Dynamic Grid Tariffs for Electric Vehicle Charging: Results from a Real-World Experiment

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Abstract—**Shifting the charging demand of electric vehicles away from peak load times is regarded as one of the most important challenges to keeping electricity grids operational. One way to achieve this is through dynamic grid tariffs. Dynamic grid tariffs provide a financial incentive to charge point operators and EV owners to move the charging demand of electric vehicles to moments at which the grid is not congested. In this work, a novel stacked dynamic grid tariff system is proposed. This grid tariff system is applied to electric vehicle charging in a large-scale, real-world experiment. This experiment is conducted at >150 low-voltage grids and >300 public charging stations in the city of Utrecht, the Netherlands. This work provides insight into the practical potential of mitigating grid congestion problems by reporting the results of the experiment for five grids. The results of this experiment are that the share of time with grid congestion is reduced by 21% compared to uncontrolled charging. In addition, model simulations have been performed to analyze the theoretical potential of the proposed system in contributing to the mitigation of grid congestion problems. Theoretically, the share of time with grid congestion can be reduced to 0.9% of the time, but the difference with day-ahead market optimization without considering grid tariffs is marginal. Furthermore, the results of this study show that the effectiveness of the grid tariff system can be considerably increased if no minimum charging current for EV charging is required.**

Index Terms—**Electric Vehicles, Dynamic Grid Tariffs, Pilot, Grid Congestion**

I. INTRODUCTION

The ongoing energy transition will put considerable stress on low-voltage (LV) electricity grids, operated by distribution system operators (DSOs) [1], [2]. On the one hand, the electricity generation system will become more decentralized, due to the introduction of photovoltaic (PV) systems. On the other hand, energy and transport systems will be increasingly electrified, for instance through the introduction of electric vehicles (EV) chargers and heat pumps (HPs) into the LV grid. Both trends will considerably increase the power flows through LV grids.

Currently, most LV grids cannot manage these extra power flows; a large share of the LV grids was installed long ago, and the rapid energy transition we are currently undergoing could not be foreseen when designing these grids. As a consequence, DSOs are increasingly exposed to the risk of grid congestion in their LV grids, potentially inducing blackouts.

Traditionally, DSOs solved grid congestion problems by reinforcing the grid. However, it is undesirable to apply this solution on a large scale with the further integration of EVs, HPs and PV systems into our electricity grid. First, grid reinforcements are expensive, resulting in high societal costs [3]. Second, many DSOs have too few technically-skilled personnel to reinforce all LV grids in a short time span [4].

Alternatively, grid congestion can be avoided by using the flexibility of different distributed energy resources (DERs). In particular, the charging of EVs is highly flexible; there is considerable room to shift the charging demand over time without compromising the user comfort at departure. EV smart charging has received wide attention in scientific literature and can be used for a wide range of applications. For grid operators, smart charging can help in mitigating grid congestion problems [5]. When considering congestion at the LV/Medium Voltage (MV) transformer level, EV smart charging is the most cost-effective method to mitigate congestion problems [6].

The main challenge for DSOs is to assure that the flexibility of EV charging is released for the mitigation of grid congestion, and not for other applications that do not benefit the grid. Different systems have been proposed to achieve this. Some studies have proposed methods in which the available charging power for EVs is reduced at moments with a high transformer load, using both static [7], [8] and dynamic [9] profiles. Similarly, different local flexibility markets have been proposed, in which DSOs purchase flexibility offered by different market participants in case of grid congestion [10], [11].

A third option is to change the grid tariff structure to unlock the flexibility of EVs for the mitigation of grid congestion. Grid tariffs are paid to the grid operator for the transmission of electricity. In most countries, the grid tariffs for smaller grid connections, such as EV charging stations, are currently flat and time-independent [12]. The introduction of dynamic grid tariffs, in which grid tariffs are higher at moments with a high grid load and lower at moments with a low grid load, could provide a financial incentive to charge point operators (CPOs)

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and EV owners to shift their charging demand to moments with low grid congestion. In this way, grid congestion problems induced by EVs can be reduced.

As outlined in the literature review performed by [13], dynamic grid tariffs can be implemented in a wide variety of forms. In [14], a system is proposed in which the grid tariffs for EV charging were based on the locational marginal price. Ref. [15] compared a static grid tariff with a capacity subscription grid tariff model in Norway. Ref. [16] proposed a grid tariff system in which the grid tariffs were based on the square of the load of a grid connection.

This study will expand on the current literature on dynamic grid tariffs for EV charging. It proposes a new stacked grid tariff design for EV charging and other flexible assets. This grid tariff design is implemented and tested in a large-scale smart charging experiment, conducted on a large number of public charging stations in the city of Utrecht, the Netherlands. In this experiment, the charging costs of EVs were minimized when considering day-ahead market prices for electricity and the dynamic grid tariffs. This work reports the results of this experiment. In addition, model simulations are conducted in this work to get insight into the theoretical potential of the proposed system in mitigating grid congestion problems.

The contributions of this work are as follows:

1) The presentation of a novel grid tariff design that is simple and effective in the mitigation of grid congestion problems;
2) Results of the world's first large-scale experiment on the implementation of dynamic grid tariffs for EV charging in a real-world environment;
3) Insight into both the theoretical and real-world potential of mitigating transformer congestion using dynamic grid tariffs.

Section II describes the proposed grid tariff system in this work. Subsequently, an optimization model to schedule EVs using the proposed grid tariff system is proposed in Section III. The real-world experiment using the proposed grid tariff system is described in Section IV and the simulation outline is presented in Section V. Results are presented in Section VI. Lastly, the discussion and conclusion are presented in Sections VII & VIII.

II. SYSTEM AND GRID TARIFF DESIGN

This study proposes a dynamic grid tariff system in which the tariffs for a certain grid connection are directly related to the load of the LV/MV transformer it is connected to. This implies that there is differentiation in the grid tariffs between grid connections in different LV grids. Moreover, the grid tariffs in the proposed system depend on the aggregated demand of all charging stations operated by one CPO and are not determined for individual grid connections, unlike the current grid tariff system.

In the proposed system, a DSO can distinguish a set of $\mathcal{I}$ different grid tariffs (indexed by $i = 0 \dots I$). Based on the forecasted transformer load, the DSO makes a specific capacity available for each tariff to the CPO. In case of a high forecasted transformer load, the CPO can only charge for a high grid tariff, while at a low forecasted transformer load, the CPO has a specific capacity available ($\mathrm{P}_{\max,i}$) to charge for a low grid tariff at the considered timestep. If the aggregated charging demand exceeds this capacity, a higher grid tariff applies for this exceedance.

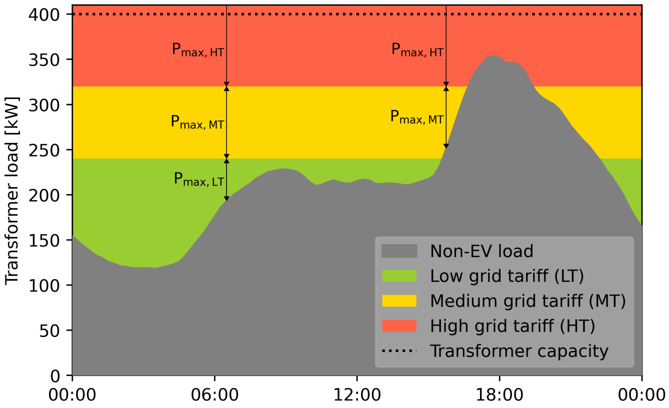

Fig. 1. Example of the proposed stacked grid tariff design when considering a 3-tariff system which is based on the transformer loading. The arrows show the available capacity for the low, medium and high grid tariff at different timesteps. Note that in this example, there is no constraint on the available capacity for the high grid tariff.

The following steps are executed in this grid tariff system:

1) The DSO forecasts the base load of each LV/MV transformer (i.e., total load without the EV load) for each timestep of the day;
2) Based on the forecasted transformer load, the DSO determines the available capacity for each grid tariff ($\mathrm{P}_{\max,i}$) for each CPO at each timestep;
3) The DSO communicates the available capacity for each grid tariff at each timestep to the CPO through an API;
4) The CPO optimizes the charging schedules of their EV fleet based on the available capacity per grid tariff and on the day-ahead market prices for electricity.

Fig. 1 presents an example of a 3-tariff system for one LV-grid. In this system, only one CPO is present in the considered grid, and the available capacity to the CPO for each grid tariff is based on the transformer loading (as a percentage of the transformer capacity).

Unique of this proposed system is that it avoids a delayed EV charging peak. In a grid tariff system in which there are no limits on the available capacity for low grid tariffs, the whole charging demand of EVs might be delayed to the first moments at which low grid tariffs apply, inducing a new EV charging peak. By limiting the available capacity for low grid tariffs at specific moments, the charging peaks will be limited.

III. OPTIMIZATION MODEL

This section presents an optimization model to optimize the charging schedules of an EV fleet when considering the proposed grid tariff system and day-ahead electricity prices.

$$\min_{\substack{\mathrm{C_{DA}},\mathrm{C_{GT}},\mathrm{P}_{\mathrm{tot},t},\\ \mathrm{P}_{i,t},\mathrm{P}_{\mathrm{ch},n,t},\phi_{n,t},}} \quad \mathrm{C_{DA}} + \mathrm{C_{GT}} \tag{1a}$$

$$\text{s.t.} \quad \mathrm{C_{DA}} = \sum_{t=0}^{T} \mathrm{P}_{\mathrm{tot},t} \mathrm{c}_{\mathrm{DA},t} \Delta \mathrm{t}, \tag{1b}$$

$$\mathrm{C_{GT}} = \sum_{t=0}^{T} \sum_{i=0}^{I} \mathrm{P}_{i,t} \mathrm{c}_{\mathrm{GT},i,t} \Delta \mathrm{t}, \tag{1c}$$

$$0 \leq \mathrm{P}_{i,t} \leq \mathrm{P}_{\mathrm{max},i,t} \ \forall i, t, \tag{1d}$$

$$\mathrm{P}_{\mathrm{tot},t} = \sum_{i=0}^{I} \mathrm{P}_{i,t} \ \forall t, \tag{1e}$$

$$\mathrm{P}_{\mathrm{tot},t} = \sum_{n=0}^{N} \mathrm{P}_{\mathrm{ch},n,t} \ \forall t, \tag{1f}$$

$$\sum_{t=\mathrm{t}_{\mathrm{arr},n}}^{\mathrm{t}_{\mathrm{dep},n}} \mathrm{P}_{\mathrm{ch},n,t} \Delta \mathrm{t} = \mathrm{E}_{\mathrm{dem},n} \ \forall n, \tag{1g}$$

$$\mathrm{P}_{\mathrm{min},n} \phi_{n,t} \leq \mathrm{P}_{\mathrm{ch},n,t} \leq \mathrm{P}_{\mathrm{max},n} \phi_{n,t} \ \forall n, t, \tag{1h}$$

$$\phi_{n,t-1} \geq \phi_{n,t} \ \forall n, t, \tag{1i}$$

$$\phi_{n,t} \in \{0, 1\} \tag{1j}$$

The objective of this model in (1a) is to minimize the sum of the day-ahead market costs ($\mathrm{C_{DA}}$) and the grid tariffs ($\mathrm{C_{GT}}$). $\mathrm{C_{DA}}$ is defined in (1b), where $\mathrm{P}_{\mathrm{tot},t}$ resembles the total charging demand of all EVs at time t, $\mathrm{c}_{\mathrm{DA},t}$ is the day-ahead price at this time, $\Delta\mathrm{t}$ is the timestep duration and $\mathcal{T}$ (indexed by $t = 0 \ldots T$) is the set of timesteps in the assessment timeframe. $\mathrm{C_{GT}}$ is determined according to (1c). In this equation, the total charged power at grid tariff i ($\mathrm{P}_{i,t}$) is multiplied with the corresponding grid tariff ($\mathrm{c}_{\mathrm{GT},i,t}$) for each grid tariff in $\mathcal{I}$. In (1d), $\mathrm{P}_{i,t}$ is limited by the maximum available capacity for this specific grid tariff. The total charging power ($\mathrm{P}_{\mathrm{tot},t}$) is equal to the summed total charging power for each grid tariff in (1e). $\mathrm{P}_{\mathrm{tot},t}$ is in (1f) also equal to the summed charging power of each individual charging transaction ($\mathrm{P}_{\mathrm{ch},n,t}$) in the set of charging transactions $\mathcal{N}$ (indexed by $n = 0 \ldots N$). (1g) assures that the charging demand ($\mathrm{E}_{\mathrm{dem},n}$) of each individual charging transaction is met at departure, where $\mathrm{t}_{\mathrm{arr},n}$ and $\mathrm{t}_{\mathrm{dep},n}$ represent the arrival and departure time of transaction n, respectively. $\mathrm{P}_{\mathrm{ch},n,t}$ is constrained by the minimum and maximum charging power of the respective charging transaction ($\mathrm{P}_{\mathrm{min},n}$ & $\mathrm{P}_{\mathrm{max},n}$) in (1g). A minimum charging power is considered in the analysis to account for the fact that many EV models need to be charged continuously above a specific minimum charging power to prevent it from turning to idle mode, at which it does not respond to charging signals anymore. The binary variable $\phi_{n,t}$ assures in (1g) that the EV charging power is between $\mathrm{P}_{\mathrm{min},n}$ and $\mathrm{P}_{\mathrm{max},n}$, or 0 otherwise. Lastly, (1i) assures that once an EV stops charging, it does not restart charging at a later moment.

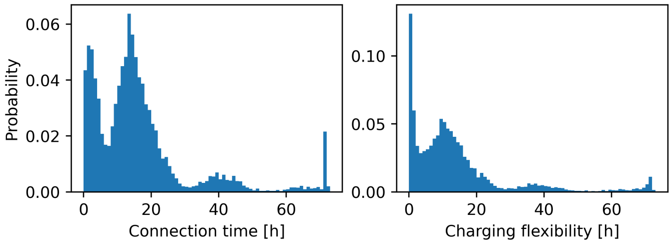

Fig. 2. Distribution in connection times to the charging station and the charging flexibility (i.e., the difference between connection time and required charging time to meet the charging demand) for all controlled charging transactions in the experiment.

IV. SMART CHARGING EXPERIMENT USING DYNAMIC GRID TARIFFS

The FLEET project is one of the world's first large-scale real-world experiments for using dynamic grid tariffs for EV charging. In this research project, the proposed grid tariff system in this work is applied to >300 public charging stations from the CPO *We Drive Solar* at >150 LV-grids in the city of Utrecht, the Netherlands. The dynamic grid tariffs are determined by the local DSO *Stedin*. The aggregator company *Enervalis* optimizes the EV charging schedules at the *We Drive Solar* public charging stations. This experiment is fully operational since January 2021 and the dynamic grid tariff system has been applied to >90,000 charging transactions. In this work, the outcomes of this experiment are presented from 1 April 2022 (to account for startup problems) for 5 grids, hosting 28 public charging stations with two charging points per station. 73.3% of the charging transactions were controlled in this experiment. The remaining charging transactions were from guest users. Fig. 2 presents the distribution of connection times and charging flexibility of the controlled charging transactions in the experiment.

The 3-tariff grid tariff system from Fig 1 was considered in this experiment. In this stacked tariff system, the grid tariffs for EV charging depend on the sum of the forecasted transformer load (excl. EV charging) and the EV charging load in relation to the transformer capacity. Transformer loadings of 60% and 80% of the transformer capacity were the switching points from the low grid tariff (0.00 €/kWh) to the medium grid tariff (0.012 €/kWh), and the medium grid tariff to the high grid tariff (0.04 €/kWh), respectively. This means that a CPO can charge at a low grid tariff until the total transformer loading reaches 60%, after which it has to pay the medium grid tariff for all extra EV charging until 80% transformer loading.

As the current EV penetration rates do not induce transformer congestion problems yet, a virtual transformer capacity has been used in this experiment. This virtual capacity equals 110% of the highest forecasted value of the transformer load excluding EV charging in the next 72 hours. Forecasts of the transformer load were performed by the DSO using a boosted tree model based on historical transformer loads and weather forecasts (most notably wind speed and solar strength). The load forecasting is done excluding known EV charging to correctly determine available EV charging capacity.

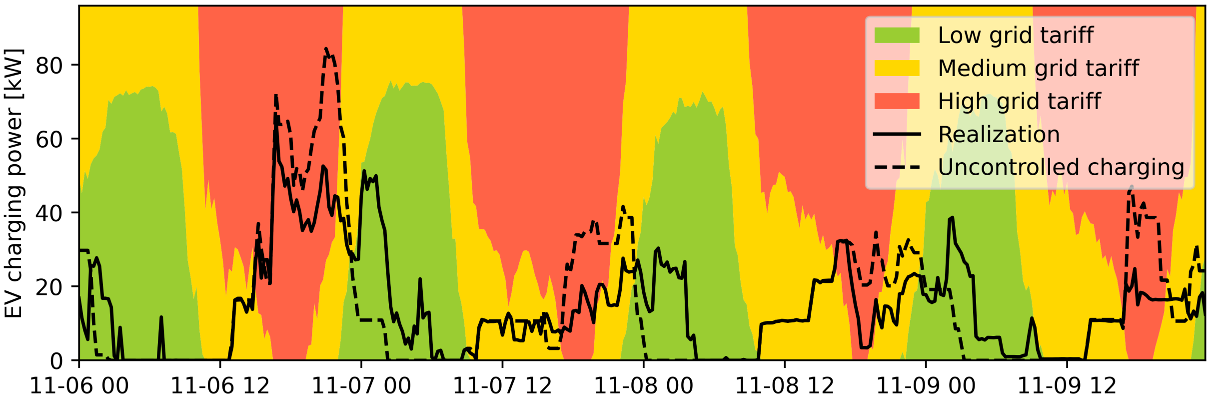

Fig. 3. Example of the realized charging patterns using smart charging in the considered experiment and the charging patterns in case of uncontrolled charging for one LV grid for four example days.

The EV charging schedules in this experiment were cost-optimized, considering both the day-ahead electricity price for the Netherlands and the grid tariffs in the proposed system. In order to perform the cost optimization, the departure time and energy demand of each connected EV were forecasted at each time step. Every 10 minutes, the forecast and charging schedules were updated. No forecasts were made on the number of EVs arriving in the next timesteps. To reduce the risk of EVs turning to idle mode, EVs were charged with a minimum charging current of 8 amperes until 15 Aug 2022. Since no major problems occurred, the minimum charging current was reduced to 6 amperes after this date. Also, a conservativeness factor was considered in the cost optimization to reduce the impact of smart charging on user comfort. Charging transactions of guest users (i.e., EVs that did not charge regularly at those charging stations, less than 4 charging sessions in total, or less than on average <0.3 charging sessions/week) were excluded from the cost-optimization.

V. ANALYSIS OUTLINE

To compare the realized impact of the proposed grid tariff system with the impact that could be achieved theoretically, the optimization model presented in Section III is applied to the considered charging transactions in the experiment. Also in the model simulations, guest users were excluded from the optimization. To account for the uncertainty in the future number of charging transactions, a rolling-horizon optimization approach was used in the model simulations, in which only the charging transactions connected to a charging station at a specific timestep were considered in the optimization. Minimum amperages of 0, 6 and 8 amperes were considered in the model simulations, to find the impact of this minimum amperage on the effectiveness of the considered grid tariff scheme. Simulations were performed in Python using Gurobi.

The realized and simulated charging schedules are compared with the charging schedules in case of uncontrolled charging and in case of day-ahead market optimization without considering grid tariffs.

TABLE I
SHARE OF THE CHARGING DEMAND (IN KWH) MET AT THE DIFFERENT GRID TARIFF CATEGORIES FOR DIFFERENT SCENARIOS FOR ALL CONSIDERED TRANSFORMERS.

	Uncontrolled charging	**Realization**	**Model simulations: day-ahead optimization with grid tariffs**	**Model simulations: day-ahead optimization without grid tariffs**
Lowest grid tariff category	25.5%	33.2%	41.1%	39.8%
Middle grid tariff category	40.6%	38.7%	37.0%	37.1%
Highest grid tariff category	34.0%	28.1%	22.0%	23.1%

VI. RESULTS

A. *Results of the experiment*

Fig. 3 presents the realized charging patterns in the project and the charging patterns if uncontrolled charging would have been applied for four example days for one transformer. From the figure can be observed that the realized charging patterns considerably deviate from the uncontrolled charging patterns. It is clearly visible that the charging demand in this project is shifted away from moments with high transformer loading, marked by the red area, to moments with low transformer loading, marked by the green area. Not all charging demand is shifted to moments with low transformer loading, as i) guest users were excluded from the optimization, ii) EVs need to be charged with a minimum charging current and iii) some EVs need to be charged at moments with high transformer loading to be fully charged at departure.

The shift away from moments with high transformer loading can also be observed in Table I, which shows the share of the EV charging volume that is met in each grid tariff category for different charging scenarios. The charged volume in the highest grid tariff is an indicator for the charged volume at moments with high transformer loading, since this grid tariff applies when the transformer loading is above 80% of the transformer capacity. The realized charged volume in the highest grid tariff is 17.3% (i.e., 5.9 percent point) lower than the charging volumes in this grid tariff with uncontrolled EV charging.

The effectiveness of the experiment in reducing grid congestion can be determined from Fig. 4, which portrays a load

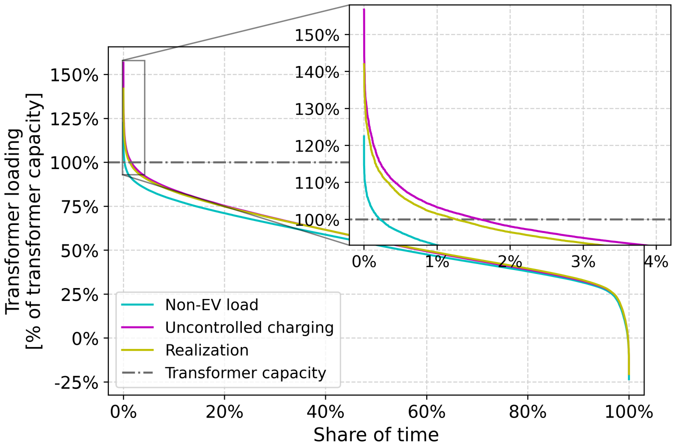

Fig. 4. Load duration curve of the transformer loading for all considered transformers for three scenarios: i) non-EV transformer loading, ii) uncontrolled EV charging, iii) realized EV charging patterns.

duration curve of the transformer load for three scenarios: i) no EV charging, ii) uncontrolled EV charging and iii) realized EV charging patterns. It is visible that even without EV charging, the virtual transformer capacity is exceeded for 0.2% of the time. This can be solely attributed to forecasting errors in the non-EV transformer load. The share of time with congestion (i.e., a transformer loading of >100% of the virtual transformer capacity) is reduced by 21%, from 1.6% of the time with uncontrolled charging to 1.3% of the time with the realized charging schedules in the project.

B. *Results of model simulations*

The results of the model simulations are presented in Fig 5. The share of time with grid congestion is considerably lower with the simulated charging patterns compared to the realized charging patterns (0.9% and 1.3% of the time, respectively). This discrepancy can mostly be attributed to the perfect foresight in the charging demand and departure time of EV charging transactions in the model simulations. In practice, there was uncertainty about the departure time and charging demand of EV charging transactions and conservativeness had to be included in the optimization of charging schedules to assure that the EV charging demand is sufficiently met at departure. In addition, EVs do not always adequately respond to charging signals in practice. This effect was not captured in the model simulations.

The added value of the use of grid tariffs can be determined by comparing the load duration curve of the model simulations which consider both day-ahead prices and grid tariffs with the load duration curve of the model simulations which only consider day-ahead prices in Fig 5. The share of time with transformer congestion is only marginally lower for the model simulations that do consider the proposed grid tariff scheme (0.9% and 1.0% of the time, respectively). At most moments, cost-optimization of EV charging based on day-ahead prices already causes EV charging to be shifted away from peak transformer loading moments, as these peaks generally coincide with high day-ahead market prices. Also, the setup of the proposed grid tariff system considered in this experiment is not perfectly efficient. A high grid tariff applies to a forecasted transformer loading above 80% of the transformer capacity. Once the transformer loading has exceeded this 80% threshold, there is little incentive to reduce the peak charging power of charging transactions with relatively low charging flexibility to avoid the transformer loading exceeding the transformer capacity. A different setup, for instance through the introduction of an extra grid tariff category for a transformer loading above e.g. 95% of the transformer capacity, could increase the added value of the proposed grid tariff system.

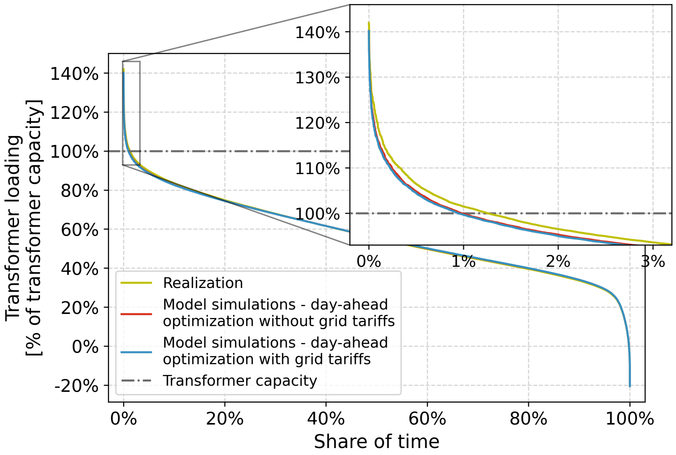

Fig. 5. Load duration curve of the transformer loading for all considered transformers for three scenarios: i) realized EV charging patterns, ii) model simulations without considering grid tariffs, iii) model simulations with considering grid tariffs.

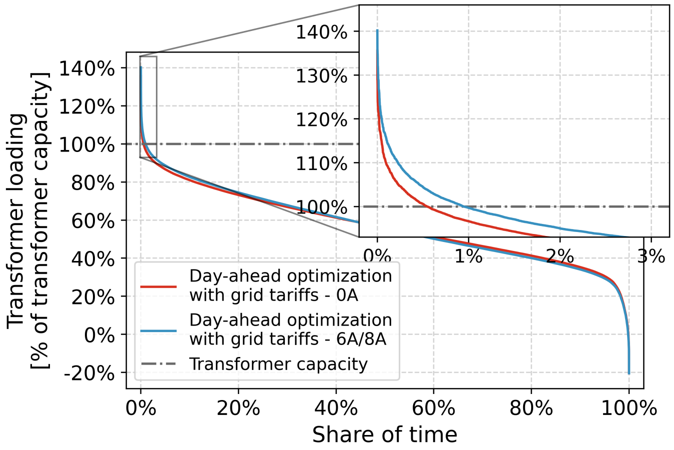

Fig. 6. Load duration curve of the transformer loading for all considered transformers for two scenarios: i) model simulations with a minimum charging current of 0 amperes ii) model simulations with a minimum charging current of 8 amperes (until 15 August 2022) and 6 amperes (after 15 August 2022).

C. *Importance of the minimum required charging current*

As explained in Section V, a minimum charging current of 8 amperes (until 15 August 2022) and 6 amperes (after 15 August 2022) was considered in the optimization of EV charging schedules in this experiment, to avoid that EVs turn to idle mode and do not respond to charging signals anymore. Fig. 6 shows the impact of this minimum charging current on the effectiveness of the proposed grid tariff system. It displays the load duration curves of the model simulations with a minimum charging current of 0 amperes on the one hand, and the considered minimum charging currents in the project on the other hand. When no minimum charging current is considered, the share of time with congestion is almost halved, from 0.9% of the time to 0.5% of the time. The large impact of this minimum charging current on the effectiveness of the proposed grid tariff system can be explained by the fact that EVs are forced to charge at moments with high transformer load. Hence, more grid congestion can be expected if a minimum charging current needs to be considered.

VII. DISCUSSION

Different aspects should be considered when interpreting the results of this work. First, a virtual transformer capacity was used in this work. The considered transformer capacity was independent of the number of charging stations in the grid and was reduced in this study to be able to simulate congestion also during lower congestion times, e.g. in summer. Therefore, the congestion levels reported in this study do not represent the expected future transformer congestion levels.

In addition, the design of the proposed grid tariff scheme was not optimized in this experiment. Variations in the number of considered grid tariffs, the value of the specific grid tariffs, and the capacity limits of each grid tariff could improve the effectiveness of the proposed system. As discussed in Section VI, it is strongly advised to introduce a higher grid tariff when the total load almost exceeds the transformer capacity.

It is unsure whether the regulators will allow the grid tariff system proposed in this work. Besides the effectiveness of a grid tariff scheme in reducing grid congestion, regulators also consider other principles, including their cost-reflectiveness, the non-distortionary principle and the non-discrimination principle [17]. Future work should look into the performance of the proposed grid tariff system at those values, for instance using the methods proposed in [18].

Lastly, future work should address how vehicle-to-grid services can be included in the proposed grid tariff system.

VIII. CONCLUSION

This work has presented a novel dynamic grid tariff system for EV charging. This grid tariff system has been tested in one of the world's first large-scale experiments with dynamic grid tariffs for EV charging. The share of time of virtual transformer congestion was reduced by 21%, from 1.6% of the time with uncontrolled charging to 1.3% in this experiment. Model simulations indicated that in theory, the share of time with transformer congestion could be further reduced, but that difference in results with day-ahead market optimization without considering dynamic grid tariffs is minor. With further optimization of the design of the specific grid tariff structure, its effectiveness could increase.

Moreover, the results showed that the required minimum charging power for EV charging has a considerable impact on the effectiveness of the proposed scheme in mitigating congestion problems. Therefore, it is of high importance that EVs are technically capable to pause their charging session. Therefore, it is recommended that future research studies how this can be achieved most effectively.

REFERENCES

[1] B. Thormann and T. Kienberger, "Evaluation of grid capacities for integrating future E-Mobility and heat pumps into low-voltage grids," *Energies*, vol. 13, no. 19, 2020.

[2] J. Von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel, "Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid," *IEEE Power and Energy magazine*, vol. 11, no. 2, pp. 55–64, 2013.

[3] A. S. Sidhu, M. G. Pollitt, and K. L. Anaya, "A social cost benefit analysis of grid-scale electrical energy storage projects: A case study," *Applied Energy*, vol. 212, no. January, pp. 881–894, 2018.

[4] Alliander, "Shortage on the electricity grid affects everyone," 2021. [Online]. Available: https://www.alliander.com/en/news/shortage-on-the-electricity-grid-affects-everyone/

[5] N. Brinkel, T. AlSkaif, and W. van Sark, "Grid congestion mitigation in the era of shared electric vehicles," *Journal of Energy Storage*, vol. 48, no. January, p. 103806, 2022.

[6] N. Brinkel, W. Schram, T. AlSkaif, I. Lampropoulos, and W. v. Sark, "Should we reinforce the grid? Cost and emission optimization of electric vehicle charging under different transformer limits," *Applied Energy*, vol. 276, no. October, p. 115285, 2020.

[7] P. C. Bons, A. Buatois, G. Ligthart, F. Geerts, N. Piersma, and R. van den Hoed, "Impact of smart charging for consumers in a real world pilot," *World Electric Vehicle Journal*, vol. 11, no. 1, pp. 1–21, 2020.

[8] M. Verhoog, N. Brinkel, and T. Alskaif, "Congestion management in LV grids using static and dynamic EV smart charging," *SEST 2020 - 3rd International Conference on Smart Energy Systems and Technologies*, 2020.

[9] P. C. Bons, A. Buatois, F. Schuring, F. Geerts, and R. van den Hoed, "Flexible charging of electric vehicles: Results of a large-scale smart charging demonstration," *World Electric Vehicle Journal*, vol. 12, no. 2, 2021.

[10] T. Schittekatte and L. Meeus, "Flexibility markets: Q&A with project pioneers," *Utilities Policy*, vol. 63, no. January, p. 101017, 2020.

[11] T. Dronne, F. Roques, and M. Saguan, "Local Flexibility Markets for Distribution Network Congestion-Management in Center-Western Europe: Which Design for Which Needs?" *Energies*, vol. 14, no. 14, p. 4113, 2021.

[12] European Union Agency for the Cooperation of Energy Regulators (ACER), "ACER Report on Distribution Tariff Methodologies in Europe," Tech. Rep. February, 2021.

[13] K. Christensen and Z. Ma, "Technical, Economic, Social and Regulatory Feasibility Evaluation of Dynamic Distribution Tariff Designs," *Energies*, vol. 14, no. 10, p. 2860, 2021.

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

[15] S. Backe, G. Kara, and A. Tomasgard, "Comparing individual and coordinated demand response with dynamic and static power grid tariffs," *Energy*, vol. 201, p. 117619, 2020. [Online]. Available: https://doi.org/10.1016/j.energy.2020.117619

[16] S. Huang, Q. Wu, M. Shahidehpour, and Z. Liu, "Dynamic power tariff for congestion management in distribution networks," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 2148–2157, 2019.

[17] Council of European Energy Regulators (CEER), "Electricity Distribution Network Tariffs - CEER Guidelines of Good Practice," Tech. Rep. January, 2017. [Online]. Available: https://www.ceer.eu/documents/104400/-/-/1bdc6307-7f9a-c6de-6950-f19873959413

[18] R. J. Hennig, D. Ribó-Pérez, L. J. de Vries, and S. H. Tindemans, "What is a good distribution network tariff?—Developing indicators for performance assessment," *Applied Energy*, vol. 318, no. April, p. 119186, 2022.