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# Capacity Subscription Tariffs for Electricity Distribution Networks: Design Choices and Congestion Management

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**Residential distribution networks in Europe are undergoing rapid changes. As high-power flexible loads, such as electric vehicle (EV) chargers, become more prevalent, the risk of network congestion increases. This is exacerbated by tariff structures which do not give incentives to limit simultaneous power consumption. Network charges in this case may not reflect the true costs of usage, as network costs are driven mainly by simultaneous load peaks.**

**We present a systematic assessment of a new class of tariffs that is currently gaining attention in the Netherlands: capacity subscription models. We argue that this tariff structure is more cost-reflective and fair than the current fixed network fee and show how it helps to prevent transformer overloading in a simple simulation model of a neighborhood of 100 households constrained by a LV transformer, where a varying number of EVs are added.**

**Index Terms: Demand Side Management, Electricity Distribution Tariffs, Power Distribution, Smart Grids, Electric Vehicles**

## I. INTRODUCTION

The requirements for electric distribution grids are changing. Much of the current infrastructure was built decades ago and was adapted for a time that was dominated by a few large electricity producers and relatively stable, predictable loads. Power flow was predominantly unidirectional from these large generators to consumers, whose demand was considered relatively inflexible and predictable on average. Networks were dimensioned in a way to ensure they could handle the maximum simultaneous peak demand of all users at each grid node. Nowadays, distributed generation and new high-power flexible loads, such as electric vehicle (EV) chargers and heat pumps are becoming more common and present new challenges to these grids. Due to potential high simultaneity of drawing power from or feeding it into the grid, these devices can lead to voltage problems [1] and overloading of lines and transformers. These congestion problems can be

handled in different ways: by upgrading distribution grid infrastructure such as lines and transformers [2], by adding storage at the distribution level [3], by direct control of power flows in network assets [4] and by indirect control through markets and incentive-based systems for distribution grid usage [4]. The first two of these approaches require physical infrastructure upgrades which are quite costly and can only be done at a limited pace. The third, direct control, can only relieve congestion that can be resolved through network reconfiguration, which is rather limited, or curtailment, which causes discomfort for customers. Thus, indirect methods to resolve congestion management have received much attention in the literature lately.

Some of the indirect methods for congestion management that are discussed in the literature are: flex markets, where the Distribution System Operator (DSO) procures flexibility in a local market from a third party [5]; dynamic tariffs, where the DSO predicts network load and set tariffs in advance in a way that is anticipated to resolve congestion [6] and capacity markets [7], which require an iteration between aggregator's scheduling and DSOs calculations of network congestion. A problem that these approaches have in common, is that they have a high implementation burden as they require the setup of a new market or substantial expansion of the responsibilities of the DSO, such as the forecasting of network load. DSOs may not be ready or able to take on these additional responsibilities.

Thus, it seems more likely that in the near future a simpler alternative that can reduce network congestion has to be found. One potential avenue to achieve this is to adjust network tariffs to more accurately represent the burden that the addition of, e.g., EVs cause on the grid. In this paper, we discuss a relatively new idea that has recently gained attention among DSOs in the Netherlands: network capacity subscription tariffs [8].

The paper is organized as follows: Section 2 recaps fundamental network principles for evaluation of network tariff performance, Section 3 introduces the current situation in

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the Netherlands and the capacity subscription concept It discusses this tariff system in terms of the regulatory principles and highlights critical design choices. Section 4 describes the simulation setup that was used to investigate the effect of introducing the new tariffs on network congestion. Section 5 presents the results of this simulation and Section 6 concludes.

## II. NETWORK TARIFF REGULATORY PRINCIPLES

The regulatory principles underpinning network tariff design are well covered in the literature [9][10][11][12][13][14]. Some of the most often discussed principles are:

- Financial sustainability or cost recovery: revenues from tariffs have to cover the costs of the network operator.
- Economic efficiency: tariffs should be social welfare optimizing and provide incentives to optimize the utilization of infrastructure.
- Cost-reflectivity: charges to consumers should reflect the costs the consumer causes by using the grid.
- Non-discrimination or equity: customers using the grid in the same way should be charged the same. Note however that equity does not imply equality – customers can be charged differently for different uses of the grid.
- Understandability, transparency and predictability: customers should be able to easily understand their tariffs and “bill shock” should be avoided, i.e. they should know or be able to accurately estimate their bill in advance.

In addition, the aims of the whole energy system more generally are often referred to as the “Energy Trilemma” [15]: balancing affordability with security of supply and environmental sustainability. Just like with the objectives in the Energy Trilemma, there are frictions and trade-offs between the network principles. A more complex tariff structure may be economically efficient and more cost-reflective, but quite hard to understand for customers and it could hit them with unexpected charges.

## III. CAPACITY SUBSCRIPTION MODELS

### A. Current Tariff in the Netherlands and Challenges

In the Netherlands, most households currently pay a fixed network charge of around 250 Euro per year (including VAT). This holds for all consumers with a physical connection limit to the network of up to 17.3 kW. This tariff design was chosen with a relatively homogenous population in mind, where the typical energy demand is far lower than the physical connection limit. The assumption was, that the typical household peak would be around 4 kW and that that coincidence of peaks is limited by diversity of usage [8][16]. In this situation, costs were mostly driven by building the physical connection to the network [8]. Thus, in terms of the network principles given in the last section, the tariff is fair in terms of cost-reflectivity and

equity. It also is evidently one of the best possible choices for understandability and predictability, as it is only based on having a connection to the network and is known in advance with certainty. Furthermore, it reduces the need for data exchange between consumer, energy supplier and network operator, which leads to cost savings for network management. It does not give any incentives to households for more efficient use of the network, but in the past households were not expected to be able to respond to these incentives in a significant way anyways. And since the network was typically strongly over-dimensioned, supply security was not an issue, as long as households did not deviate too far from the assumptions above.

However, this situation is currently changing with the increasing penetration of EV and, to a lesser extent, heat pumps in the grid. These devices have in common that they have a very high power consumption compared to the typical household peak load, and that they can show strong simultaneity. Typical household loads are dominated by short spikes of high power, such as for cooking and heating water, and longer plateaus of relatively low power, such as lights or watching TV. EVs, on the other hand, can charge at very high power (3.6 kW, 7.3kW and 11kW are typical sizes for current chargers), and they can do so constantly over several hours until the required charge is met. Simultaneity occurs as many consumers may arrive back home and start charging around the same time in the evening. Another situation that can lead to high simultaneity is, when many consumers sign up with a smart charging company, which can deliver reduced electricity costs by charging the car when wholesale electricity prices are low. Or consumers may respond to a peak pricing scheme in electricity costs, by delaying the charging until the time when the peak price ends. In all of these situations, a strong peak can occur as many customers may follow the same behavioural pattern.

In this situation, the performance of the fixed tariff with respect to the regulatory network principles declines. Consumers with EVs have much higher peak loads and, due to the potentially high simultaneity of charging, are much more likely to contribute significantly more to the network peak load. As EV penetration is increasing further, network constraints for active power and voltage drops are likely to be exceeded. This can lead to damaged network components and voltage issues and may threaten supply security and may require costly network upgrades. As the need for these upgrades would be driven predominantly by EV owners, the current tariff structure would not be cost-reflective anymore.

In addition to these challenges that EVs bring, they also bring opportunities. Unlike traditional household loads, which are typically considered relatively inflexible, EV charging is only bound by a minimal charge requirement at a given deadline. Consumers are not likely to care when exactly their EV is charging, as long as they have enough charge in the battery when they need to leave. Thus EVs also introduce a lot of flexibility in the system and charging can be used, for example, to absorb excess renewable energy and provide services to the balancing market [17][18]. This flexibility could also be used to ensure that EV charging does not violate network constraints but provide a more even and efficient use of the network. However, the current fixed tariff gives no incentives for this.

### B. Capacity Subscription Tariffs as a Solution

With regard to these problems, Dutch DSOs and related stakeholders are currently discussing updates to the network tariff structure for the new regulatory period in the Netherlands starting from January 2024 [8], [16]. A proposal that has received particular attention recently is that of subscriptions for network capacity [19], [20]. In this proposal, consumers subscribe in advance to a specified level of network capacity, within which they are free to use the network without any additional charge at any time. If their load is higher than the subscribed capacity on average over a given time interval (e.g. 15 minutes), there are currently two main variants for how this is penalized. In one variant they incur an extra fee per kWh of exceedance, while in the other they are moved to the next higher subscription category for the next settlement period.

This tariff system is inherently more cost reflective than the fixed tariff, as load peaks above the subscribed capacity are charged more. Moreover, it provides strong incentives to limit EV charging power to below the subscribed capacity at all times and thus leads to spreading out charging over a longer time period, which leads to more efficient network usage and reduces the risk of overload of network components. This will be demonstrated by use of a simplified neighbourhood model in the next sections. In terms of understandability, this tariff model is a bit more complicated, as the subscription concept has to be explained. DSOs will have to educate and help customers understand the principles and reasons for the switch of tariffs and resulting difference in charges. In terms of predictability of charges, the settlement fees for exceeding the subscribed capacity make this tariff less predictable. However, in practice the resulting charges are not too volatile, as in the case of many exceedances a household could just select the next higher subscription level.

### C. Critical Design Choices of the Subscription Model

In the previous section we already introduced the question and potential solutions for how to address the situation when a household is exceeding the subscribed capacity. Further important design choices of the model are:

- What is the time interval over which to average load for computing the exceedance? Options are, e.g., 5, 15 or 60 minutes. A shorter time interval would be more reflective of customers' true peak load, but also increase data transfers and give customers less flexibility to use devices with short high-power spikes.
- Are subscriptions fixed for a whole year or re-selected every month or even week? In terms of cost-reflectivity the yearly subscription seems more suitable, as the costs for network reinforcement are driven by the highest network peaks.
- How many subscription bands should be offered, at which sizes and prices? A stronger differentiation allows for more customization and cost-reflectivity, but current thinking among the Dutch DSOs is to keep the number of subscription levels to around 4, in order to keep the tariff simple. The capacity levels then have

to be chosen based on what works well for many customers and the prices should be set in accordance with the cost-recovery criterion.

- How is feed-in of electricity from PV cells or batteries back into the grid handled in the subscription model? The DNV GL report [20] proposes a symmetric subscription where the capacity for feed-in is exactly equal to the capacity for load and, by default, at no extra charge. It could be more cost reflective to offer asymmetric subscriptions and charge separately for feed-in, but an in-depth treatment of this problem is outside the scope of this paper.

## IV. MODEL DESCRIPTION

### A. Households and Transformer Capacity

In order to assess the effectiveness of the capacity subscription approach for reducing network congestions, we simulated this tariff structure in an urban residential neighborhood. The network consists of 100 households with one month (January) of simulated realistic load profiles that were generated by the Load Profile Generator<sup>1</sup>. This open tool uses realistic behavioral simulations and individual devices in typical households in order to produce load profiles that emulate real household load curves, and has been extensively validated with real data [21]. The network for this simulation was created using the settlement template for the average German population distribution. The households are all behind one low voltage transformer with a rated capacity of 188 kVA. Assuming a power factor of 0.85, this translates to an active power capacity of 160 kW. This is based on [20], where the network design parameter for the low voltage distribution grid is given as 1.6 kW per household. It is also close to the design parameter used by Enexis in research on subscription models [19], where a transformer with active power capacity of 268 has been used to study a neighborhood of 146 households.

Table 1: EV characteristics

Parameter	Value
Arrival Time Mean	18:30
Arrival Time Std	1h
Daily Demand Mean	12 kWh
Daily Demand Std	2 kWh
Battery Size	60 kWh
Charger Capacity	11 kW
Charging Efficiency	90%
Departure Time	8:00
Min Charge at Departure	70%, 42 kWh

<sup>1</sup> <https://www.loadprofilegenerator.de/>

## B. EV Characteristics

The main purpose of the simulation was to investigate the effect of subscription based tariffs on transformer overloading at increasing levels of EV penetration in the neighborhood. To this end, we assigned a specific number of EVs (varying from 5 to 35) randomly to the given household load profiles. In order to approximate realistic charging needs, the arrival times and daily charge requirements were randomized as well and are drawn from Gaussian distributions with means and standard deviation that were motivated by data on real-world EV charging from the Dutch Elaad platform.<sup>2</sup> Initial charges of the EVs were set to the minimal charge at departure minus the EV's daily demand. For each EV, sampled values of the daily demand and arrival time were kept constant for the simulation horizon of 3 days. All EV charging parameters are summarized in Table 1.

## C. Charging Strategies and Modeling Cases

We implemented two different charging strategies that individual households may use to charge their vehicles:

**Charge-on-Arrival:** The vehicle is plugged in and starts charging as soon as it arrives home. It charges until the required demand for departure has been met.

**Individual-Optimization:** The model is additionally fed with wholesale electricity-market prices, taken from historical EPEX data.<sup>3</sup> Households optimize the charging of their vehicle based on these prices over multiple days (assuming perfect foresight). This can be realized by signing up with a smart charging company like gridX<sup>4</sup> or Jedlix<sup>5</sup>.

For both of these charging strategies we simulate the case without capacity subscription tariffs, where the charging is only constrained by the power of the charger, and with subscription tariffs. When these tariffs are applied, the charging capacity of the EV is constrained to the subscribed capacity minus the household load at any time, or zero, in case the household load already exceeds the subscribed capacity at a given moment. This leads to a combined total of 4 modeling cases: 2 charging strategies, with and without subscription each. Note that in practice consumers may still decide to charge their EVs outside of their subscription, if they need to do so urgently, but we do not include this in the simulation. They are not likely to do so on a regular basis, as each charging cycle would incur a fee of an extra 5 Euro for every 10 kWh out of subscription, due to the exceedance fee which was set to €0.50/kWh (see next section).

## D. Capacity Subscription Tariffs

The available capacity levels for household subscriptions are summarized in Table 2. The cost parameters are taken from an internal study of the Dutch DSO Alliander, and are based on calculations to achieve the same revenues as under the current tariff system, fulfilling the regulatory principle of cost recovery. In the Alliander setup there is also a 17 kW subscription at a price of 900 Euro, but for the simulated set of households that we consider this was not an ideal choice for any household.

The choice of subscription for each household is based on the simulated one-month load profile. For each household, we compute the cost of each tariff choice for the complete load curve and assign the best choice with the lowest resulting total cost to this household (based on the load profile before adding an EV). Note that currently we use only one month of simulated data, but the tariff cost is for a whole year. Thus, we compute the total exceedance fee for each household for the month where we have data and multiply it by 12 to get an estimate of the total exceedance fee for the whole year.

Table 2: Capacity Subscription Tariff Parameters and number of households for each subscription level in the data sample

Subscribed Capacity in kW	Cost in Euro per Year	Exceedance price Euro per kWh	Households in data sample
2	192	0.50	37
4	252		61
8	480		2

## V. RESULTS

The results of our simulation runs are summarized in Figs 1-3. Fig. 1 shows the household load and EV charging load for a single random draw for each of the four different modeling cases over two nights, starting at 16:30 on the first day and ending at noon on the third day. It is clear to see how unconstrained charging up to the charging capacity (top row) leads to dangerous overloading of the transformer in situations of high simultaneity, even at relatively low numbers of EVs already (15 EVs for 100 households here). When charge-on-arrival is used, the effect of simultaneity is diluted a bit due to the randomized arrival times for each household. In individual optimization by smart charging companies on the other hand, the simultaneity factor of EVs is 100%, as they all charge at the time of lowest wholesale prices. In a realistic setting, the charging load of many EVs over many different areas that sign up with a smart charging company would likely lead to a feedback on the wholesale price and thus could lead to some spreading out of the charging over the lowest-price hours. However, the simultaneity of EVs charging during these hours would still be very high [22]. In the Fig. 2, we can see that using the capacity subscription tariff model strongly reduces the danger of transformer overloading. Even though there are now more than twice as many EVs as before (35), there are only a few time steps where the transformer is at its maximal rated capacity. On the other hand, we can also see that charging is more spread out over the night, even though the transformer is not used to full capacity at the lowest priced hours due to the limitation to subscribed capacity. This shows that some efficiency is sacrificed in favor of simplicity.

Fig. 3 shows the maximal transformer loading percentage as a function of the number of EVs. For every number of EVs we

<sup>2</sup> [https://platform.elaad.io/analyses/ElaadNL\\_opendata.php](https://platform.elaad.io/analyses/ElaadNL_opendata.php)

<sup>3</sup> <https://www.eex.com/en/market-data>

<sup>4</sup> <https://gridx.de/solutions/smart-charging/>

<sup>5</sup> <https://www.jedlix.com/en/>

averaged over 20 realizations of the random assignments of EVs to households and demand patterns in order to get a smoother curve. Even after this smoothing, we can still see the influence of randomly assigning EV charge requirements in the raggedness of the curves. Furthermore, there are marked differences between the charge-on-arrival and individual optimization behaviors. In charge-on-arrival the load peak depends strongly on when the majority of EV owners come home, thus especially the curve flat tariff result shows a large variance. In individual household optimization, the wholesale prices induce maximum simultaneity. However, since the lowest prices are observed at night, this occurs against a background of low demand, leading to lower peaks overall. This shows that it is hard to predict what exactly the influence of adding EVs to the maximal grid load is – it depends strongly on the characteristics of the households charging demands and in particular their arrival time relative to network peak load. However, it is clear that the introduction of the capacity subscription model in both cases substantially reduces the peak network load and thus enables the network operator to keep the same infrastructure in place for longer until overloading occurs.

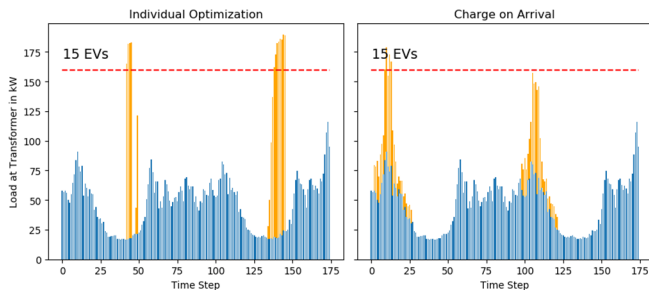


Figure 1: charging of 15 EVs with flat tariffs. Blue bars: household load without EVs over a span of two nights. Orange bars: charging load of randomly assigned EVs. Red dashed line: transformer rated power maximum. Time steps are in 15 minutes and starting time is 16:30 on a Monday in January.

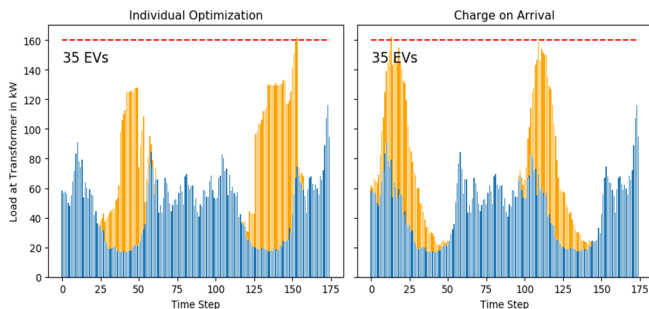


Figure 2: charging of 35 EV's with capacity subscription tariffs. Coloring same as Fig 1.

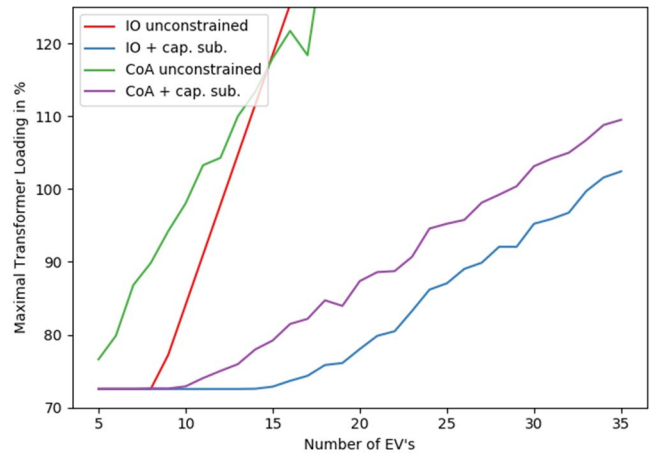


Figure 3: Maximal load at the transformer in % of transformer rated capacity (100% = 160 kW) for the four scenarios. Results are averaged over 20 random realizations of EV constraints (see section 4.) for each number of EVs. IO: Individual Optimization. CoA: Charge on Arrival.

## VI. CONCLUSION

We have described a new class of electric distribution network tariffs that is being discussed by Dutch DSOs as a model for the next regulatory period – network capacity subscriptions. We have assessed these tariffs in terms of the standard regulatory principles for network tariffs and argue that they are more cost reflective than the existing fixed charges in the current situation where EVs are becoming more prevalent. We have further demonstrated the proposed tariff structure in a simulation of 100 households and showed how it reduces network congestion when more EVs are added to the system.

In future work, we plan to include more elaborate load models as the model currently uses a simulated set of household consumption patterns that do not account for any changes in non-EV consumption introduced by the tariffs. We will also investigate how this tariff structure can be amended in order to accommodate even higher numbers of EVs and incorporate a treatment of PV feed-in and communal batteries in the analysis.

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