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# EV Tariff Design Can Optimize Grid Resources and Save Drivers Money — Selected Examples and Lessons Learned from the U.S. and Europe

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**Summary**

This paper identifies lessons learned from successful utility tariffs and programs that enable beneficial EV grid integration in the United States (U.S.) and Europe: the design of time-varying electricity tariffs for specific electric vehicle use cases (e.g., residential, workplace) as well as strategies to ensure that the potential benefits of these tariffs are realized. The paper offers best-practice insights from U.S. states and European countries and concludes with high-level policy insights that are relevant across these regions.

*Keywords: charging, electric vehicle (EV), electric vehicle supply equipment (EVSE), regulation, policy*

## 1 Introduction

The way electric vehicles (EVs) will be charged, and how charging infrastructure will be deployed, will determine the environmental and economic benefits that EV users, and ultimately all electricity users, can reap from transport sector electrification. Previous research has shown how managed EV charging through direct controls or pricing can make efficient use of grid capacity, optimally exploit EVs as a flexible resource for the power grid, bring down system costs and encourage use of renewable electricity [1]. Evidence also suggests that without policy tools or incentives to encourage otherwise, EV users will charge when it is most convenient for them, without regard to grid impacts, often leading to costly consequences such as an exacerbation of existing peaks [2]. One of the tools found to be effective are electricity tariffs specifically designed to encourage EV users to charge at optimal times for the grid [3]. However, it is less well known how the effectiveness and optimal design of EV tariffs varies according to the ways electric vehicles are charged.

This paper compiles experience from selected EV tariffs across different use cases of light-duty vehicle charging, covering residential charging, charging in multi-unit dwellings, at workplaces and commercial areas and public fast charging, which together represent the vast majority of EV charging. It discusses lessons from consumer response where data are available. Comparing U.S. and European markets, this paper describes lessons that are valid across these regions, with implications for electricity grid planning, charging infrastructure deployment and customer-facing technology. The paper concludes that transparent, time-varying tariff designs and integrated infrastructure planning are key to successfully integrating EVs with the grid.

# 2 Tariff Design for Different EV Charging Use Cases

## 2.1 Impact of Tariff Design on EV Charging

Tariff design — the structure and levels of prices that consumers pay for electricity, often referred to as rate design in the U.S. — influences the economics of charging an EV. Thus, it also has an influence on the charging behavior and preferences of EV drivers and the overall economics of owning an EV as compared to a petroleum-powered car. By influencing how and when drivers charge their vehicles, tariff design also influences the impact that EV charging will have on the grid and can be a useful tool to facilitate EV-grid integration. This section examines examples of EV tariff designs from Europe and the U.S. We discuss how different tariff structures have influenced the economics of EV charging and the impact of EVs on the grid. First, we review some key points about tariff design economics, which we illustrate with examples.

Well-designed rate structures will lead to EV charging that is aligned with grid needs, as well as help increase utilization of existing resources and reduce costs for all ratepayers. By contrast, poorly designed rates may lead to increased system costs, which can result in higher rates for all ratepayers. Typical residential tariff structures in the U.S. and Europe consist of a fixed monthly charge and an energy charge (price per kWh of consumption) that is not time-varying — that is, it does not vary over the course of the day. With these rate structures, EV drivers are likely to charge whenever is easiest for them because the cost is the same during all hours. Time-varying rates are better able to communicate that at certain times of the day, power is cheaper to produce and deliver and EV charging is beneficial to grid management because it can increase utilization of grid assets during low-usage hours. Time-varying tariffs include designs that set prices for specific times of day, as well as more dynamic pricing structures that vary daily according to projected wholesale market prices [4].

Tariffs similarly influence the economics of using workplace, commercial and other publicly located chargers, including Level 2 and direct current (DC) fast chargers. In the U.S. and in Europe, the default tariff structure for such chargers includes a demand charge that is applied based on the maximum amount of power that a customer uses during a billing cycle. This structure does not provide good incentives for charging operators (and drivers) to help manage system costs by better managing the timing of charging. In addition, such chargers can effectively become a fixed charge that cannot be avoided, which can lead to a total cost of ownership for EV users that is greater than the costs of gasoline or diesel, eliminating potential economic benefits of electric transportation [5]. They also make it more difficult for charging service providers to build a business case. Our examples review some tariff design options that can more accurately align EV charging with grid needs and improve the economics of EV charging for drivers and service providers.

## 2.2 Use Cases

Time-varying energy tariffs are available across half of the European Union's Member States, mostly in a simple two-time-period structure, for example a day and night tariff [6]. The availability of dynamic tariffs, such as those reflecting the price variation in the spot market, is expected to grow beyond the eight Member States where they currently exist following the advancement of smart-meter rollout across countries and passage of recent enabling legislation [7]. In the U.S., about 50% of utilities offer a time-of-use (TOU) rate option, but their adoption by consumers is limited overall [8]. In both regions there is limited experience applying these tariffs to EVs specifically. In the sections below, we review lessons learned from selected examples from the U.S. and Europe, with empirical data wherever possible, to illustrate the importance of tariff design. For all use cases, we were able to find fewer European empirical examples than for the U.S., likely because monitoring of tariffs is generally less developed in Europe. Most European electricity markets resemble U.S. restructured markets in which only the network (delivery) companies and their prices are regulated. In addition, European regulators do not require the same amount of reporting from regulated companies as their U.S. counterparts, which means less experiential data is available. The availability of information on customer response to prices set by energy suppliers participating in the liberalized wholesale market depends on what evidence those companies choose to release.

### 2.2.1 Residential, Single-Family

Experience from residential tariff design examples in the U.S. and Europe indicate that clear, explicit time-varying rate designs are effective at encouraging EV drivers to charge at optimal times for the grid. The examples highlighted here also point to the usefulness of consumer-facing technology — such as vehicle software systems, programmable chargers and smartphone applications — that helps drivers respond to price signals.

Xcel Energy in Minnesota offers two similar tariff structures that illustrate the above key points. The company's optional Residential EV Charging Service tariff consists of a $4.95 monthly meter charge and per-kWh energy charges of $0.04 during off-peak times (a 12-hour period from 9 p.m. to 9 a.m.) and much higher charges of $0.20 (summer) and $0.17 (nonsummer) during peak times (9 a.m. to 9 p.m.). This steep differential of prices between peak and off-peak hours provides a strong incentive for drivers to charge vehicles overnight. Xcel reports that the monthly percentage of off-peak charging has ranged from 90% to 94% [9]. However, as of April 2019, the company had enrolled only 473 customers in this tariff, representing just 6.7% of all the registered EVs in its service territory [10]. The low participation rate is likely because the tariff requires installation of a second meter at the customer's premises, which can be prohibitively expensive. Xcel has attempted to address this barrier by introducing a second tariff option.

The Residential EV Service Pilot, launched by Xcel more recently, allows customers to use EV charging equipment that is capable of transmitting billing quality data to communicate their on- and off-peak charging behavior to the utility rather than install a second meter. Similar to drivers on the Residential EV Charging Service tariff, participants in the pilot overwhelmingly charge off-peak (96% of all charging was off-peak among these drivers as of April 2019). Xcel reported that the technicians hired to install charging infrastructure in this pilot also confirmed that customers had a functional Wi-Fi connection with the charger and demonstrated to customers how the charger worked, including how to schedule charging [11]. These steps during installation may have contributed to the high off-peak charging rate.

Initial results from a small group of first subscribers to one of the available EV tariffs in Europe, the Octopus Agile tariff, show that EV drivers shifted their charging almost entirely away from the peak hours (4-7 p.m. in Great Britain). One of the features that allowed the average EV driver to save around 132 pounds per year (or around 150 euros) compared with the alternative Octopus Energy 12-months-fixed tariff is that the Agile tariff offers prices that are linked to the half-hourly wholesale market prices, informing consumers about prices for EV charging one day ahead. Details of the design are documented elsewhere [12].

The largest European trial for residential smart EV charging (referred to as the Electric Nation trial), conducted in the United Kingdom between January 2017 and December 2018, confirms tariff design is a powerful tool for shifting EV consumption for a larger customer base. A representative sample of 673 households participated throughout the service area of UK grid company Western Power Distribution in Midwest England. Results show that time-varying pricing encouraged residential EV owners to shift their charging into hours when electricity was less expensive. It offered electricity at peak time prices of 28 pence per kWh from 4:30-7:30 p.m., gradually decreasing to 10 pence per kWh after 10 p.m. [13]. Participants used a smartphone application that allowed them to optimize their charging profile and earn rewards on the tariff. According to GreenFlux, the provider of the smart charging platform in the trial, the phone application contributed to the impact of the trial. Results summarized in Fig. 1 [14] show that the time-varying pricing structure was highly effective at moving demand away from evening hours, helping to avoid the evening consumption peak expected from EV charging.

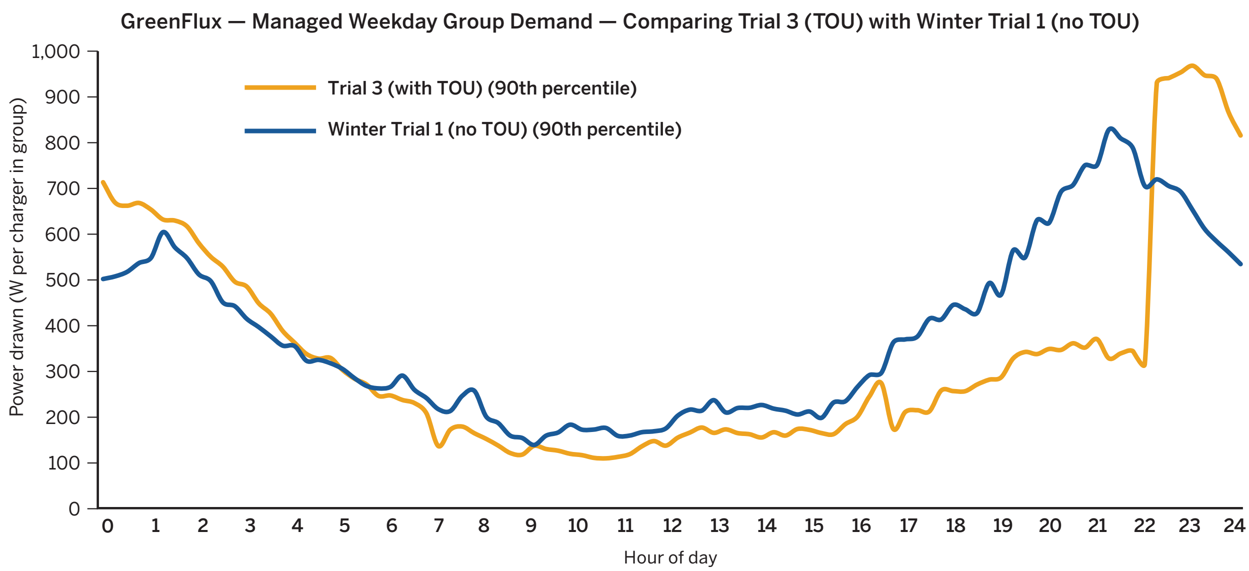


Figure 1: Results from Electric Nation trial

The graph also illustrates that a time-varying tariff can create a spike in EV demand at a new time of day (e.g., around 10 p.m.), due, for example, to a sharp price difference or a technology feature that sets specific charging start times. This may or may not create challenges for local grid operators, depending on EV adoption and grid conditions. Over time, as more EVs are charging in a given geographic area, it will be important to manage this effect through tariff design or some other method. For example, staggering the exact start of the off-peak period for groups of customers can help spread the necessary charging across more of the off-peak hours, while still ensuring all drivers can achieve desired levels of charge. Alternatively, a third party or utility could manage charging start times to avoid negative cost impacts of these new spikes. The example suggests that these kinds of unwanted effects should be considered when designing tariffs and programs.

Evidence from Europe and the U.S. demonstrates that time-varying tariffs are effective at encouraging residential users to charge during off-peak hours. Large price differentials, transparent information and programmable technology can make tariffs even more effective and help consumers benefit from low off-peak pricing.

### 2.2.2 Multi-Unit Dwellings

Governments, charging companies and utilities are working to expand access to charging infrastructure to citizens who live in multi-unit dwellings (MUDs). In 2018, more than 4 out of every 10 people in the EU lived in apartments or flats, which makes access to charging infrastructure for these residents an essential element of widespread transportation electrification [15]. In addition, to ensure the same kinds of grid and customer benefits previously discussed, it will be important to ensure that drivers living in MUDs have access to the same kinds of time-varying tariffs discussed above. A complication for MUDs is that the tariff structure may not be directly communicated to drivers, depending on which entity owns and operates the chargers, which may make the tariff design itself less effective at influencing charging behavior.

Data from different MUD offerings from one California utility illustrate two key lessons: Time-varying rates are effective at encouraging charging during off-peak periods, and communication of cost-based time-varying rates to drivers can ultimately result in lower fuel costs for drivers than some other tariff structure. Available data from experience in Europe is very limited at this point, and as such we focus on U.S. examples to illustrate lessons that could be valuable for European countries.

Southern California Edison (SCE) offers residences, including MUDs, the option of being on a time-varying tariff using a single meter for all the home's electricity usage. The time-of-use periods are designed to accommodate EV charging but apply to all household loads. As of December 2018, SCE reported 3,465 singlemetered EV owners in multifamily units on this tariff. Data on when these households use energy show that they respond to the time-varying rates' price signal. As Table 1 [16] shows, the greatest share of these households' overall usage occurs during the off-peak window (48%), higher than the residential population as a whole (34%). Customers in MUDs have only 16% of their average usage falling in the on-peak window of 2 to 8 p.m.

Table 1: Energy usage patterns for residences on single-meter time-varying rates versus residential population as a whole in SCE territory

| | On-peak TOU (2-8 p.m. all weekdays except holidays) | | | Off-peak TOU (10 p.m.-8 a.m. daily) | | |
|---|---|---|---|---|---|---|
| | All residential | Single-family | MUD | All residential | Single-family | MUD |
| Average share of household energy use by period (September 2017 to December 2018) | 22% | 16% | 16% | 34% | 46% | 48% |

These results can be contrasted with the usage behavior of EV drivers at MUDs participating in a different SCE program, known as the Charge Ready pilot, where evidence indicates that a lack of a visible time-varying price signal for EV drivers has resulted in drivers beginning to charge immediately upon arrival at their destination, as shown in Fig. 2 [17] and discussed below.

A key design feature of the Charge Ready pilot is that site hosts at MUDs are charged a time-varying rate for usage of the chargers, but site hosts are not required to pass that rate signal through to drivers. Instead, site hosts can develop other fee structures to charge drivers, which may or may not be time-varying and may include additional fees. The lack of time-variant price signals seen by drivers has resulted in suboptimal charging behavior, as Fig. 2 shows. During weekdays, EV load grows throughout the afternoon and noticeably jumps during peak hours from 5-8 p.m. In fact, a significant proportion (roughly 40%) of the charging at these sites occurs during the peak window of 2-8 p.m. While some charging does occur during the off-peak hours of 9 p.m. to midnight, it tapers off significantly after 1 a.m. A time-varying price signal that is transparent to drivers could lead to a shift in some of the on-peak charging to the early morning hours when the electric grid is underutilized. As is the case for other use cases discussed in this paper, on-site energy storage could provide additional ability to shift charging times at MUDs, but this is not explored in detail.

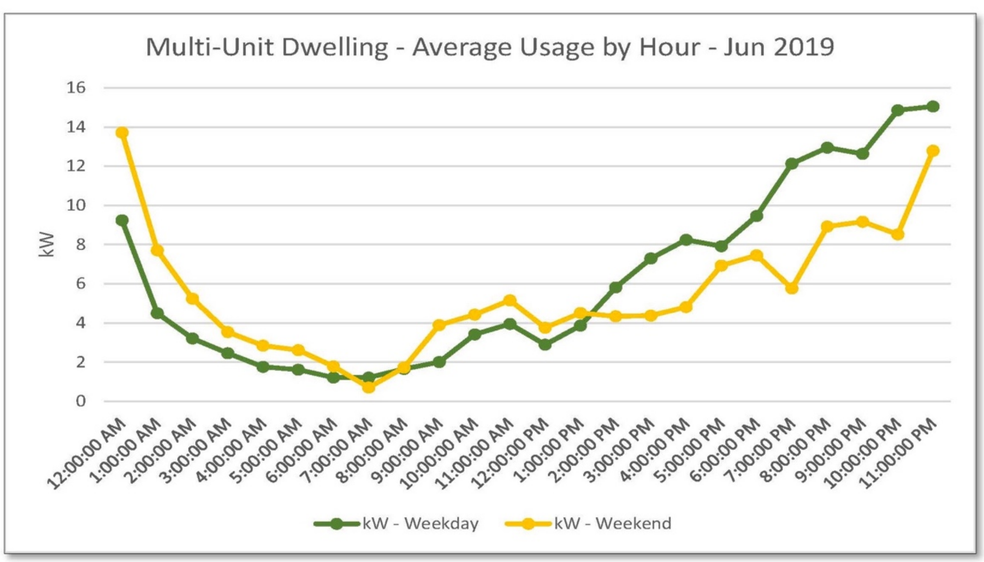


Figure 2: EV charging usage in the SCE Charge Ready pilot (three sites with 35 charging ports)

In addition, the lack of a visible price signal to drivers means they miss an opportunity to take advantage of low-cost electricity in off-peak hours, potentially leading to fuel costs for EVs that far exceed the equivalent fuel cost of a gasoline-powered car. SCE reported that in the Charge Ready pilot, 53% of sites charge fees to drivers based on energy usage, with the average fee charged at $0.76 per kWh. For an EV driver, that is the equivalent of paying $6 per gallon of gasoline [18] — much more expensive than the prices drivers pay on the whole-home time-varying tariff offered discussed above, which are $0.12 and $0.13 per kWh for off-peak charging (the equivalent of $1 per gallon of gasoline).

The evidence from the two SCE programs and tariffs indicates that EV drivers who live in MUDs respond to time-varying pricing in much the same way as drivers in single-family residences. If price signals are transparent, they will charge during less expensive times of the day, which will lead to better integration of EVs with the grid and better economics for EV drivers. In circumstances where it is not possible to directly communicate prices to drivers, some other form of direct load control by an aggregator or utility that ensures the grid and customers benefit from low-cost times may be warranted.

### 2.2.3 Workplace and Commercial

Workplace charging and customer charging at commercial locations such as hotels or sports facilities share some similarities with residential and multi-unit dwelling charging in that drivers tend to spend several hours parked at these locations. This means that there is an opportunity to manage EV charging to the benefit of the grid and EV drivers. Site hosts at both workplace and commercial charging locations will choose whether to pass through price signals to customers, which will influence how well charging can be optimized through tariff design.

Results from San Diego Gas & Electric's (SDG&E's) Power Your Drive (PYD) program illustrate similar points for workplaces and commercial charging as described above for multi-unit dwellings. That is, transparent time-varying prices influence driver charging behavior to be more beneficial to the grid, which helps reduce overall grid costs and improve EV charging economics. These results are summarized in Fig. 3 [19] and described further below.

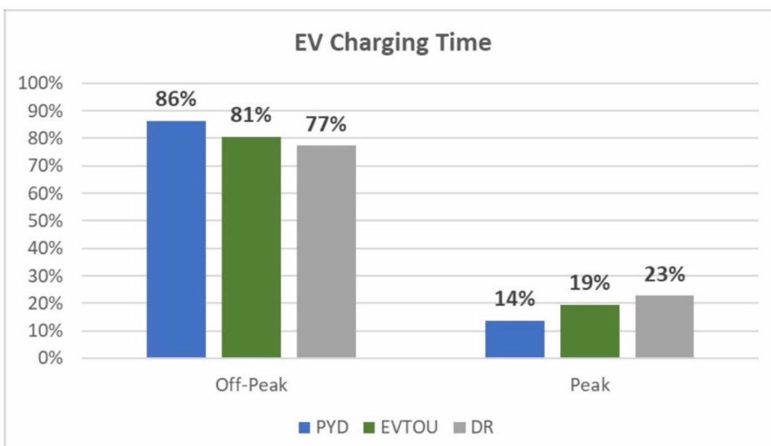


Figure 3: Percent of EV charging load occurring during off-peak and peak hours for three SDG&E rate options

Participating sites in SDG&E's PYD program can either be multi-unit dwellings or workplaces. As of July 31, 2019, 47% of PYD sites were workplaces (120 sites with 1,617 charging ports). The program seeks to integrate charging of EVs with the grid through a day-ahead hourly rate. Site hosts have two billing options: Rate-to-Driver, where the EV driver receives the rate directly, and Rate-to-Host, where the site host receives the rate. Selection of the Rate-to-Host option requires site hosts to submit a load management plan that details how they will discourage on-peak charging. Of site hosts, 74% have opted to pass through the dynamic prices to drivers.

Data from the pilot show that during high pricing events (driven by high temperatures and high cooling loads), workplace PYD EV chargers reduce load compared with what would be expected during those same hours in months with normal pricing [20]. Although the PYD program uses dynamic hourly pricing, which means that the high-priced times change on a daily basis, the charging data can also be displayed according to the peak pricing hours from SDG&E's other time-of-use rates. Fig. 3 shows that the PYD rate (the blue bar) is effective at encouraging charging outside the peak hours of 4-9 p.m. The other two rate options shown in the chart are EVTOU (submetered EV usage) and DR (whole-home usage of EV drivers).

SDG&E's data also show that drivers using PYD sites on the Rate-to-Driver pricing option save more money compared to a gasoline car than those using Rate-to-Host sites. As Fig. 4 [21] shows, the average price per kWh for charging an EV at a Rate-to-Host site is higher than a Rate-to-Driver site ($0.29 compared with $0.18), likely because drivers themselves do not necessarily see the dynamic rate and therefore are not sensitive to the need to avoid charging at peak times. As a result, the estimated savings that drivers are receiving by driving an EV instead of a gasoline car are smaller for the Rate-to-Host sites than the Rate-to-Driver sites. Similar to the MUD examples above, this indicates a benefit to drivers from seeing transparent time-varying pricing communicated to them at the charger. Technology in the vehicle or charger that allows drivers to program their charging to respond to price changes would lead to more savings.

| | **Rate-to-Host** | **Rate-to-Driver** |
|---|---|---|
| Usage (kWh) | 781,713 | 686,574 |
| Average $/kWh | $0.29 | $0.18 |
| Total Cost | $223,983.81 | $121,353.16 |
| | | |
| Approx Gas Equivalent (Gallons)[3] | 94,945 | 83,390 |
| Average $/gal[4] | $3.52 | $3.52 |
| Total Cost | $334,395.88 | $293,698.01 |
| | | |
| Estimated Savings | $110,412.07 | $172,344.85 |
| Average Savings per kWh | $0.14 | $0.25 |

Figure 4: Estimated fuel cost savings of EV drivers charging at SDG&E Power Your Drive sites

The above examples have illustrated how time-varying tariffs can be used to encourage EV drivers to charge during beneficial times for the grid. The U.S. examples thus far have focused on vertically integrated utilities that combine charges for energy and distribution costs into one pricing structure.

A similar approach has been taken in Denmark following recent regulatory reform that requires network operators to introduce time-varying tariffs by the end of 2020 to encourage companies to make their consumption overall more beneficial to the grid [22]. Network tariffs, which are the charges consumers pay to companies for using the network, are growing and currently represent about a third of the average electricity bill in Europe [23]. Designing network charges in a time-varying way can help shift all consumption, not just EV charging, away from peak hours into hours with more grid capacity. One network company, for example, has introduced a three-part network tariff for commercial consumers, such as workplaces or commercial buildings. The tariff comprises a low nighttime charge (applying between midnight and 6 a.m.) and a daytime charge (between 7 a.m. and 11 p.m.) about twice as high. In the winter period (October to March), a peak time charge, about three times the low charge, will replace the daytime prices between 7 a.m. and 8 p.m. [24]. Time-varying network charges are expected to deliver clear price signals to shift flexible consumption to low-tariff hours. This will help large electricity users beneficially integrate EV charging equipment and avoid potentially high electricity costs for vehicles that charge at their facilities. For example, a hotel or sports arena offering charging at its customer parking would have an incentive to avoid these EVs charging at peak hours on the grid. This price signal needs to be reinforced by an equally time-varying energy tariff to be fully effective. The adoption of time-varying tariffs in Denmark is helped by advanced rollout of smart meters in the country [25].

The evidence from programs and incentives for workplace and commercial charging suggests that time-varying tariffs encourage companies to develop strategies to optimize EV charging and their consumption in general.

Transparent time-varying tariffs that are directly passed on to EV drivers are more effective at shifting charging to off-peak times and ensuring that drivers get the greatest benefit of lower off-peak prices.

#### 2.2.4 Public Fast Charging

Public fast charging presents unique considerations for optimization of charging through price signals to consumers. First, faster charge speeds will enable EV drivers to spend less time at charging points, which means a reduced ability to shift charge timing in response to dynamic tariffs. Second, as for commercial charging, the end price to the consumer depends on the business model of the site host or charging service provider and is likely to include various fees in addition to the cost of electricity consumption.

Evidence from Europe demonstrates that high and fixed network costs not only negatively affect the economics of charging for EV drivers but also create cost barriers for service providers to invest in building fast charging infrastructure, in particular at initially low utilization of fast charging points. Initial estimates of the impact of high demand charges in the U.S. point to similar conclusions [26]. However, there is not yet much experiential data regarding how tariff redesign impacts customer behavior at fast charging points. Based on evidence from Europe, this section discusses strategies related to network tariff design to address the cost barrier, as well as additional optimization options through technology use and planning.

Across the emerging market for EV fast charging throughout Europe, costs for public fast charging are found to be high and difficult to compare [27]. Prices for EV charging vary considerably and often substantially exceed prices for household electricity. In Germany, for example, charging services in 2019 were up to 80% more expensive than household tariffs [28]. One reason for this are high network charges, known as demand charges in the U.S. These charges tend to be capacity-based — that is, based on the measured peak demand in the billed period (usually a month or year). For operators of fast chargers, this can become a barrier to creating a business case, as many fast chargers have an overall low consumption (in kWh) compared with the peak demand (kW). In the early market development phase, when a smaller number of EVs can be expected, these charges can represent a very high share of the total electricity bill of the EV charging service provider.

Estimates from Germany illustrate how high and fixed network tariffs are likely to discourage investment in building public fast charging sites, in particular in very expensive grids. Table 2 [29] shows estimated tariffs for a large metropolitan grid in the western part of Germany (Westnetz), where network costs for operating a 50-kW charging point with very low usage (assuming 10 EVs per month) would require 63 euros per EV per year in network charges only. Increased charging point utilization can reduce costs.

Table 2: Estimated network tariffs in euros/EV/year at 50-kW fast charger connected to low-voltage grid in Germany

| | 10 EVs | 100 EVs | 1,000 EVs | 10,000 EVs |
|---|---|---|---|---|
| Dense (Westnetz) | 63.20 | 7.13 | 1.53 | 0.85 |
| Rural (Edis) | 219.20 | 22.78 | 3.14 | 1.11 |

Table 2 also shows substantial cost differences between urban and rural grid areas, where costs per EV are considerably higher in particular at a low utilization rate of charging points. This suggests a higher investment barrier and resulting higher prices for public fast EV charging in rural areas. This evidence suggests that in the case of fast charging, strategies are needed to address cost barriers to infrastructure investment and to reduce the risk these costs get passed on to drivers in the form of expensive charging fees. Network costs for businesses deploying fast charging points could be reduced or phased in as utilization increases or designed in a time-varying manner as shown in the previous example from Denmark.

Another optimization approach is for utilities or third parties to manage charging in such a way that avoids the times of greatest grid stress. In Germany, grid operators currently offer a reduced flat volumetric network charge if customers agree to allow them to interfere with EV charging to avoid exacerbating peak load. This approach was originally developed for storage heating systems, and EV consumer uptake is very low, likely due to a lack of tangible benefits, transparency and controllability for consumers [30]. Another approach to active grid management and optimal EV integration was piloted in Amsterdam in the Netherlands, where grid operators optimized charging at public locations by adjusting charging speed according to grid capacity [31]. Other options of making fast charging independent from peak hours and peak prices are being piloted, including using secondhand EV batteries as intermediary storage [32].

This section showed that tariff design may encourage charging service providers to enable grid-friendly EV charging but reduced or time-varying network charges are likely needed to help reduce the costs of fast charging. Additional means of optimizing electricity consumption at fast charging points are likely to be needed, such as utility-managed charging, provided it results in consumer benefits. An additional use case not included in this research due to limited data availability is charging of the growing numbers of electric fleet vehicles (utility vehicles or buses). Charging patterns of these vehicles are highly constrained by their usage in logistics or transport schedules, which means that other methods to optimize charging will be needed in addition to tariffs.

### 2.3 Concluding Thoughts on Tariff Design

Section 2 of this paper has shown that for charging in residential settings, including multi-unit dwellings, carefully designed tariffs are an effective tool for optimal EV grid integration. In use cases involving intermediaries such as site hosts for charging at workplaces or commercial locations, more grid and consumer benefits can be achieved if site hosts choose to pass on time-varying rates directly to customers. Across use cases, examples showed that EV tariffs require supportive technology to maximize benefits for consumers. In both the U.S. and EU, the design of network charges needs to be addressed to enable public fast charging deployment. Use cases also suggest additional planning instruments, such as optimization of charging by location, may be needed to ensure beneficial EV grid integration. This is discussed further in Section 3.

## 3 Lessons Learned for Charging Infrastructure Deployment

Tariff design is essential in encouraging smart charging, but it needs to be part of a broader EV charging policy framework to be effective for consumers. Based on evidence reviewed in the previous section, we find:

- Advanced tariff structures are needed that reflect location and time-based cost variants depending on specific charging use cases, with the aim of avoiding costly investments in building out grid infrastructure.
- Deployment of responsive, consumer-friendly technologies can make time-varying tariffs more accessible, transparent and beneficial to customers.

### 3.1 Advanced Tariff Structures

While tariff design can be effective at optimizing the timing of charging, in some use cases such as public fast charging it is more difficult for users to shift the timing of consumption significantly. In these cases, it may be prudent to explore how charging can be optimized by location. In other words, encourage charging infrastructure to be built in locations that make use of existing grid capacity, take advantage of locally available renewable energy sources and also meet EV drivers' charging demand. This also includes addressing potential disadvantages for rural fast charging sites in which demand or network charges may be higher, as the above evidence suggested.

One current example of optimizing the location of charging infrastructure is the price-based instrument to locate charging points based on grid capacity being used in Norway. Builders of charging infrastructure pay a connection charge that varies on the location of the charging infrastructure [33]. In locations with available grid capacity, the charge is lower. This pricing structure charge also ensures that the network companies' costs are covered. The charge provides a price-based mechanism to reveal optimal locations for charging infrastructure and provides revenue for grid companies that ensures the costs to connect charging infrastructure will not be passed on to all electricity consumers.

### 3.2 Using Technology to Ensure Transparent Price Information and Optimal Charging

Throughout the above examples, the use of technology to enable a more robust EV driver response to time-varying tariffs emerged as a theme. For example, the degree to which EV users can benefit from EV tariff designs partially depends on how transparent and understandable time-varying tariffs are for customers. This can be affected by the degree to which a charging service supplier and/or site host chooses to pass on the price signal to the end customer. Regulators can influence this by requiring utilities and grid operators to offer pricing structures that allow time-varying signals to be passed on. Technology such as software in an electric vehicle or within a charger can be effective at making time-varying pricing understandable for consumers and can enable them to easily respond and reap the benefits of low-cost charging times.

Another way to use technology to optimize EV charging is for utilities, grid operators or third parties to manage some aspects of charging on behalf of customers. In the case of residential or multi-unit dwelling charging, for example, such a strategy could ensure EVs are charged in the most grid-beneficial way over the course of many hours while ensuring drivers get their needed charge level at least cost. Such managed charging should be structured in a way that aims to maximize grid benefits and pass the resulting cost savings on to customers.

## 4 Conclusions and Outlook

Based on evidence from U.S. and EU EV charging tariffs and programs, this paper confirmed findings from previous research that time-varying tariffs encourage EV users to shift charging to off-peak hours. This helps to ensure that EV charging can be beneficial to the grid and electric customers, as well as to EV drivers themselves. In Section 2, we reviewed results from several different use cases and found that time-varying tariffs can be very effective for residential, workplace and charging in multi-unit dwellings. In addition, the growth of fast charging indicates a need to rethink high fixed and network (or demand) charges to become more dynamic or more gradually phased in as EV adoption and charger utilization increases. Given the shorter time window for charging and resulting reduced ability to shift usage, we conclude that additional measures may be needed to optimize fast charging, for example integrated planning to identify grid-optimal locations of charging points and technology support. Section 3 identifies some lessons learned for charging infrastructure deployment from the evidence on tariff design. Advanced tariff design that considers time and location elements may be useful, particularly for fast charging. Deployment of responsive technology to ensure price transparency for consumers will enhance the effectiveness of smart EV tariffs. One general conclusion from the paper is that regulators, particularly in Europe, need to monitor and require more reporting on what is learned from implementing different tariff designs and to make the data on experiences with these various tariffs available to enable faster innovation and better inform consumers

Limitations of the study are that limited data is available on experience with time-varying tariffs for EV charging, particularly in Europe. More research is needed on experience with dynamic tariffs for fleet vehicles as this segment develops. More research is also needed to better understand how intelligent technology such as smart meters can enable successful integration of EVs.

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