixed tariff. As there is no cost difference, users move towards larger connections. This becomes apparent when current data is compared to data of ten years ago, as shown in Fig. 1. Therefore, one of the main reasons for applying a capacity tariff is lost, as household consumers do not experience any monetary incentive to keep their peak load low. In the figure also the connection capacity the DNO takes into account when designing the distribution network, the design level, is indicated. This design level shows that through the low coincidence factor of the household load, the required network capacity is much lower than the contracted capacity.

2.3. Residential load

For the setting of the tariff of LV-connected consumers, the residential load plays an important role as over 90% of the connections are indeed households. It is, therefore, essential to first gain a better understanding of their energy use before the tariff for the distribution network can be discussed. The loading of the network depends on the individual residential loads. These residential loads can have a volatile nature. To illustrate what effect this has on the peak loading of the network as a whole, and thus the cost of the network, Fig. 2 has been created.

To generate this figure, the peak load of 50 households has been calculated and subsequently a single household has been removed from the aggregated set of households at a time, leading to a set of 49 households. The effect on the peak load based on a year of 15-min measured data is plotted in the figure. Also in the figure, the mean change in peak load has been added as well as the expected mean change in peak load. This expected mean change is based on the assumption that the coincidence factor of the loads is 1. It becomes clear that the effect on the peak load of removing a single household is much lower than expected. The discrepancy between the impact of different households also becomes clear. When household 1 is removed the yearly peak is reduced by over 5%, while if household 50 is removed

<table>
<thead>
<tr>
<th>Countries applied</th>
<th>Income share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy usage</td>
<td>92.6%</td>
</tr>
<tr>
<td>Fixed</td>
<td>53.9%</td>
</tr>
<tr>
<td>Capacity or peak</td>
<td>34.6%</td>
</tr>
</tbody>
</table>

Fig. 1. Overview of the current Dutch connection classes and the residential peak electricity consumption.
the change is smaller than 0.1%. This difference when it comes to aggregating the household load can and should be taken into account when one wants to create a more cost-reflective energy tariff. How this is implemented in the determination of the cost-reflectivity is discussed in Section 3.

2.4. Distribution network cost

The main costs incurred by the DNO are the investments in its network and covering the energy losses. Both these costs are for a large part dependent on the aggregated behaviour of only a small number (1–50) of consumers. The main part of the cost for the DNO is related to the low voltage network (substations and cables), as can be seen by the subdivision of the investment cost over the different network components in Table 2.

The table shows that about 50% of the costs are made within the LV-network. These costs consist, for the largest part, of the cables within the LV-network. The rest is due to the installation of MV/LV substations. The rating and length of the cables are mainly dependent on two aspects, the geographical dispersion of the consumers, and their load curve. As one of the main goals of the network tariff is universally affordable access to energy, the costs which are due to the geographical location of the consumers should not influence the cost of access to electricity. The other main aspect, the load profile of each consumer, should have an influence on the electricity tariff as to achieve the goal of creating a cost-reflective tariff. The costs within the distribution network mainly depend on the peak loading of the network. The peak loading within the LV-network is generated by the aggregated load of consumers connected to the same feeder. Depending on the geographical dispersion as well as the profile of the consumers, the number of consumers per feeder is in the range of 1–70. For the MV/LV substation, the cost depends on more consumers as there are usually somewhere between the 50 and 400 consumers connected to a single substation. A large part of the cost of the network is thus dependent on a small number of consumers. With an increase in loading, the cables within the LV-network would become shorter in order to be able to supply this additional required capacity, the cost increase in the MV/LV substations and MV-network is partly offset by the lower cost for the LV network due to these shorter cable lengths. To generate a cost-reflective network tariff, the most important parts of the network to take into account are the LV-cables and the MV/LV substation. These two parts of the network only have 1–70 and 50–400 customers connected. When designing the tariff the effects of an individual household at these aggregation levels should be taken into account.

2.5. Energy consumption based tariff

As seen in Section 2.2 the energy consumption of a household is most often used in the EU as the basis for the network tariff. The energy use has a very close correlation with the losses in the distribution network, as the loss is a function of the transported energy. However, the peak loading of the network, and thus the level of the necessary investments in the network, is less clearly linked to the energy consumption of the household. The implicit assumption that if a household uses a large amount of energy it would also use a lot during the peak moments does not always hold. To illustrate this, Fig. 3 has been created, based on one year of measured data from a Dutch DNO.

In the figure, the highest (peak) load during a year versus the average loading of the household in that same year is plotted. The trend of an increase in average loading for an increase in peak loading is visible. The correlation between the average loading and the peak loading is 0.71. This is due to the spread in behaviour among the different households, which show both households with a high average and a low peak loading and households with a low average loading but a high peak. This is an indication that the cost-reflectivity of energy consumption based network tariff based might not generate the desired results. This was already noted by some DNOs who moved from a purely energy consumption-based distribution network tariff to a multiple tier time-of-use based version. As the peak load for a large number of consumers always occurs during the same time of the day, the energy use during that time of the day should be a better reflection of the contribution to the network cost of a single user.

In Fig. 4 the hour in which the peak load occurs is shown, for different sizes of consumer groups. From the figure, it becomes clear that as the number of aggregated consumers decreases, the chance of the peak load occurring during the conventional peak hours (from 6 P.M. till 10 P.M.) also decreases. The cost of the network is to a large extent dependent on a limited number of users, so the application of a multi-tier tariff structure should only make a limited difference to the cost-reflectivity of the network tariff. Therefore, to set the energy consumption-based network tariff, a single tier approach is taken in this work. This is given by the following equation:

![Figure 2](image-url)  
Fig. 2. Change in the aggregated peak load of 49 households when adding an additional household to the distribution network.

![Figure 3](image-url)  
Fig. 3. Yearly peak load versus average load of 2500 individual households.

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost [€]</th>
<th>Connected consumers</th>
<th>Cost per connection [%]</th>
<th>Losses [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV-network (150 kV)</td>
<td>10 000</td>
<td>200 000</td>
<td>3.6</td>
<td>28.7</td>
</tr>
<tr>
<td>HV/MV substation</td>
<td>2 000</td>
<td>50 000</td>
<td>2.9</td>
<td>10.0</td>
</tr>
<tr>
<td>MV-network (10 kV)</td>
<td>1 200</td>
<td>2 000</td>
<td>43.2</td>
<td>31.0</td>
</tr>
<tr>
<td>MV/LV substation</td>
<td>40 000</td>
<td>200</td>
<td>14.4</td>
<td>15.9</td>
</tr>
<tr>
<td>LV-cables (0.4 kV)</td>
<td>500</td>
<td>1</td>
<td>35.9</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Table 2  Division of the investment cost and the losses for the different parts of the network estimate based on the network of the Dutch DNO Liander.
2.6. Fixed tariff

A fixed tariff, $T_{fix}$ in [€/year], where every user pays exactly the same, is the easiest tariff to implement. The cost consists only of a fixed part.

$$T_{fix} = p_{fix}$$

For the determination of the fixed tariff, the yearly cost of the DNO would have to be divided by the number of connected consumers to gain the level of the tariff. This tariff can be implemented without the need for any kind of measurement equipment.

2.7. Peak load tariff

The peak-based tariff, $T_{peak}$ in [€/year], depends on the maximum power the users draw from the network during the year. With the implementation of smart meters, the yearly peak loading can be measured at each household. This would allow the DNO to generate a network tariff based on the measured peak loading of each consumer, as follows:

$$T_{peak} = p_{fix} + p_{peak} P_{peak}$$

in which $p_{peak}$ is the tariff per kW in [€/kW] and $P_{max}$ is the maximum absolute value of the load the household has experienced during a year in [kW]. This tariff is thus determined by a single time instance in the year. The absolute value of the maximum load is chosen to allow the tariff to also take into account the production peak introduced by PV.

2.8. Peak load contribution

As using purely a peak load tariff does not include the effects of the coincidence between the peak loading of different households, a tariff may be constructed based on the contribution of the household to the peak at the MV/LV transformer. The tariff can be determined by the peak a consumer has when the network peak occurs. By applying this tariff, users with a high peak loading during off-peak hours are not penalised for this high peak as it has little effect on the sizing of the distribution network as a whole. The network tariff based on the peak load contribution, $T_{con}$ in [€/year], is given by:

$$T_{con} = p_{fix} + p_{peak} \frac{P(t_{peak})}{R_{peak}(t_{peak})}$$

where $R_{peak}$ is the tariff dependent on the peak load contribution in [€], $P(t_{peak})$ is the time at which the MV/LV transformer experiences the peak load and $P(t_{peak})$ is the aggregated peak in [kW]. The peak load contribution tariff also depends on a single moment in time, the time when the peak load in the network occurs. The load of the household at this single yearly instance thus determines the height of the tariff the consumer has to pay. The absolute value of the load peak is considered when assessing the peak time, in case the peak introduced by PV is higher than the load peak.

2.9. Capacity based tariff

A capacity-based tariff is a tariff which falls somewhere in between a fixed and a peak load tariff. Instead of a pure peak load tariff, where the tariff is based on the measured yearly level of the peak load, the capacity tariff, $T_{cap}$ in [€/year], uses a multi-tier peak load structure. Multiple capacity classes exist and depending on the peak load of the user, the user falls into one of these classes. This can be expressed as follows:

$$T_{cap} = R_{cap} \left(\frac{|P_{max}|}{d_{Rcap}}\right)$$

where $R_{cap}$ indicates the cost of each of the kW capacity classes in [€], $|\cdot|$ indicates the integer value closest to positive infinity and $d_{Rcap}$ is the step size for the different capacity classes in [kW]. This multi-tier capacity tariff tries to combine the relation between the peak load and the investment cost with the simplicity of the fixed tariff. For the step size, a value of 2 kW is chosen here. The user tariff will increase if its peak load falls into another tier of 2 kW, this gives an increased predictability of the tariff.

2.10. Evaluated tariffs

To generate a clear overview of the differences between the network tariffs discussed in the previous sections, an overview of the various tariff structures is given in Fig. 5.
For all households $n$ in $N$ 

- Take a household load curve $n$

For groups of 1, 2, 5, 10, 20 and 50 households

- Add additional household load curves based on MC simulation
- Determine peak load per household
- Fit the peak load values to the Veelander equation
- Run the network planning optimisation to obtain network cost $C_n$
- Determine $P_{fr}$

For each tariff structure $trf$

- Determine $T_{n, trf}$
- Determine reflectivity $R_{n, trf}$
- Determine predictability $Pr_{n, trf}$

Fig. 6. Overview of the procedure to calculate the reflectivity of the different network tariffs.

In this figure, each of the five different tariff options is indicated, based on the characteristics of a typical 24-h loading profile. The differences between the tariffs become apparent from the main aspects they are based on. Whereas the peak and capacity tariffs both take into account the peak loading of the household, the peak contribution takes into account the loading of the household when an aggregated group of households experience a peak in the total loading. The energy-based and fixed tariff have no direct link with the peak loading.

3. Assessment of network tariffs

The methodology for assessing the tariffs discussed in the previous section will be described in this section, and numerical results will be presented in the next section. The assessment is based on the following criteria: to what extent is the tariff cost-reflective, predictable and robust with respect to technology changes introduced by the energy transition. An overview of the method employed for the assessment of the different tariff structures is given in Fig. 6.

The procedure starts with the determination of the effect of each individual household on the loading of the network. This is estimated through the use of the Veelander load equation as explained in Section 3.1. The network cost is subsequently estimated for the individual Veelander load equations, by applying a network planning optimisation as shown in Section 3.2. These network cost for the individual user $C_n$ in [€] allow for calculating the constants in the different network tariff structures explained in Sections 2.5–2.9. With the constants in the tariffs defined, the amount, $T_{n, trf}$ in [€/year], each user $n$ pays based on tariff structure $trf$ can be determined. Based on the tariffs paid based on all the users and the individual network cost the reflectivity $R_{n, trf}$ can be calculated for each household, as shown in Section 3.3. Next to the reflectivity, the predictability of the network tariffs can also be obtained from the tariffs paid based on all the users, $T_{n, trf}$, as shown in Section 3.4.

3.1. Residential load characterisation

To generate a difference in the network investment cost between the households, the load which is employed during the assessment of the required network capacity needs to be defined for each household. Simply using the load profile of a single household when determining the network strength will not work. This will generate a coincidence factor of 1 between the different households, leading to a much higher loading than experienced in practice. In the planning of LV-networks the Veelander equation (Axelsson and Strand, 1975) is often used to characterise the household load:

$$P_{n, trf} = \alpha n + \beta \sqrt{n}$$

where, $P_{n, trf}$ is the maximum aggregated load for a group of $n$ households and $\alpha$ and $\beta$ are empirical factors which need to be estimated from measurements of the household loads. To implement the effect a single household has on this formula, the following approach is used. From a database of household load profiles, the load profile of the household for which one wants to know the impact on the required network capacity is taken. For this household, Eq. (6) is estimated. This is done by creating measurement points from which the factors $\alpha$ and $\beta$ can be determined. The first measurement point which is created is the point for a single household, this point is given by the maximum load of the household in question. Next to this measurement point, points with 2, 5, 10 and 20 households are created. For these measurement points, the peak loading is estimated based on Monte Carlo sampling from the database of household load profiles. With the sampling, the household in question is always taken as part of the group for which an estimate is made. This leads to the creation of the different measurement points for the household load curve. The measurement points and the resulting maximum load per household are given in Fig. 7.

In the figure, the estimated aggregation of the peak load is given for a household with a high, medium and low peak contribution. There is a clear difference between the households, it can also be seen that this difference does not necessarily relate to the difference in peak load. This makes sense, as a household can have a high peak during off-peak hours with limited effect on the required network capacity, while another household can have a medium peak during peak hours with a far larger effect on the required network capacity. By characterising the household load curves in this way, the difference in required network capacity for each household can be determined. For each household the individual Veelander Eq. (6) can be determined, based on this load equation the network can be planned for each individual household as shown in the following section.

Fig. 7. Estimation of the maximum load and coincidence factor of different types of households.
3.2. Network planning

For the assessment of the cost of the distribution network, reference network models can be employed (Jamash and Pollitt, 2008). In these models the network is planned with measured consumer load data, to gain insight into how much a DNO should be spending. For the determination of the difference in network costs for different consumers, a slightly different network planning approach needs to be employed, as follows. The goal of network planning is to generate a network which is capable of serving all the loads at the lowest possible cost. The costs considered during the network planning consist of capital cost, i.e. the investment cost to build the network, and operational cost, i.e. the cost of the energy losses in the network. The investment cost, considered in this work, consists of the cost for the LV-network, the MV/LV substation and an estimate of the cost for the MV-network. The network is subjected to a number of constraints. Firstly, all the households need to be connected to the network. Secondly, the LV-network should have a radial structure, which can be enforced by setting the number of nodes in the network equal to the number of branches minus the number of substations. The loading of all the components – branches and MV/LV substations – should be below their rated limits and the node voltages should stay within the limits. All of the above can be expressed as the following optimisation problem:

$$
\min \sum_{n=1}^{N_{SS}} \left( C_{SS} + C_{MV} l_{a, MV} \sum_{m=1}^{M_{DF,n}} C_{DF} + \sum_{r \in R_{DF,n}} l_r C_{DF} \right)
$$

subject to,

$$
B_{hh} \subseteq B, \\
|R_{DF}| = |B| - N_{SS}, \\
S_r \leq 1 \quad \forall r \in R_{DF}, \\
S_r \leq 1 \quad \forall r \in R_o, \\
U_{min} \leq U_b \leq U_{max} \quad \forall b \in B_{hh}
$$

where,

- $N_{SS}$ is the number of MV/LV substations
- $C_{SS}$ is the cost of an MV/LV substation [€]
- $C_{MV}$ is the cost of a meter of MV cable [€]
- $l_{a, MV}$ is the distance to the nearest other MV/LV substation [m]
- $M_{DF,n}$ is the number of feeders connected to substation $n$
- $C_{DF}$ is the cost of an LV-feeder [€]
- $R_{DF}$ is the set of branches
- $l_r$ is the length of branch $r$ [m]
- $C_{DF}$ is the cost of a meter LV-cable [€/m]
- $B$ is the set of all connected nodes
- $B_{hh}$ is the set of all households
- $S_r$ is the apparent power loading of component $r$ [p.u.]
- $R_{DF}$ is the set of MV/LV transformers
- $U_b$ is the voltage at node $b$ [p.u.]
- $U_{max}$ and $U_{min}$ are the voltage limits [p.u.]

This optimisation problem is similar to the strategy employed in Diaz-Dorado et al. (2003) and Nijhuis et al. (2017b). The approach is altered to have a slightly different cost structure: to install a feeder are considered, while maintenance costs are neglected since solely underground networks are planned. These changes still allow for the use of the same genetic algorithm approach for solving the optimal network planning problem. Based on the geographical characteristics other distribution network planning approach can be applied as well. The values of the parameters defined in the network planning approach can be found in Table 3 as well. With these values, the required network cost can be calculated based on the load curve for each of the consumers.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Component</th>
<th>Cost [€]</th>
<th>Lifetime [Years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{SS}$</td>
<td>LV-Cable [m]</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>$C_{MV}$</td>
<td>MV-Cable [m]</td>
<td>95</td>
<td>45</td>
</tr>
<tr>
<td>$C_{SS}$</td>
<td>Substation</td>
<td>40,000</td>
<td>60</td>
</tr>
<tr>
<td>$C_{DF}$</td>
<td>LV-feeder</td>
<td>1750</td>
<td>60</td>
</tr>
<tr>
<td>$C_{inv,fix}$</td>
<td>Fixed investment cost</td>
<td>2600</td>
<td>–</td>
</tr>
</tbody>
</table>

3.3. Reflectivity

The cost obtained from the network planning process needs to be translated into a metric for assessing the cost-reflectivity. This metric should be the same for all different network tariff structures. The reflectivity should give an indication of how well the tariff a specific individual user pays, reflects the cost incurred by the DNO. This can be defined as the ratio of the user specific network tariff divided by the network tariff paid. The paid network tariff is constructed by taking all users into account. This can be expressed as follows:

$$
R_n = \frac{T_{n,df} - C_n/N_{La}}{T_{n,df}}
$$

with $T_{n,df}$ the network tariff in [€/year] for user $n$ based on the tariff structure $trf$ and $C_n$ the network cost in [€] based on user $n$, $L_n$ the weighted average lifetime of the components of network $C_n$ in [year] and $N$ the total number of consumers connected to the network. By defining the reflectivity in this way a positive reflectivity indicates a user pays more than it should, based on its network utilisation. In order to compute the cost-reflectivity, both $C_n$ and $T_{n,df}$ need to be known. The individual network cost for the specific user is calculated as explained in Section 3.2. This cost is divided by the tariff the user pays based on every connected consumer. This tariff related to all the users combined can be computed by estimating the two parameters, the fixed and the variable tariff part, in the defined network tariff structure. The parameter estimation is based on minimising the difference between the calculated individual network cost and the tariff calculated by the estimated parameters:

$$
\min \sum_{n=1}^{N} \left( \frac{C_n}{N-L_n} - T_{n,df}(P_{fix}, P_{trf}) \right)
$$

where $P_{fix}$ the tariff structure dependent part (e.g. $R_{wol}$) of each tariff. The network planning approach is applied to the consumers of the DNO Liander (large DNO in the Netherlands, 2.7 million LV-connections). For each consumer their geographical location is used as well as an estimate of their load curve, taking into account the local neighbourhood statistics. The current Liander network is used to initialise the genetic algorithm and the possible branch positions have been determined based on the layout of the streets. By applying the approach to all the connected consumers the differences in the geographical dispersion of the consumers should be captured and a representative overview of the required network cost should be obtained. The downside of using the complete number of connections is the large computational requirements. To keep the computational burden in check, the cost for a specific user is estimated based on an estimated piecewise linear relation between both household load parameters and the calculated network cost. In this way, the number of loading conditions which have to be assessed is reduced.

3.4. Predictability

The second metric which is used for the evaluation of the different policy structures is the predictability. The predictability should give an indication how well the consumer can predict the height of its tariff. In order to quantify this, the difference in cost which arises when
analysing two consecutive years with the same tariff is calculated. The defined predictability \( P_h \) is calculated by using the following expression:

\[
P_h = \frac{T_{h,off,1} - T_{h,off,2}}{T_{h,off,1}}
\]

(10)

where \( T_{h,off,1} \) and \( T_{h,off,2} \) are the tariff consumer \( h \) has to pay in year 1 and year 2 respectively. To calculate this predictability the reference data (half-hourly measurements from 2430 households over two years) from the Low Carbon London project are used (UK Power Networks, 2015).

4. Results

The results of the calculation of the reflectivity and predictability for the five different tariff options are shown in this section. Next to these, the results for the robustness of the tariff structures are assessed by applying the tariff based on a load situation with a high PV penetration and a high penetration of EV. First, the results of the reflectivity and predictability for the current situation are shown.

Fig. 8 depicts the probability densities of the calculated reflectivity metric for the five tariff structures. These distributions indicate how cost-reflective a proposed tariff is. In all sub-figures the two things to notice are the peak around zero (with a higher peak indicating more consumers with a near perfect cost-reflectivity), and how fat the tail of the distribution is (with a fat tail indicating many users pay a network tariff which is significantly higher or lower than it should be). To gain more insight into these results Table 4 has been created, which shows the median, the variance, and the 5th and 95th percentile values of the distributions.

From the Table 4 and the Fig. 8 a number of conclusions can be drawn. First of all, the tariff structures all have a median value higher than 0. This implies that the majority of the users overpay for their connection, namely those in the skew of the probability densities.

Another thing which becomes clear is that the tariff based on peak loading generates the most cost-reflective tariff structure, it has the lowest variance and both the 5th and 95th percentile values are closest to zero. The peak contribution method, which one might expect to have a better cost-reflectivity, actually performs comparably to the capacity-based tariff structure. The reason for the lower performance of the peak contribution is the difference in time when the peak may occur for different combinations of a small number of households. While for hundreds of households the peak always will be within a narrow time-frame, between 8 P.M. and 9 P.M., for a small number of households the influence of a single household is still significant, leading to a shift in peak times which can, for instance, depend on when four out of ten households switch on their washing machine. The energy consumption-based tariff shows a poor cost-reflectivity, with more than 5% of the consumers paying a tariff which is 30% lower than what is considered cost-reflective. The fixed tariff shows an almost flat distribution, with more than 5% of the consumers paying a tariff which is less than half of what can be considered cost-reflective.

The other main aspect on which the network tariffs should be analysed is the predictability. Similar to the reflectivity, the probability densities of the predictability metric are shown in Fig. 9 and the same set of statistical indicators are shown in Table 5. For the probability density functions, the fixed tariff is omitted as the predictability of the fixed tariff is perfect as there is no change in cost with a change in network usage.

From the figure, the large difference between the capacity-based and energy consumption-based tariffs, and the peak and peak contribution-based tariffs becomes clear. The first two have a very high peak around zero, indicating that for many consumers the tariff between two consecutive years remains is constant. This high predictability also shows up in the table when it comes to the energy-based tariff, for the capacity tariff the descriptive statistics tell a different story. Though for many consumers the capacity tariff offers perfect predictability, a small but significant group of users (16%) faces a change in tariffs, for this group the predictability is low as the step between two tariff classes is high compared to the incremental changes in the other tariff structures. All the probability densities have a slight skew to the right, as the network usage has increased in the second year. The peak contribution has a higher peak at zero compared to the peak tariff, indicating more users have the same tariff in two consecutive years, however, the tail of the predictability distribution of the peak contribution tariff is fatter, meaning a large change in tariff is more likely as can also be seen from the percentile values.

Table 4

<table>
<thead>
<tr>
<th></th>
<th>Capacity tariff</th>
<th>Energy usage</th>
<th>Peak contribution</th>
<th>Peak tariff</th>
<th>Fixed tariff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.004</td>
<td>0.004</td>
<td>0.014</td>
<td>0.001</td>
<td>0.062</td>
</tr>
<tr>
<td>Variance</td>
<td>0.006</td>
<td>0.025</td>
<td>0.005</td>
<td>0.001</td>
<td>0.076</td>
</tr>
<tr>
<td>95th percentile</td>
<td>-0.118</td>
<td>-0.194</td>
<td>-0.087</td>
<td>-0.037</td>
<td>-0.358</td>
</tr>
<tr>
<td>5th percentile</td>
<td>0.114</td>
<td>0.303</td>
<td>0.130</td>
<td>0.041</td>
<td>0.512</td>
</tr>
</tbody>
</table>
4.1. Robustness evaluation

Another important aspect to look at is how well the distribution network tariffs would handle changes in the energy consumption. With the outlook of a high penetration of PV and the electrification of transportation via electric vehicles, the energy usage is changing. For a tariff structure to be effective, it should retain its favourable cost-reflectivity and predictability aspects during this energy transition. To gain insight into how the reflectivity changes, the five tariff structures investigated in this paper have also been assessed with increased PV-penetration rates of 40% and 80% and EV penetration rates of 40% and 80%. To generate the required Veeleander curves (6) for the household load with an increased PV-penetration, the household load is modelled with a bottom-up Markov Chain approach as developed by the authors in Nijhuis et al. (2016). In this model, a PV system is randomly assigned to a percentage of households equal to the PV penetration rate. The PV systems will have a rated power uniformly distributed between 2 and 5.5 kW. The resulting reflectivity for the various tariff structures is shown as probability densities in Fig. 10 and the relevant statistics are shown in Table 6.

In the figure, the different probability density functions are shown with different stroke thickness and shades of the same colour. The lighter the stroke and shade the lower the PV-penetration level. From the figure, it becomes clear that the reflectivity of the capacity-based tariff actually increases with an increasing amount of PV generation, while for the other tariff structures the reflectivity decreases or remains more or less the same. For the peak load method, the 40% PV penetration level has by far the lowest reflectivity. This can be explained from the different times at which the peak loading occurs. With an

![Fig. 9. The probability density of the distribution of the predictability of the different tariff structures.](image)

![Fig. 10. The tenability of the reflectivity of the different tariff structures for increasing amounts of PV generation.](image)

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Energy</th>
<th>Peak contribution</th>
<th>Peak</th>
<th>Fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0</td>
<td>0.002</td>
<td>0.012</td>
<td>0</td>
</tr>
<tr>
<td>Variance</td>
<td>0.012</td>
<td>0.001</td>
<td>0.010</td>
<td>0</td>
</tr>
<tr>
<td>95th percentile</td>
<td>−0.214</td>
<td>−0.020</td>
<td>−0.142</td>
<td>−0.159</td>
</tr>
<tr>
<td>99th percentile</td>
<td>0.176</td>
<td>0.051</td>
<td>0.282</td>
<td>0.159</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Energy</th>
<th>Peak contribution</th>
<th>Peak</th>
<th>Fixed</th>
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</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.004</td>
<td>0.004</td>
<td>0.010</td>
<td>0.001</td>
</tr>
<tr>
<td>Variance</td>
<td>0.005</td>
<td>0.022</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>95th percentile</td>
<td>−0.105</td>
<td>−0.194</td>
<td>−0.087</td>
<td>−0.037</td>
</tr>
<tr>
<td>99th percentile</td>
<td>0.114</td>
<td>0.269</td>
<td>0.130</td>
<td>0.041</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Energy</th>
<th>Peak contribution</th>
<th>Peak</th>
<th>Fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.006</td>
<td>0.020</td>
<td>0.014</td>
<td>0.008</td>
</tr>
<tr>
<td>Variance</td>
<td>0.007</td>
<td>0.025</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>95th percentile</td>
<td>−0.121</td>
<td>−0.215</td>
<td>−0.107</td>
<td>−0.072</td>
</tr>
<tr>
<td>99th percentile</td>
<td>0.144</td>
<td>0.303</td>
<td>0.136</td>
<td>0.120</td>
</tr>
</tbody>
</table>

Table 5

Descriptive statistics of the predictability of the different tariff structures.

Table 6

Descriptive statistics of the reflectivity with PV penetration levels between the 40% and the 80%.
intermediate level of PV penetration, there are neighbourhoods where the PV-peak determines the required network strength and also networks for which the evening peak remains the driving factor. This diversity reduces the cost-reflectivity of the peak load significantly. As the PV penetration level reaches 80% this diversity is somewhat reduced, because the PV peak determines the network cost and 80% of the households contribute to this peak.

In Table 6, the statistical indicators for PV penetration levels of up to 80% are shown. From the tight ranges in the table for the peak contribution method and the capacity-based tariffs, it can be seen that especially these tariff structures can keep their performance levels constant as the amount of PV increases. The peak load based tariff structure seems to outperform the other tariff structures on almost all cost-reflectivity metrics, only the capacity-based tariff has a lower 95th percentile value compared to the current loading situation.

The same analysis is done, for an increasing EV penetration rate. The EVs are modelled in such a way that when a consumer returns home the charging will start and will finish when the battery of the EV is full. For the arrival and departure times, synthetic driver profiles are used (Verzijlbergh et al., 2014). The EV charging rate is assumed to be between 3 and 8 kW. The resulting reflectivity for the different tariff structures is shown as probability densities in Fig. 11.

From the figure, it can be seen that the detrimental effect which the PV has on the reflectivity is not present. The reflectivity of most tariff structures actually increases as the EV penetration level increases. For the peak tariff, there does not seem to be much difference between the original reflectivity and the reflectivity with a high EV penetration. The medium level of EV penetration only has a positive effect on the peak contribution based tariff. As the EV peak already becomes the dominant network peak, the users with EV are all contributing relatively a lot to this peak. Based on the results in the figure, it would be safe to conclude that the increase in EV penetration would not be a risk for the cost-reflectivity of the network tariff. The reflectivity of the network tariff can actually be improved in most cases.

5. Conclusions and policy implications

In this paper, the consequences for the cost-reflectivity, predictability and robustness of different types of network tariffs are shown. The main tariff component for the distribution network tariffs currently used in the EU is an energy consumption-based component. The reflectivity of such a tariff is shown to be low. This can easily be explained, since the energy consumption is a measure of the average load, while the network adequacy is more based on the peak load. The peak load-based tariff does show the best reflectivity of the evaluated distribution network tariffs, even though the reflectivity decreases with the introduction of PV, the reflectivity is still better than for all the other tariffs. The predictability of the peak load-based tariff is however lower. The peak load differs from one year to another, as it is based on the combination of appliances that are active at the same moment time. The peak load based tariff is dependent on a single moment in a year, meaning that a single momentary lapse in keeping the peak load below a certain value affects the tariff. Whereas for the energy consumption-based tariff, the predictability is much higher. The energy usage based tariff can be influenced much easier by the consumer, as the load on all the hours of a year actually contributes to the tariff. The effect on the network of this reduction in loading is more opaque. The reflectivity of this tariff is not high enough to assume that a decrease in energy consumption would definitely also mean a decrease in the contribution to the cost of the network.

From a DNO point of view, the reflectivity is far less important than the predictability of the network tariff. Due to the changes imposed by the energy transition, it becomes harder for the DNO to set the tariff in such a way that the revenue it collects is equal to the allowed revenue as determined by the regulator. Therefore, the lower predictability of the peak load distribution tariff is undesirable from a DNO point of view, and an energy consumption-based tariff or a fixed tariff would be most desirable. The DNO can in those cases easily predict the amount of revenue a certain tariff will generate. In the EU the distribution network tariff structures are predominately based on the energy consumption of the household consumers. With the introduction of smart meters across Europe the implementation of a peak load-based tariff, instead of a capacity tariff based on the rating of the main household protection device, becomes possible. A change in policy towards a more peak load based network tariff should therefore be considered. This will further decouple the commodity of electricity from the service of providing access to the network. Especially with the introduction of more PV in the LV-network, the reflectivity of the peak tariff starts to decrease. The reverse power flows which can occur at higher PV penetration rates make the peak introduced by PV the predominant peak. However, the peak tariff makes no distinction between the load and generation peak. This leads to a lower cost-reflectivity, especially for consumers who have no PV installed. If the PV penetration increases to 80% the reduction in reflectivity is mostly undone, indicating that it is hardest to have a cost-reflective network tariff during the transition period.

In this paper, only tariff structures based on a single indicator (e.g.

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![Fig. 11. The tenability of the reflectivity of the different tariff structures for increasing amounts of EV penetration.](image-url)
energy consumption or peak load) and not combinations of two or more indicators for the network use (e.g. energy consumption and peak load) have been evaluated. The use of these hybrid tariff structures should be further investigated as it can lead to a better trade-off between the predictability and cost-reflectivity.

References


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