REALISE FLEXIBILITY POTENTIAL OF EV FLEETS THROUGH GRID-SERVING CHARGING STRATEGIES

Jan Timo Meyer[1], Carolin Daam[1], Jakob Gemassmer[1]*

[1]Reiner Lemoine Institut gGmbH, Rudower Chaussee 12, 12489 Berlin, Germany
**E-mail: timo.meyer@rl-institut.de*

Keywords: BEV, SMART CHARGING, FLEXIBILITIES, ENERGY SYSTEM, GRID CHARGES

Abstract

Making flexibility of electric vehicles usable for distribution system operators is crucial to further integrate large portions of renewable energy sources into the energy system as well as high power loads. This paper provides a better understanding of a fleet's flexibility potential with a nightly dwell time and its deployment using indirect control schemes related to grid charges. Three grid-serving charging strategies were modelled (time-variable grid charges (TV), flexible time window (FL), and schedule (SC)) and compared for local setup configurations using a photovoltaic (PV) system, stationary battery, and vehicle-to-grid (V2G) in varying grid situations.

In comparison to simple balanced charging, all grid-serving strategies can achieve a higher utilisation of energy from periods with generation surplus and reduce residual load peaks. TV has substantially higher precision in increasing energy withdrawal during curtailment, while FL performs comparable in utilising generation surplus. Both can be extended by additional flexibility through battery and V2G; an additional PV system, however, decreases the volume of shiftable load. In most variations, grid-serving charging results in savings for the DSO which are not fully reflected by the consumer grid charges. The results indicate how feed-in from flexible components has to be remunerated to render it more attractive for both DSO and customer.

1 Introduction

Due to the continuing increase of volatile feed-in of renewable energies (RE) and the need to integrate new loads due to the electrification of various sectors, the use of flexibility is becoming increasingly important for grid operators. In 2020, the share of renewable energies in electricity generation in Germany exceeded 50 % for the first time [1]. At the same time, the share of electric vehicles (EVs) is increasing. Last year, the share of new registrations in Germany doubled to 13.6 % [2], so that now more than one percent of registered passenger cars are electric [8]. EVs are not only a challenge, but an opportunity, due to the built-in storage and long parking times, which permit flexible charging.

Using EV inherent flexibility to relieve grids from stress caused by rising peak loads and high volatile feed-in is extensively studied in the literature. In simulations, demand-side management is often carried out based on different charging strategies that vary in complexity and higher level goals: e.g. balancing user utility, reducing personal cost, maximizing welfare, efficient use of infrastructure or accessibility of flexibility. Charging strategies can be distinguished into direct, centralised control schemes and indirect, decentralised schemes. Direct control by the DSO compensated by a reduced grid charge, as similarly indicated by § 14a EnWG, still lacks a concrete regulation. Therefore, indirect mechanisms are often favoured, mostly based on price.

The study Gong et al. [3] proposes a dynamic spike pricing policy on top of a time-of-use smart charging to prevent a residential distribution transformer from overloading. Szinai et al. [4] study a future scenario with high adoption of residential electric vehicles while comparing the performance of overnight time-of-use charging and optimal smart charging. The study uses a high resolution power sector dispatch model within a large grid area with high penetration of solar generation. In a local network area, Sachan et al. [5] examine the influence of charging technologies and smart charging based on price signals or reactive power with regard to various performance parameters including cost and demand. Dixon et al. [6] argue that CO_2 emissions of private individually used EVs can be reduced by smart charging, when using wind power that would otherwise be curtailed. Their simulations are based on Mixed-Integer-Programming to solve a time-coupled linearised optimal power flow formulation.

Kikusato et al. [7] proposes a second-price sealed-bid auction for achieving an economical maximum of a Japanese distribution grid. A smart charging procedure is applied, that shifts charging-demands, reduces PV-curtailment indicated by voltage-rise in the low-voltage distribution system.

The analysis in this work concerns especially higher grid costs imposed by high penetration of mostly wind dominated RE generation in higher voltage levels, which provokes energy loss through necessary curtailment due to missing local loads. This work focuses on applicable indirect control schemes using external signals, that could be communicated and adapted by distribution system operators (DSOs) on a daily basis. The signal structure varies from time window definitions expressing when energy withdrawal is desired or cheaper, while a schedule-based strategy also defines the desired energy volumes per time step, similar to a direct control. The conceived control signals relate to real grid situations, take customer needs into account, and aim to compensate for the regional oversupply from RE. Development of strategies was conducted alongside the BMUV-funded Netz_eLOG project and their effects were investigated for varying grid characteristics using the example of an operational electric logistics fleet [9]. This application domain is especially interesting due to the certain regularity and expected high economical efficiency.

2 Methodology

2.1 Model and Charging Strategies

To analyse the influence of grid-serving charging strategies, an energy system consisting of a vehicle fleet and a grid connection as well as optional components for RE generation (PV system (*pv*)) and energy storage (stationary batteries (*bat*) and vehicle-to-grid-capable vehicles (*v2g*)) is considered. The modelling is carried out over a six-month period with the open-source simulation model SpiceEV [10] developed by the Reiner Lemoine Institute (RLI).

2.1.1 Model Parameters: A fleet consisting of 123 EVs of type sprinter van with a capacity of $\hat{E}_{\text{ev}} = 76$ kWh was selected; with a core time between 11 pm and 5 am plus every Sundays where all vehicles are available. The energy demand and availability characteristic was derived and generated from realistic driving patterns in the logistics sector.

At the customer's site, the grid connector power limit is set to $P_{\text{gc, max}} = 530$ kW. Besides the vehicles with exclusive charging points, the local energy system setup can include additional assets and features in various combinations, whose simulation results are compared to each other: Local RE generation by a PV system rated at $\hat{P}_{\text{pv}} = 185.5$ kWp can be used to charge vehicles directly behind the grid connector and feed excess energy into the grid. A stationary battery with a capacity of $\hat{E}_{\text{bat}} = 350$ kWh and C-Rate$_{\text{bat}} = 0.5$ can provide additional flexibility (e.g. for storing locally generated energy) also when vehicles are on the route. Moreover, some setups enable vehicles to use V2G and thereby the flexibility to discharge vehicle batteries depending on the charging strategy.

A constant load curve with $P_{\text{ev, max}}(SOC) = 11$ kW was chosen for simulations in SpiceEV to simplify the analysis. Depending on whether the specific setup is using *v2g* or not, the minimal power $P_{\text{ev, min}}$ is either $P_{\text{v2g}} = -0.99 \cdot P_{\text{ev, max}}$ kW or 0 kW, respectively.

The aggregated energy consumption to be charged during the simulation period of six months amounts to ≈ 380 MWh, while PV - if existing - generates -144 MWh, that is consequently partly fed into or avoided to be drawn from the grid.

2.1.2 Grid-serving Strategies: Three models with different control options for the DSO were developed to investigate the effects of grid-serving charging strategies:

- **Time-variable grid charges (TV) strategy:** The DSO sends grid price signals in the form of energy price rates defining the commodity grid charges of connected users. They can then adjust their electricity consumption in a price-optimized manner. Fleet operators, who flexibly adjust their load to the external signals, benefit directly through lower operating costs. The considered tariff model is based on three levels (low, medium, high tariff) and depends on the regional grid situation of a specific area. A low tariff at a time step reflects existing curtailment or that the grid area's residual load is in it's lower annual 25 %-percentile, while high tariff represents the higher annual 25 %-percentile. This promotes the absorption of feed-in peaks and potentially

even reduces curtailment. At the same time, the increase of existing load peaks is avoided through higher grid charges.
- **Flexible time window (FL) strategy:** This charging strategy is an enhanced version of the already applicable peak load time windows (§19.2 StromNEV, German ordinance on grid charges). These daily adapting flexible windows are defined based on the grid situation: If curtailments or generation surplus is expected, these periods become windows where procurement is desired, regardless of the resulting peak power. However, during time windows with excess load in the grid area, the power becomes relevant and should be reduced. This binary strategy is less sensitive and is more expensive compared to strategy TV.
- **Schedule (SC) strategy:** Here, the DSO sends an individual charging schedule to the connected user, which contains the time and amount of energy to be withdrawn by all flexible loads, thus achieves higher certainty about the resulting charging profile compared to TV and FL. The schedule is created on the basis of the flexibility potential of the user, the expected grid situation and takes into account the requirements of the fleet operators. For this purpose, some key data (core time, total charging demand, and maximum total power of the fleet, along with a schedule proposition) are communicated to the DSO, from which the flexibility potential of the fleet is derived. As in TV, the grid situation is transferred into a multi-level model: Time steps in which curtailment exists or the residual load is in it's lower annual 25 %-percentile belong to priority one; Priority four represents the higher annual 25 %-percentile and the range in the middle is divided into time steps with residual load < 0 (priority two) or > 0 (priority three).

In all three strategies, charging takes place evenly distributed within a time window, given the availability of flexibility. Two charging strategies that are not aligned with the grid situation and run without control signals from the DSO serve as reference models: uncontrolled charging of the fleet with maximum power when the vehicles arrive (uncontrolled - UC) and balanced charging with minimum possible charging power over the dwell time of the vehicles (balanced - BA) to reach the desired minimal state of charge (SOC) before leaving.

If a stationary battery is specified, it is charged during time slots with a price signal beneath a parameterized threshold, whereas SC integrates the additional flexibility into the schedule and FL is charging the battery based on the flexible window rather than the price signal. Further existing local renewable energy generation is used to charge present vehicles with first priority, stationary battery second and via grid connector last.

Smart charging schedules are planned with a shifting horizon of $\Delta t_{\text{horizon}} = 24$ h. While the strategies have to guarantee a $SOC_{\text{ev, required}} = 80\ \%$ of each vehicles battery at the end of the dwell time, it is allowed to discharge down to $SOC_{\text{dch, min}} = 50\ \%$ in V2G mode.

In order for a charging strategy to use flexibility in a grid-oriented manner, an incentive structure has to be defined, that is practical and transparent for billing and should reflect the positive effects on the grid costs.

2.2 Grid Cost and Charges

In a lot of cases, service cost based on the annual peak load prohibits flexible charging. An incentive is required to remunerate flexibility that is used to shift energy consumption away from time steps of regional deficit to times of generation surplus or even curtailment. In turn, this grid-serving behaviour potentially decreases network costs. The grid charges should more than compensate the otherwise increased cost due to a higher local annual peak demand compared to a balanced i.e. non-flexible charging.

In the following, estimations of three network cost components are presented, that provide a basis for designing customer grid charges per charging strategy. Further elements of the electricity costs are not considered.

Additional power-based service charge (sc) by the transmission system operator (TSO): $C^{sc_{\text{TSO}}}$ is estimated based on the regional increase of the residual peak-power within the grid area $\Delta\hat{P}_{\text{<area>}} = \hat{P}^{\text{new}}_{\text{<area>}} - \hat{P}^{\text{prev}}_{\text{<area>}}$ when the new customer is added, multiplied by a service rate, e.g. given by public TSO price sheets.

Additional commodity charge (cc) by the TSO: $C^{cc_{\text{TSO}}}$ is estimated based on the assumption that all energy that is withdrawn at time steps without regional surplus $(E_{\text{total}} - E^{\text{surplus}}_{\text{<area>}})$ in the specified grid area has to be procured from the TSO at a specific price rate.

Prevented curtailment costs: $E^{\text{curt}_{\text{<area>}}}$ at DSO level is estimated by a linear relation of a cost constant C^{RED} and the aggregated energy $E^{\text{curt}_{\text{<area>}}}$ drawn during time steps of 15 min. with curtailment in the grid area for the duration of the simulation. The constant $C^{\text{RED}} \approx \frac{1398 \text{ M EUR}}{23358 \text{ GWh}} \approx 0.0598 \frac{\text{EUR}}{\text{kWh}}$ is defined as the average cost for congestion management (incl. redispatch, curtailment, network reserve, adaption measures, countertrading) [11], assuming a direct effect within a regarded grid area independent of the exact target location.

Customer grid charges: $C^{\text{charge}}_{\text{<strategy>}}$ are composed of service and commodity charge as shown in equation (1):

$$C^{\text{charge}}_{\text{<strategy>}} = C^{sc}_{\text{<strategy>}} + C^{cc}_{\text{<strategy>}}. \tag{1}$$

Commodity charges are based an a fix price rate $C^{cc_{\text{DSO}}}$ with the exception of the TV strategy, which has a time-variable tariff $C^{cc_{\text{DSO}}}_{\text{TV}}(t)$ as defined in Subsection 2.1:

$$C^{cc}_{\text{TV}} = \sum_{t \in T} P_{\text{gc}}(t) \cdot \Delta\, t \cdot C^{cc_{\text{DSO}}}_{\text{TV}}(t), \tag{2}$$

where $P_{\text{gc}}(t)$ is the average power withdrawal at the customer's grid connector (gc), i.e. does not include feed-in power.

The service charge refers to the peak demand during specific time slots depending on the strategy: For the TV strategy, the peak power is only relevant where the price signal is in high tariff. Similarly, this applies for FL with respect to designated charging time windows. Finally, as the schedule for the SC strategy is not defined by the customer, a grid charge related to the implicit schedule's peak demand would be misleading, which why it is initially set to zero.

This selection of cost components at the level of the DSO can be compared to the grid charges, especially with regard to status quo grid charges in combination with simple strategies as UC and BA. If the grid-serving strategies in fact improve the grid situation both the customer grid charges C^{charge} and the DSO balance of all components $C^{\text{diff}}_{\text{DSO}}$ (3) should decrease.

$$C^{\text{diff}}_{\text{DSO}} = C^{sc_{\text{TSO}}} + C^{cc_{\text{TSO}}} - C^{\text{curt}} - C^{\text{charge}} \tag{3}$$

Further DSO cost reductions like avoided grid expansion are not considered. Also, additional expenses for additional equipment is not included.

Cost Parameter: The considered service price rates for the grid connection originate from a recent public price sheet of the studied DSO grid[12] of which the power-based charges (JLP) in the medium voltage level are relevant. UC and BA service price rates regarding with < 2500 full load hours amount to 41.06 EUR/kW per year and accordingly commodity price rate at 0.0349 EUR/kWh. For grid-serving strategies, the higher price rates, related to $>= 2500$ full load hours, were considered as the grid charge is related to shorter time (e.g. high tariff and non-charging time windows). Namely, the according service price rate is 70.14 EUR/kW per year and the commodity charge is 0.0232 EUR/kWh.

The TV commodity price rate, however, is based on the study commissioned by BMWi [13] according to which around 68 % of the grid cost in the medium voltage level is of structural nature, while only 32 % depends on operational aspects. All grid users profit from a grid connection and the grid structure in general, independently of how grid-friendly the energy consumption is operated. Consequently the low tariff level is set to 68 % of the mid level, i.e. 0.0237 EUR/kWh and 0.0349 EUR/kWh, respectively. Custom high tariff levels are considered per grid area, that relate to the availability of surplus energy, i.e. (N1) 0.037 EUR/kWh, (N2) 0.0404 EUR/kWh or (N3) 0.0393 EUR/kWh.

Commodity costs values are linearly scaled to a year, while the service cost already corresponds to a year. The service cost is considered relevant as the observed simulation duration is long enough and covers both winter and summer characteristic.

3 Results

All strategies are investigated in three different grid areas, which differ in terms of feed-in, load, and curtailment, provided by a DSO. The grid situation is based on real-world data provided by the DSO within the project.

3.1 Grid Area Situations without Additional Components

Before evaluating the performance of all simulations, we first concentrate on the strategies in the *basis* setup, i.e. without any other components.

Grid area N1 has with high excess load due to low RE generation. Fig. 1 shows an exemplary section over three days from the simulation period. It shows the load profiles of all charging strategies (left axis) and the grid situation (right axis). The coloured background shows the price signals: Green indicates a low tariff and red a high tariff. The price signal only influences the TV charging strategy directly, but is similar to the window definition of FL.

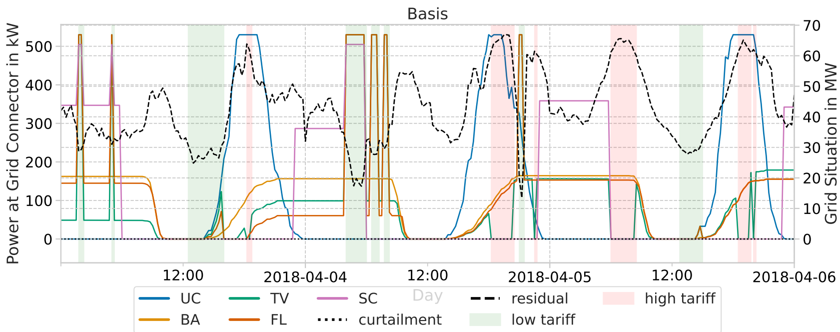

Fig. 1 Load profiles of charging strategies (left axis) in a three-day example of grid area N1 (right axis) showing high residual load and no curtailment.

While the two reference strategies, UC and BA, act independently of the grid situation and the price signals, the grid-serving charging strategies TV, FL, and SC increase the power consumption especially during low-load periods with low prices. The strategies react with different sensitivities. TV charges primarily during the low-tariff windows or, if necessary, at medium tariff. In this example sequence, it is the only strategy that never loads in high-price windows. FL also prefers to charge in low-price windows, but does not distinguish between medium and high tariffs. This strategy is therefore less sensitive than the previous one. The special characteristic of strategy SC is that it can only consider the grid situation during the core standing time, but still concentrates the charging with higher precision on low residual valleys than reflected by the price signals. As on the second day, SC responds with a power increase in the low price time window.

Grid area N2 has a particularly high generation surplus and a high level of curtailment, which in turn leads to predominantly low prices as shown in Fig. 2. During the daytime curtailment at the beginning of the sequence, the grid-serving charging strategies can only partially react, because the vehicles are on the road. As long as this situation does not change, the grid-serving strategies can charge balanced over the standing time. As in grid area N1, TV reacts more sensitively than FL. This can be seen by the fact that TV charges in advance with slightly higher power and ends abruptly the charging process before the high tariff begins.

In grid area N3, loads and generation are quite balanced and there is rarely any curtailment. As shown in Fig. 3 all three grid-serving charging strategies react to the generation surplus during the night from day 2 to day 3. While the charging process with FL is equally distributed over the feed-in time window, the other two grid-serving strategies react somewhat more sensitively and charge with higher power in a shorter period of time.

3.2 Effects of Component Setups Variation

In the following, the three grid-serving charging strategies are discussed in more detail with regard to their charging behaviour in different setups of the local energy system. Depending on the integration of local PV systems (*pv*) or energy storage systems in form of stationary batteries (*bat*) or V2G-capable vehicles (*v2g*) on site, the flexibility potential to be used by charging strategies varies. The additional components act as local generator, of which energy can be used without grid utilisation, or as temporal energy storage that increases the flexibility to charge the vehicles at a later time. The management of additional flexibility is integrated into the charging strategies discussed in Subsection 2.1. Additional consumers are not taken into account.

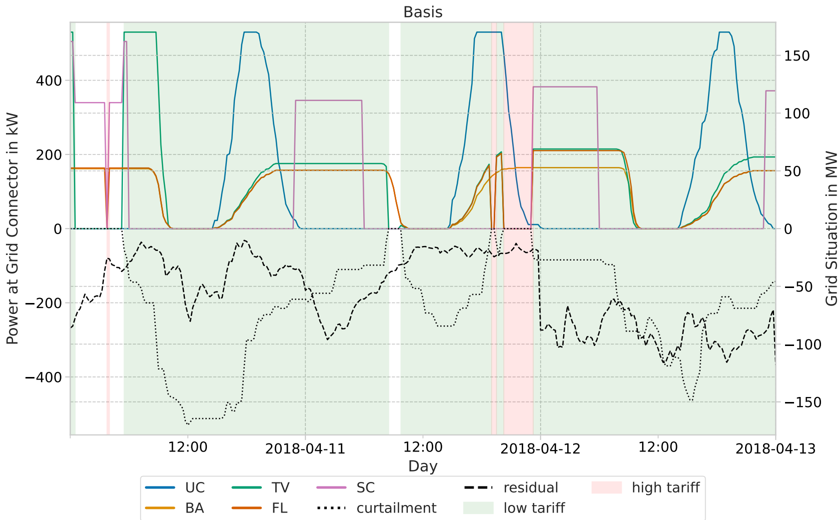

Fig. 2 Load profiles of charging strategies (left axis) in grid area N2 with high generation surplus and curtailment (right axis) resulting in (green) low tariff windows.

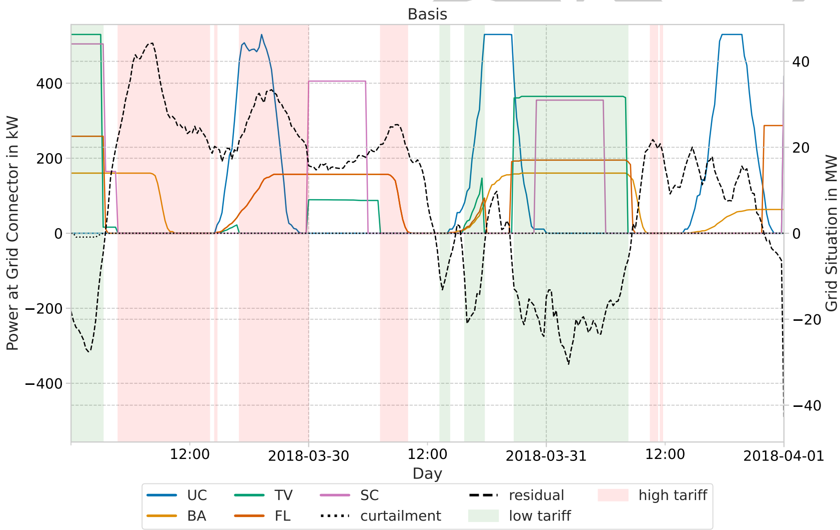

Fig. 3. Load profiles of the charging strategies (left axis) in grid area N3 with balanced grid situation (right axis).

The various combinations are analysed regarding energy withdrawal during times of curtailment E^{curt}, generation surplus E^{surplus} within the given grid areas as well as the peak load increase $\Delta\hat{P}_{\text{<area>}}$ the local system would cause when added to the area. The existence of curtailment or surplus energy during a time step determines the classification, while the volume is not relevant. In contrast, the residual percentile used within the grid-serving strategies TV, FL and SC is representing volumes relative to minimum and maximum. All strategies are analysed in the context of three grid areas: i.e. with dominant excess load, generation surplus, or grid in balance.

3.2.1 Energy withdrawal during curtailment and generation surplus: The two following Figures show the energy withdrawal during curtailment (Fig. 4) and generation surplus periods (Fig. 5) in the three different grid areas.

In all grid areas and charging strategies, a setup with *pv* leads to less energy withdrawal in both periods. In grid area N1, even negative values (dark blue) appear in all setups with *pv*, especially in charging strategies BA and SC. However, since there is hardly any curtailment in N1, the effects are almost negligent in absolute values.

In N1, a high-load grid, grid-serving charging strategies outperform UC and BA in terms of energy withdrawal in generation surplus periods on a low level and were only slightly better in absorbing energy during curtailment. Moreover, additional storage options (*bat*, *v2g* or *bat+v2g*) lead to an increased volume for both measures. Especially FL and TV can increase withdrawal of energy during generation surplus with combined *bat+v2g*, which however still covers only less than 10 % of the fleet's six-month demand of around 380 MWh.

In N2, most time steps offer energy surplus (≈ 97 %) and often curtailment (≈ 30 %), which is why even the simple strategies UC and BA can charge vehicles with 96 % of their demand during times of surplus. Considering only the dwell times of vehicles, curtailment especially appears in the evening hours right after arrival, which explains the relatively good performance of UC compared to BA and even outperforms FL in that measure. Grid-serving charging strategies as TV and FL can even further exploit additional flexibility available through *bat* and *v2g* to expand energy withdrawal during curtailment, especially TV. In this grid area N2, TV even doubles the volume of FL and triples the amount of BA. The same applies to the use of energy during times of surplus, which can be withdrawn most efficiently by FL with additional flexibility. The simple strategies UC and BA, in turn, cannot profit from additional flexibility to improve grid serving behaviour. It can only be used to store local PV energy to charge it with priority later.

In N3 energy surplus (≈ 37 %) and fewer curtailment time steps (≈ 2 %) lead to less energy withdrawal during these periods, in contrast to N2. This leads to the effect of grid-serving charging strategies being more visible than in the other two grid areas. TV makes the most of additional flexibility in terms of curtailment while FL achieves higher consumption during energy surplus.

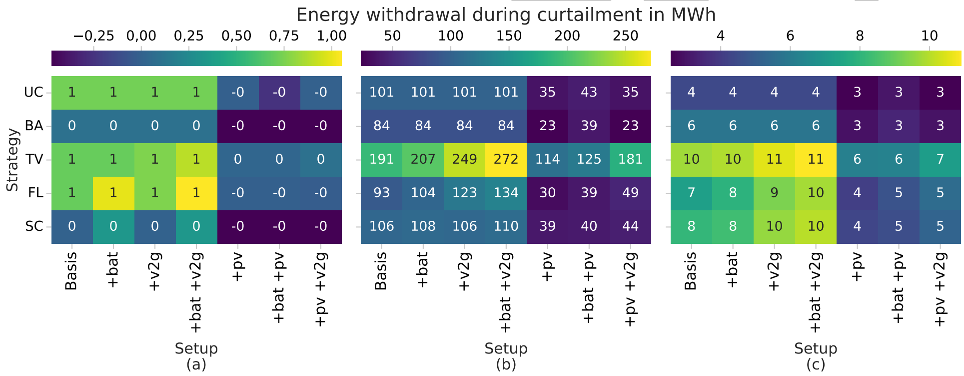

Fig. 4 Effect of strategy and setup on the customers energy withdrawal during curtailment in MWh within each grid area N1-N3 from left to right.

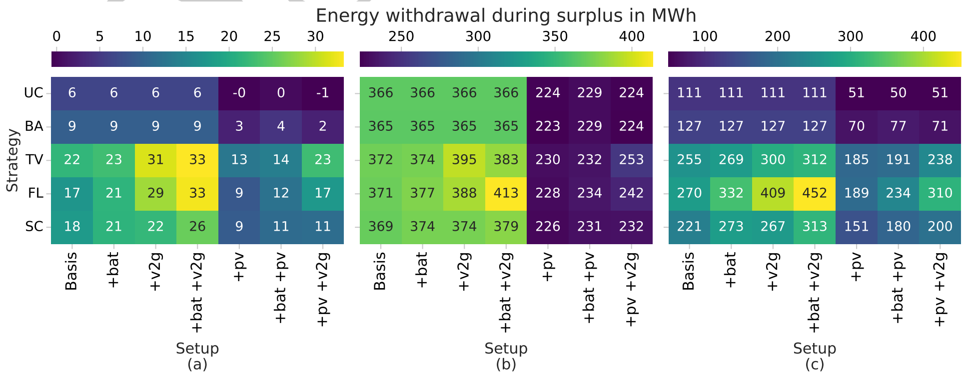

Fig. 5 Effect of strategy and setup on the customers energy withdrawal during generation surplus in MWh within each grid area N1-N3 from left to right.

Independent of the grid area all grid-oriented strategies achieve an increase of energy consumption during curtailment and surplus with additional flexibility (*bat*, *v2g* or *bat+v2g*). In all regarded cases *v2g* provides a higher usable flexibility than *bat* with the exception of SC which achieves comparable results with both options.

3.2.2 Peak power: Fig. 6 shows the increase of the grid area's residual peak power, that would be caused by the new customer, for all strategies and setups. In all considered grid areas the residual peak load appears during evening hours.

With uncontrolled charging as in UC, charging with the maximum grid connector power overlaps with the maximum residual load in all setups of the load-dominated and balanced grid area. With controlled charging strategies, the increase of the peak power, which is relevant to the grid dimensioning, can be significantly reduced. TV varies in performance mostly depending on weather *v2g* is used. As shown in Subfig. 6 (a) in N1 *v2g* even leads to a similar peak increase than BA. In contrast, FL achieves a lower increase specifically through the use of *v2g*, especially in grids without high excess load (see Subfig. 6 (b-c) i.e. N2 and N3). In other setups FL performs comparable to BA.

One curious effect within BA setups is achieved in N1 when combining *pv* and *bat*, which reduces the peak power due to self-consumption, however this is not consistent with the other areas. As the negative values in N2 and N3 show, the SC strategy can even utilise a stationary battery to a reduction in residual peak power. Also for TV, *bat* has the biggest impact in avoiding a high increase of the area's residual load peak.

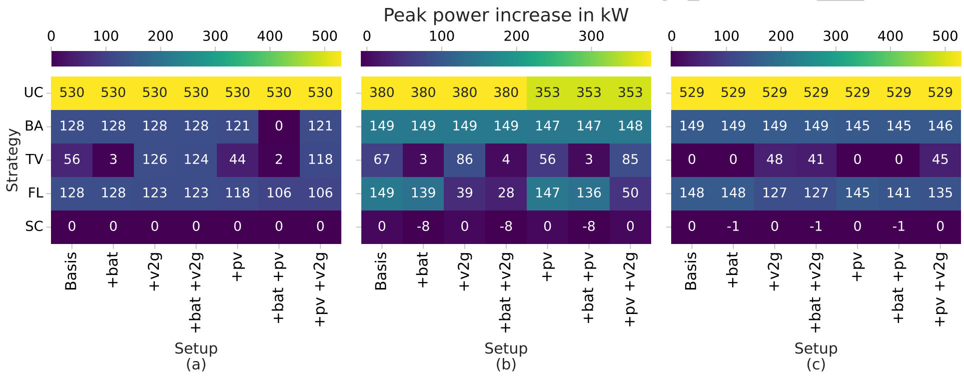

Fig. 6 Effect of charging strategy and setup on peak power increase in kW within each grid area N1-N3 from left to right, respectively.

3.3 Reflecting grid-serving effects with reduced grid charges

The grid charge payed by the customer is now compared to the resulting balance for the DSO as calculated in (1) and (3), constituted of estimations for increase of service and commodity charges by the TSO, curtailment cost reduction and the customer grid charges (Subsection 2.2). The comparison is visualised as a scatter plot per grid area in Figures 7-9. As the customer grid charge is also included into the DSO cost balance, but with a negative sign, a changing grid charge would cause a data point to move along a diagonal as suggested by the dotted aid line for each *basis* setup. In turn, if data points are situated perpendicular to a dotted line to the lower left, it means grid costs are decreasing.

In the load dominated grid area, UC generates the highest costs for both the DSO and the customer as shown in Fig. 7. BA already substantially reduces both customer charges and considered grid costs. It is also necessary to keep in mind that expenses for smart behaviour is not needed in these both simple strategies. Further, additional components do not have an effect in UC and BA. All grid-serving strategies can further reduce grid costs, as all scenario points lie beneath BA's dotted reference line. Both TV and SC *basis* setups achieve similar reduction cost reduction, while TV with *bat* has the best performance. However, mostly the DSO profits from those improvements, while for customers it depends on which components are integrated in the system. In most cases an additional flexibility leads to a rising grid charge. *V2g* specifically increases the charges for TV and FL significantly compared to the *basis* or *bat* setups. For TV, the *v2g* scenario points even show a very negative effect on the grid costs itself,

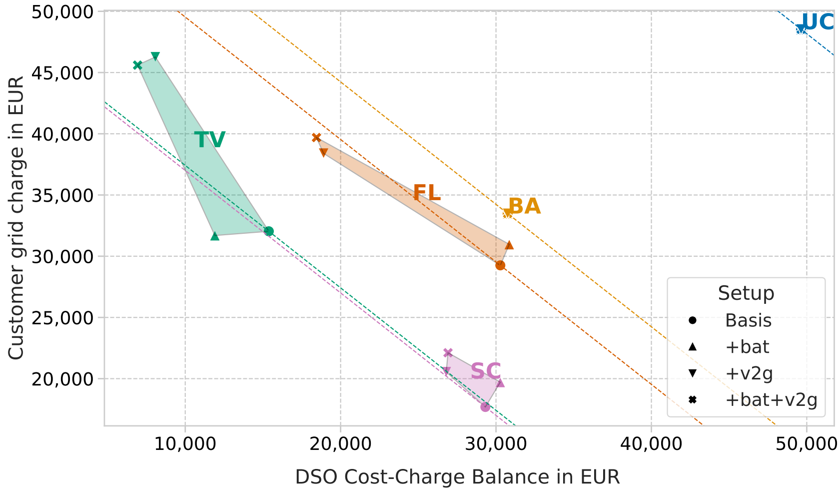

Fig. 7 Comparison of grid charge payed by the customer and the resulting balance of grid cost components and grid charges for the DSO as calculated in (1) and (3) for grid area N1: The values are highlighted by strategy (colour + guiding hull) and setups (marker type), the dotted reference lines visualises the influence of a changing grid charge on the DSO balance given otherwise constant costs components for each *basis* setup.

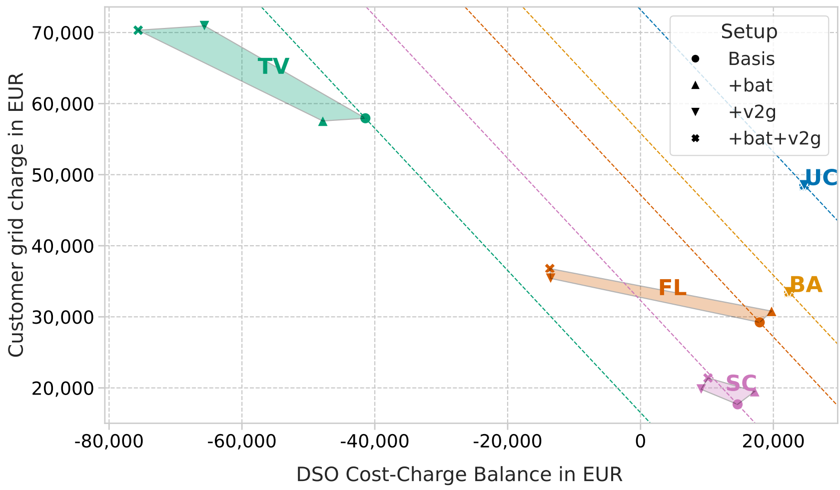

Fig. 8. Comparison of costs for customer and DSO as in Fig. 7 for grid area N2.

by the fact, that they are located above the *basis* line but still outperform FL scenarios. The same effect can be observed to a lesser extent for SC in all setups.

It should be noted that grid charges only regard withdrawn energy. Additional flexibility use leads, however, to an increased volume that is then fed back later with a grid-serving intention.

In generation surplus dominated areas, UC leads to significantly lower costs for the DSO than in high excess load areas, while the charges for customers remain about the same with exception of TV. Fig. 8 shows that regardless of the charging strategy, the DSO cost-charge balance decreases. Grid-serving strategy TV and, in some cases FL, even have a negative DSO balance, mostly due to avoided curtailment and used surplus energy while customers do not benefit from these savings. In contrast to the load dominated area N1, setups with *v2g* can now utilise flexibility to reduce grid costs, shown by points lying beneath each strategies *basis* line respectively.

Fig. 9 shows the cost distribution for a balanced grid area, which is very similar to the distribution from N1. While this is also true for the setup's effect on TV grid costs, the height of customer grid charges are rather comparable to N2.

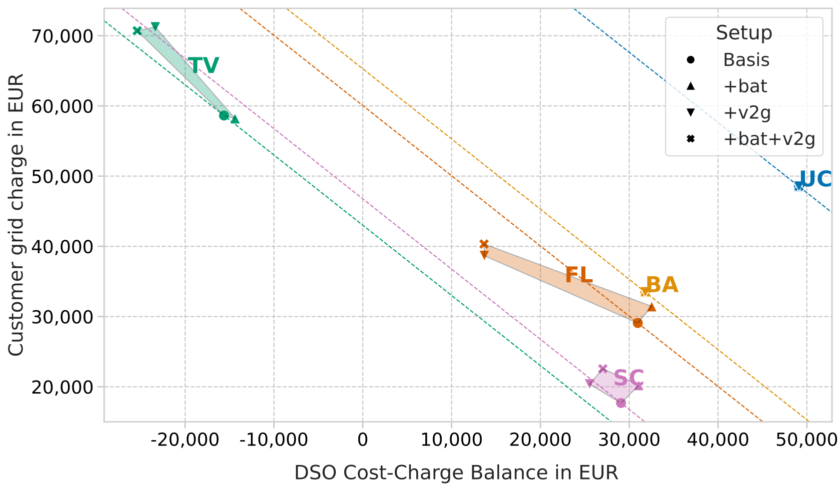

Fig. 9. Comparison of costs for customer and DSO as in Fig. 7 for grid area N3.

4 Discussion

The results of the simulations show how the three grid-serving charging strategies (TV, FL, SC) behave in relation to simple strategies (UC, BA) as well as the influence of different component setups (*basis*, *bat*, *v2g*, *pv* and variations of these) per grid region (N1, N2, N3). The discussion will focus on the effect of setup components and, if any, highlight specific utilisation in charging strategies.

The existence of a PV system decreases the volume of shiftable load in the system to provide grid-oriented flexibility, as it is always prioritized. However, PV energy is in this case charged locally without adding load or volatile feed-in to the grid and thereby has a positive effect on the grid, that is not reflected by the performance indicators.

The observed higher usable flexibility of *v2g* setups compared to *bat* can be explained by the several times bigger aggregated capacity despite a reduced availability of *v2g* during the dwell time. The SC strategy shows comparable performance for both setups. Moreover, a lot of curtailment and surplus appears also during dwell time in the evening. The fact, that SC can use less energy from curtailment and surplus periods, especially in N1 and N2, is due to the limiting core standing time that, in order to guarantee availability, does not start until 10 pm.

In N1, a *v2g* setup with TV has an dampening effect on local residual peaks, without recognition by the measures analysed in Subsection 3.2. This is shown in Fig. 10 on the date 13.2. right before vehicles are leaving in the morning *v2g* feed-in overlaps with a residual peak. In order to be able to feed-in energy, more electricity is charged during the surrounding lowest tariff windows of the scheduling horizon, i.e. the evening before. All in all, in this example TV is unable to use surplus or otherwise curtailed energy to provide this grid service in the area due to the load domination. Energy is withdrawn in deficit times resulting in a higher grid costs mainly due to higher TSO commodity charges.

As the residual load is self-similar with a periodicity of one day, especially in load-dominated areas, this local peak-shaving behaviour of TV should also translate to the global peak within the residual area load appearing the next evening (13.2.). It can be observed that the broad classification of high tariff windows and availability times prevents TV from further optimizing and therefore distributes energy during the dwell time evenly. In scenarios without *v2g*, the balanced consumption can be reduced as no energy was fed in for price optimization, explaining the observation in Subsubsection 3.2.2.

A maximum peak is a better indicator, if an assumption on transformer level is known, due to its effective influence on the grid infrastructure. In this study, however, they are not known. Although the peak residual measure

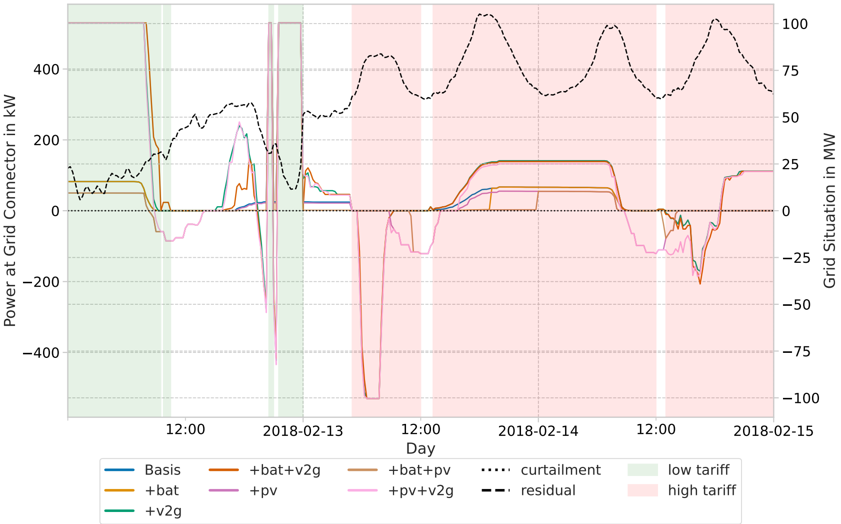

Fig. 10 Residual peak load of grid area N1 on 13.02. at 18:00 overlaps with local consumption, when TV uses V2G feature.

reveals peak shaving capabilities in this study, it concentrates on the 100. percentile of the residual load, i.e. a single point in time. A high tariff and the peak measure both aligned with the 90. percentile, respectively, are expected to achieve higher precision and a more robust representation of an increase in residual peak, also when regarding a broad adoption. This is underlined by SC, that even achieves a decrease in the residual load's peak for N2 and N3 as it can use a higher granularity in which energy procurement is prioritized.

Visible in the evening of 12.3. in Fig. 10 even short deviations are smoothened by the high performance of TV. However, a synchronization of a vast application of *v2g* in various sites has to be avoided, e.g. by increasing the ratio of low to high tariff times, but this was not in the scope of this work.

On the customer side, the extra charging is currently not compensated within the grid charges. In the visualisations in Subsection 3.3, a first estimation of a fair remuneration and compensation is indicated by the gap to the *basis* setup along the diagonal. SC cannot completely fulfill the schedule defined by the DSO, which could decrease the potential with regard to the considered measures. In spite of that fact, SC shows good performance with respect to grid costs. Nevertheless, this is another example that some behaviour is not captured by the indicators and a penalty for deviations should be introduce to avoid misbehaviour.

5 Conclusion

Three grid-serving charging strategies have been proposed, that react to daily DSO control signals based on the expected grid situation and individual cost models. The effectiveness of time-variable grid charges (TV) and flexible time window (FL) strategies and schedule (SC) was shown particularly for the increasing power consumption during times of generation surplus compared to simple non-grid-aware strategies. Also, additional flexible components could further enhance flexibility use, not only in times of surplus, but also curtailment. This enables the DSO to save costs due to a decreased load in times of regional deficit or residual load peaks and avoided curtailment costs. There is a high potential for savings especially in grid areas with a high generation surplus. However, the cost models applied in this paper, only partially reflect those savings in customer grid charges and require a parameter analysis. A visualisation was introduced that shows the effectiveness of additional flexibility on estimated grid cost components in specific grid contexts and indicates a first estimation of a fair remuneration for additional feed-in of stationary battery and V2G.

The increased certainty achieved by agreements with the DSO on a core standing time in SC comes at the cost of a constrained usable flexibility to charge during generation surplus and curtailment.

This work concludes that the TV strategy overall outperforms the other strategies due to its higher number of distinct categories representing both curtailment and residual features and consequently achieves a higher grid-serving precision. Additionally, performance indicators have to be analysed in a higher resolution of the residual in order to further reveal the effect of grid-serving behaviour.

6 Acknowledgements

The research of grid-serving charging strategies is part of the project ”Netz_eLog“, funded by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). We are grateful to the project partners and project management VDI|VDE|IT. The authors gratefully thank the Reiner Lemoine Foundation for supporting this research work.

This paper (presentation file) was presented at the 6 E-Mobility Power System Integration Symposium and published in the Symposium’s proceedings.

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