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Analysis of Tariffs and the Impact on Voltage Variations in Low-Voltage Grids with Smart Charging and Renewable Energy

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Abstract: The rapid increase in electric vehicles (EVs) and installed photovoltaic systems (PV) has resulted in new challenges for electric systems, e.g., voltage variations in low-voltage grids. Grid owners cannot directly control the power consumption of the end consumers. However, by the design of transparent tariffs, economic incentives are introduced for the end consumers to adjust their EV charging patterns. In this work, the main objective is to design a time-of-use pricing tariff to reduce the voltage variations in a low-voltage grid when introducing PVs and EVs with smart charging. Data from an existing low-voltage grid and hourly data from household power consumption, together with models of PV and EV charging, are used to simulate the voltage fluctuations based on the modified electric consumption. The results show that a time-of-use pricing tariff taking into consideration maximum peak power is important to reduce grid voltage variations. Another observation is that the use of economic incentives, such as subsidies when selling power from the household, combined with V2G technology can be economical for households but increases the voltage variations in the grid.

Keywords: electricity pricing; controlled charging; electric vehicles; solar photovoltaics

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1. Introduction

Electric energy systems have mainly been designed based on large central electricity generation units, which also contribute to voltage and frequency control. With the increasing proportion of distributed noncontrollable renewable production, mainly solar and wind-based production, there is a change in the conditions of the electric system in many countries. At the same time, significant changes in household consumption affecting low-voltage grids are expected, primarily due to the increasing number of electric vehicles (EV) charging at home and installing small-scale renewable energy production, mainly photovoltaic (PV); see, for example, [1–4]. Households thereby become a combination of consumers and producers, so-called prosumers.

Grid owners do not directly control the energy consumption of households, and it is expected that costly upgrades of the electric grids are required to cope with the additional power flows from EVs and PVs. An interesting solution is the use of technologies like smart charging and V2G that provide increased flexibility in electricity usage. One of the potentials of V2G is to charge the batteries during the daytime when the PVs produce electricity, and discharge in the evenings, when production is low but the consumption is high in residential areas. This can reduce stress on the grid by shaving the peak demand, i.e., reducing the voltage variations [5–8].

The main approach for energy companies to affect consumption patterns are in the design of the tariffs. A well-designed tariff that is transparent and easy to implement motivates consumers to use EV smart charging, to minimize the overall cost as the voltage variations in the grid decrease, and thereby reduce the need to reinforce the grid. There is great potential for both stationary battery storage systems and V2G technologies contribute to voltage stability in low-voltage grids, i.e., to reduce voltage variations. The main contribution of this work is a study of how to design the price tariff, set by the grid owner, to minimize the voltage variations in a low-voltage grid if households are using smart charging, including, e.g., with and without V2G, that is configured to minimize the household electricity cost when PV is installed.

1.1. Problem Description

The main objective is to investigate how to design a grid tariff that will reduce the voltage variations in the low-voltage grid. The focus is on the grid owner's perspective on how the tariff will affect the EV smart charging patterns. In this study, the smart charging of each household minimizes the electricity cost for a given tariff. The reduction in voltage variations in the low-voltage grid should be robust to how many EVs are parked at home and the available maximum charging power. If V2G is available, each household's smart charging will also optimize the charging patterns of the EV, or a battery storage system, to sell electricity back to the grid when it is profitable. It is assumed that all other electric consumption (e.g., heating, cooking, lighting, and electrical appliances) is not affected by the tariff. There is potential in optimizing household heating and electric usage, but this is beyond the scope of this work.

Electric consumption data have been collected from the set of households which will be used to simulate household consumption besides EV charging. This study does not take into consideration fast voltage transients since available power consumption data have only been measured once every hour. The results from this study are of great interest, primarily to grid owners, but also to authorities, to create an understanding of the expected challenges. Furthermore, the results are a basis for, for example, how to design new grid tariffs and the impact on voltage variations if the consumers behave in such a way that the electricity cost is to be minimized.

1.2. Paper Outline

The outline of the paper is organized as follows. First, related research is summarized and discussed in Section 2. The low-voltage grid that is used as a case study is presented in Section 3. Section 4 describes the modeling of the nominal grid model and models of EVs and PV. Section 4.4 describes how nominal household electricity consumption data are used to validate the grid model and estimate the voltage variations in the transformer. Section 5 presents the candidate tariff models and the results from the evaluations are presented in Section 6. Monte Carlo simulations of the voltage variations are made for different tariffs, maximum EV charging rates, and how many EVs are connected to the grid. Finally, the conclusions are given in Section 7.

2. Related Research

To keep up to date with the rapid development in the electric system, it is necessary to analyze how distributed production of renewable energy, the use of stationary energy storage, and electric vehicles, will affect the grid to find solutions to adapt to the new conditions. In [9], Gotland's (Gotland is the largest island in Sweden) electric grid has been analyzed to investigate how the grid could be supported using EVs and smart charging infrastructure. The authors of [2] showed that a high proportion of PVs and EVs in an area can have a great influence on voltage variations and in their study, 50% of the households were affected by high voltage levels.

In [10], the benefits when several households use a common battery storage system (BSS) system and a common energy meter are investigated, instead of one meter per household, so that the energy flow between the houses can be optimized without increasing the total energy cost. The authors in [1] analyze the transport network and how an increased share of EVs that are charged in different locations affect the voltage stability in different parts of the electric grid. A convex optimization-based charging scheduling algorithm of BSS is proposed in [11] to minimize the peak demand and encourage the self-consumption of PV generation. In [8], integrated energy systems are coupled with V2G. Results from different scenarios show an improvement in cost and emissions by enabling V2G for smart charging compared to without V2G. The potential of V2G for voltage peak shaving was shown in [5] using a rural area in Brazil as a case study.

Many research reports and surveys have been implemented to understand how much uncontrollable electric production can be installed and at the same time maintain stability in the electric grid; see, for example [12]. Most of these focus on the national perspective and the high-voltage grid. However, it is not certain that households are willing to allow the grid owner to use their vehicle battery to stabilize the voltage variations in the electric grid [13]. The authors in [14] analyze the impact of dynamic tariffs on EV charging behavior, which shows that charging is moved to periods with high PV production. With respect to the mentioned work, the focus here is on how to design a tariff that minimizes the voltage variations in low-voltage grids with installed PVs and EV smart charging.

The authors in [15] propose a framework based on developed indicators to evaluate different tariffs. The indicators focus on the costs for the different households and the costs of grid owners. However, the analysis in the mentioned work does not consider voltage stability in the grid. In [16], modified tariffs are evaluated in residential grids with renewable energy production and EVs. In [17], the bill of a single household using V2G is minimized for different time-of-use tariffs. The authors in [18] analyze how to use tariffs to encourage V2G participation for energy storage and grid stability in Ontario, Canada. The authors in [19] focus on tariff design for grid cost recovery in a grid with V2G, BSS, and prosumers. Analysis of the potential of V2G and the second purpose of EVs in the UK is performed in [20]. In [21], a deep learning-based predictive model for household consumption is trained to be used for the simultaneous optimization of energy storage systems and real-time pricing. In [22], a coordination strategy is proposed that combines dynamic tariffs and scheduled reprofiling products for congestion management in the distribution grid. With respect to the previous work, the effects of different tariffs on voltage variations in the grid are investigated by analyzing the robustness towards uncertainties in EV charging rates and the number of connected EVs.

3. Case Study

The low-voltage grid that is used as a case study is located in the Swedish city of Linköping, where a schematic image of the grid is shown in Figure 1. The grid has a radial structure, where node 1 is the high-voltage side of the transformer and node 2 is the low-voltage side. The power cables are branched out to 30 end consumers, of which 28 are households, one is a daycare center, and one is a connection point for street lighting. Power consumption and phase voltage data of the consumers have been measured for one month. This grid is considered to be a relatively strong grid with low impedance since it was initially built to support electrically heated homes, but the electric power consumption has decreased since district heating is currently used instead. An example of the measured power consumption for three of the 28 households is shown in Figure 2.

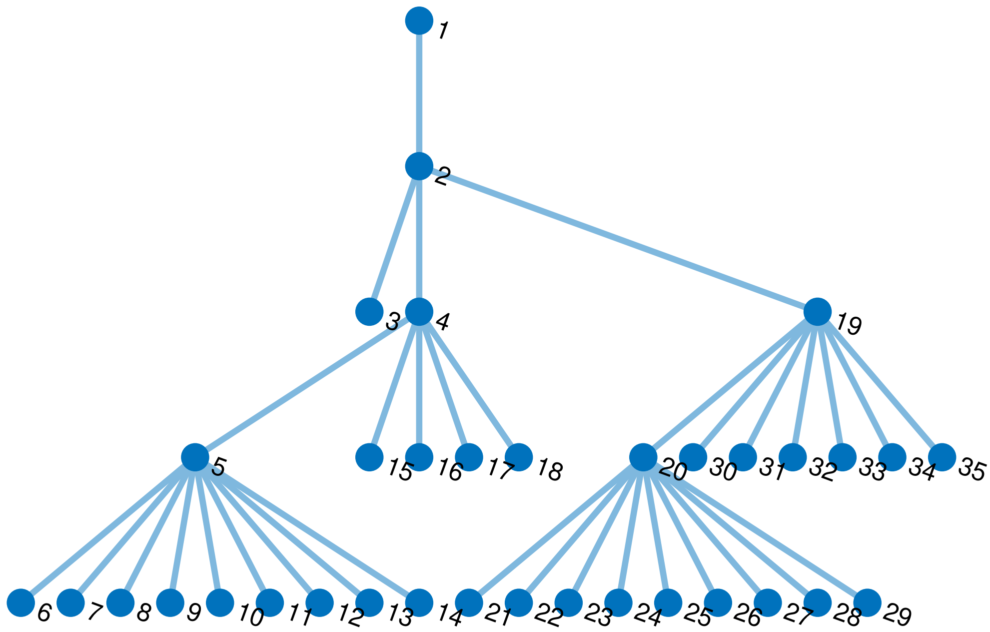

Figure 1. Low-voltage grid network structure with 30 end consumers, comprising 28 households, a daycare center (node 3), and a connection point for street lighting (node 4).

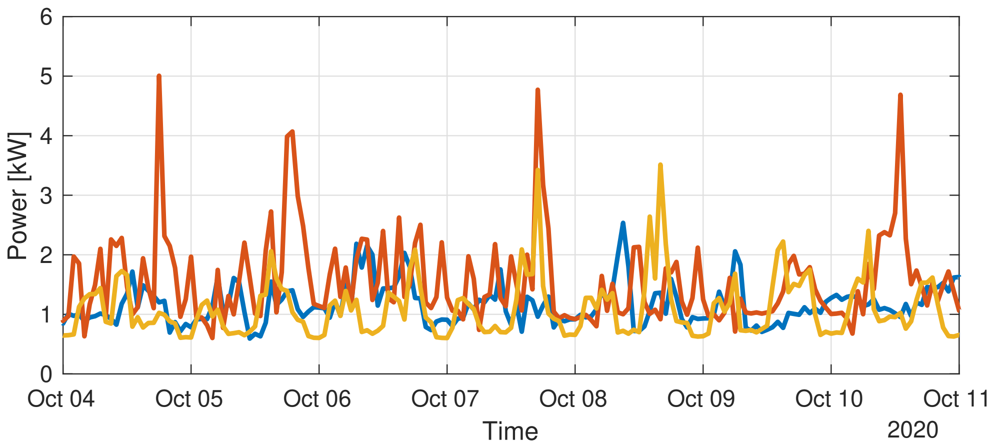

Figure 2. Example of measured power consumption in three households.

To exemplify the impact of PV and EV charging on voltage stability in the low-voltage grid, four different scenarios are presented in Figure 3, where the grid presented in Figure 1 is used as well as the measured electricity consumption. In the top left plot in Figure 3, the nominal voltage variations for all end consumers are calculated based on measured electric consumption during summer 2020, where the voltage is close to 230 V. In the top right plot, an EV that is charged every day after working time with a maximum charging power of 5 kW is added to the measured electric consumption. The effect of charging is visible where the grid voltage drops around 5–8 V in households. The voltage levels when each household installs PVs with a peak power of 10 kWp are shown in the bottom left plot, where the maximum voltage reaches 245 V during certain periods. The voltage variations in the households when adding both EVs and PVs to the measured electric consumption are shown in the bottom right plot. Note that EV charging does not affect the voltage peaks because charging takes place after working hours, while the largest electricity production takes place at noon.

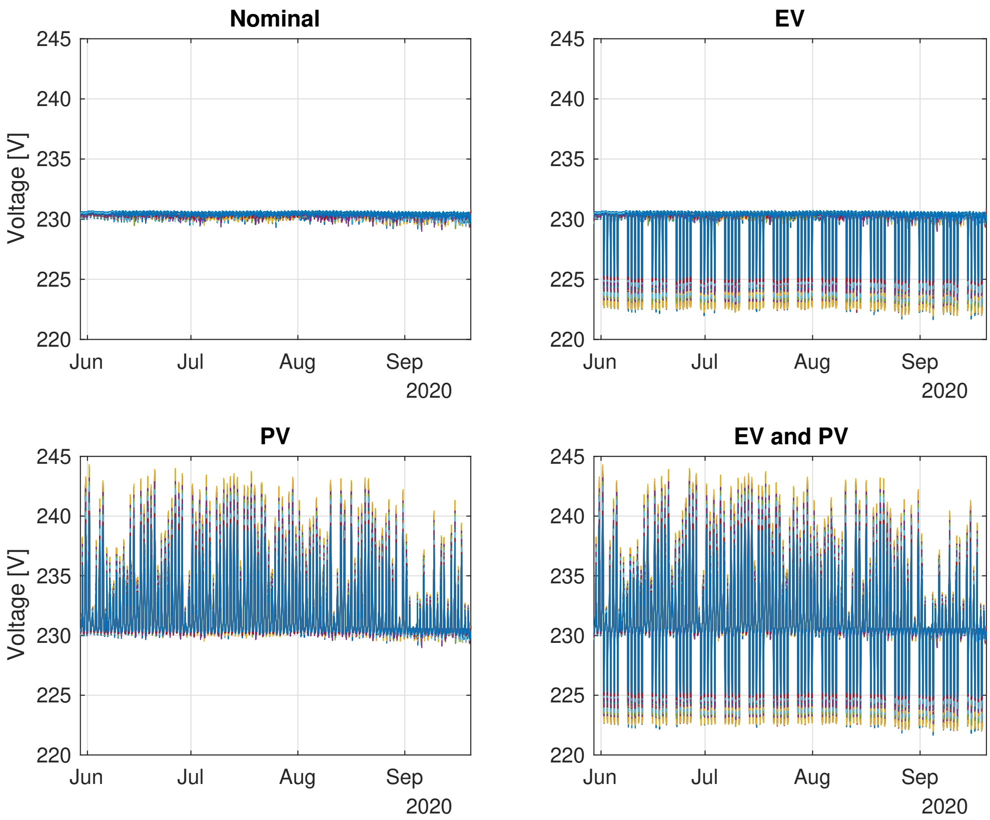

Figure 3. Phase voltages for all households in the considered grid given existing consumption data, imposed electric car charging with 5 kW (all households charge simultaneously) and solar production (10 kWp).

4. Modeling

To evaluate the effects of installed PVs and EV charging, a model of the electric grid is implemented. First, the described grid model is used for computing currents and voltages in the low-voltage grid. Household energy consumption data for the year 2020 are used. Then, EV charging and PV production, based on data for solar radiation, are modeled and presented.

4.1. Low-Voltage Grid

The low-voltage grid is modeled by assuming a balanced three-phase system. Furthermore, household consumption data are only available for active power. To simulate the grid, the power factor is assumed to be equal to one, which means that the apparent power is as large as the active power.

The electric grid in Figure 1 has a tree structure from the transformer station to all households. The complex current I_c in each cable in the grid, represented by the edges in the figure, is computed using

$$I_c = \frac{S}{\sqrt{3}U_h} \tag{1}$$

where S is the complex apparent power and U_h is the voltage in the node closest to the transformer station the cable is connected to. The losses in the cable S_{loss} are given by

$$S_{loss} = 3Z_c|I_c|^2 = 3Z_c I_c I_c^* \tag{2}$$

where Z_C denotes the cable impedance and I_c^* denotes the conjugate transpose of I_c. The voltage drop U_δ across the cable is calculated as

$$U_\delta = -\sqrt{3}I_c Z_c \tag{3}$$

and the total current through each node in the grid is given by Kirchhoff's current law.

Simulation of Electric Grid Model

In the electric grid model, the voltage of the transformer station is assumed to be known on the high voltage side. Furthermore, the hourly household energy consumption is known. To compute the complex voltages and the currents in the grid, a forward–backward sweep (FBS) algorithm has been implemented. The solver structures the grid model into two sets of equations, where the solution from one set of equations is used to solve the second set [23]. In the first phase, referred to as backward sweep, the currents in the grid are calculated given the voltages in the grid. In the forward sweep, the voltages are calculated given the currents calculated in the previous step [24]. The backward sweep and forward sweep phases are solved, iteratively, until the solution has converged.

Let $\mathcal{N} = \{1, 2, \ldots, N\}$ denote the set of N households connected to the low-voltage grid. The nominal electricity consumption in the set of households is represented by $S_{\mathcal{N}}(t) = [S_1(t), S_2(t), \ldots, S_N(t)]$. The solar production is noncontrolled and denoted $P_{pv,\mathcal{N}}(t) = \left[P_{pv,1}(t), P_{pv,2}(t), \ldots, P_{pv,N}(t)\right]$. Let $P_{ev,\mathcal{N}}(t) = [P_{ev,1}(t), P_{ev,2}(t), \ldots, P_{ev,N}(t)]$, where $P_{ev,n}(t)$ is the EV charging profile for household $n \in \mathcal{N}$. The electric grid calculations are made by the FBS algorithm, as described in, e.g., [23], according to the following notation:

$$\hat{U}_{\mathcal{N}}(t) = FBS\Big(U_{trafo}(t), S_{\mathcal{N}}(t) - P_{pv,\mathcal{N}}(t) + P_{ev,\mathcal{N}}(t)\Big) \tag{4}$$

where the voltages $\hat{U}_{\mathcal{N}}(t)$ in all households N are calculated as a function of the transformer primary voltage $U_{trafo}(t)$, household consumption $S_{\mathcal{N}}(t)$, PV production $P_{pv,\mathcal{N}}(t)$, and EV charging profiles $P_{ev,\mathcal{N}}(t)$.

4.2. PV System

The model for the energy production from installed PVs used in this study is described in [25]. The generated power is a function of solar radiation, orientation, inclination, outdoor temperature, geographical location, and time of year. Data for solar radiation have been retrieved from 2020 from the Swedish Meteorological and Hydrological Institute (SMHI), where they are available on an hourly basis. In all analyses, it is assumed that the PVs are oriented straight south with an inclination angle of 22 degrees. The considered PV installation is designed to produce a peak power of 10 kWp, which is a common size of PVs in villas according to the grid owner in Linköping municipality, where the study was carried out. An example of the modeled PV production in a household is shown in Figure 4.

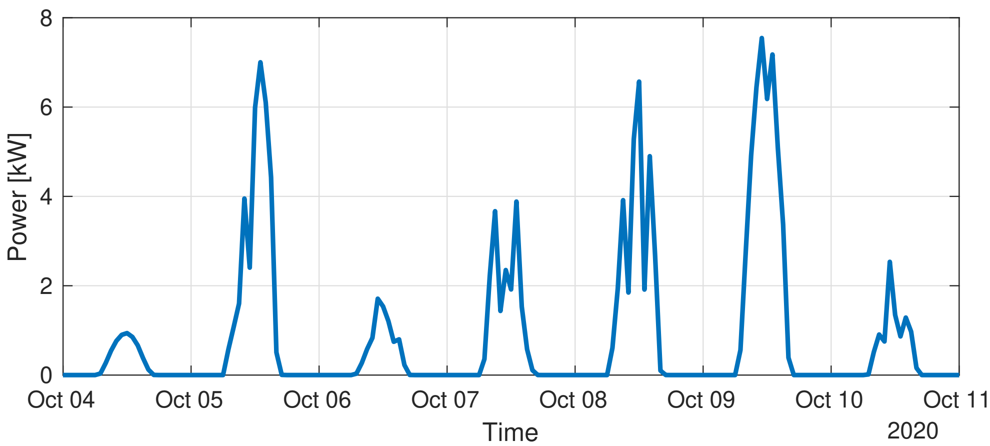

Figure 4. Simulated production from a PV installation based on data for solar radiation and outdoor temperature.

4.3. EV Charging

An EV is modeled as a battery that is connected to the grid when the vehicle is at home. The energy charge level of the battery, $S\hat{O}E \in [0,1]$, is calculated as

$$S\hat{O}E(t+1) = S\hat{O}E(t) + T\frac{1}{C_{batt}}P_{ev}\eta^{\text{sign}(P_{ev})} \quad (5)$$

where C_{batt} is the energy storage capacity of the battery, P_{ev} the power to or from the battery, η is the efficiency that here is assumed to be constant, and T is sampling time (1 h). The battery voltage when no current is drawn from the battery is assumed to be independent of SOE, which results in the battery's normalized charge level $SOC \in [0\%, 100\%]$ being the same value as its SOE.

Each EV is modeled to have an energy storage capacity of 100 kWh and is used in such a way that it consumes an energy amount of 15 kWh every weekday. For uncontrolled charging, it is assumed that all EVs are charged with maximum power immediately when they arrive home and that the charging continues until the vehicles are fully charged. Fully charged in this study means 90% because the batteries are aged faster if the vehicles are frequently charged to 100%. The charging profile is shown in Figure 5, where it is shown that the vehicle is plugged in throughout the weekend (3 and 4 October). The battery efficiency is set to $\eta = 0.95$ both during charging and discharging. In this work, the SOE is limited to vary between 10–95% when optimizing the battery charging power.

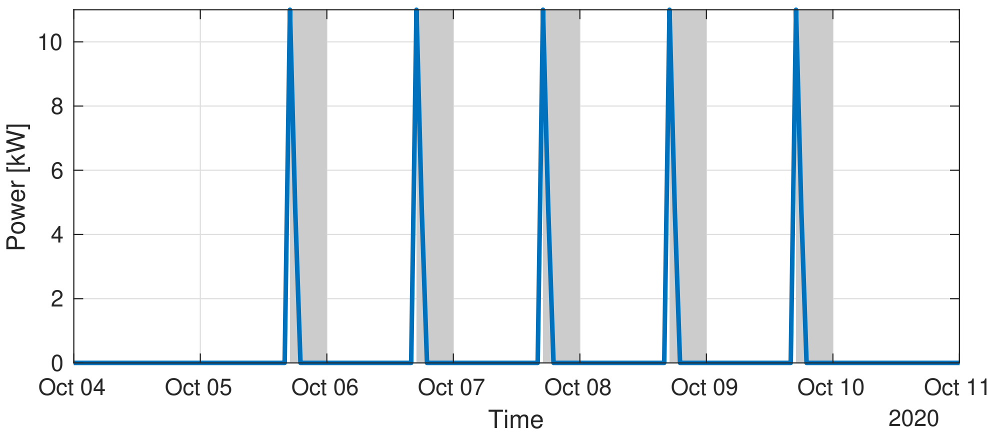

Figure 5. Charging profile for non-optimized EV charging. The car is charged with maximum power until the battery is fully charged. The gray areas represent when the vehicles are at home and connected to the grid.

4.4. Estimation of Transformer Voltage

In the data used in this study, the transformer voltage is not measured. The transformer voltage is dependent on the voltage variations in the regional grid. Thus, an accurate estimation of the nominal transformer voltage for each hour in the dataset is needed to simulate the variations in the low-voltage grid when introducing PV and EV. This is needed in the evaluation of the different tariffs but is not required in the real-time implementation of a smart charging scheme.

In this study, measurements of both power consumption and voltage in all households are available. Before analyzing the impact of PV and EVs, an optimization-based approach is used together with the grid model and power consumption data to find the nominal transformer voltage variations that best agree with the measured household voltages.

Let $\hat{U}_{\mathcal{N}} = [\hat{U}_1, \hat{U}_2, \ldots, \hat{U}_N]$ represent the estimated voltages in the N household nodes. The transformer voltage on the high-voltage side is estimated by solving the optimization problem

$$\begin{aligned} \min_{U_{trafo}(t)} \quad & \sum_{n=1}^{N} \big(U_n(t) - \hat{U}_n(t)\big)^2 \\ \text{s.t.} \quad & \hat{U}_{\mathcal{N}}(t) = FBS\Big(U_{trafo}(t), S_{\mathcal{N}}(t)\Big) \end{aligned} \tag{6}$$

for each time t where U_n is the measured voltage in the household n and $\hat{U}_n \in U_{\mathcal{N}}$ is the corresponding estimated voltage. The estimated transformer voltage $U_{trafo}(t)$ that is fed to the grid model minimizes the mean square error between simulated $\hat{U}_n$ and measured voltages U_n in the household nodes. The solution is shown in Figure 6. The top image shows the estimated transformer voltage and the bottom graph shows the corresponding average mean square error between computed and measured voltages in all the households. The accuracy in the modeling is further confirmed by comparing the computed voltages using the consumption data and the estimated transformer voltage with the measured voltage in the households; see Figure 7. The figure shows computed, and measured, voltages and prediction error, for the three households with node indices 9, 18, and 33; see Figure 1. The magnitude of the prediction error is, almost always, within 0.1–0.2 V for all households. The simulation results also indicate that the electric grid model, i.e., the given cable impedance matrix, and the estimated voltage trajectories are reliable.

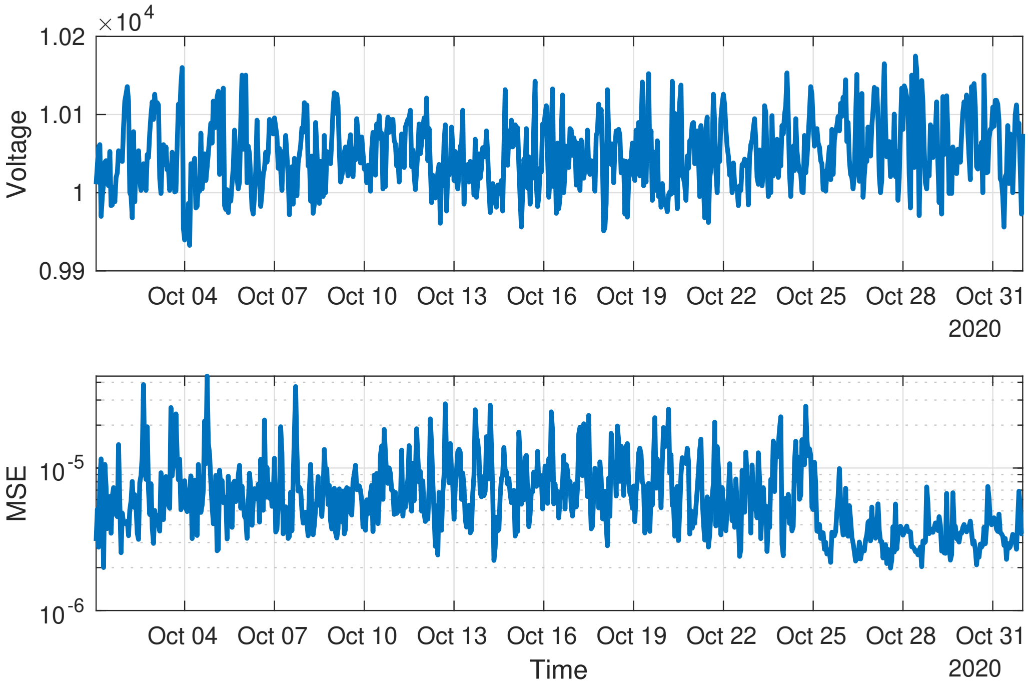

Figure 6. The top plot shows the estimated transformer voltage for the high-voltage side. The bottom plot shows the resulting optimal cost function.

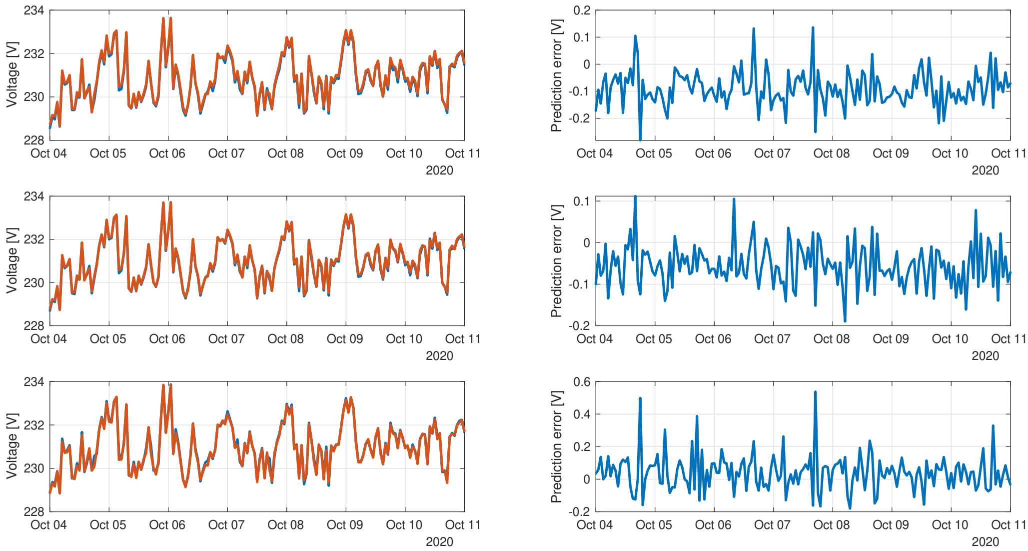

Figure 7. The left plots show phase voltage levels for three households, both measured (blue curve) and estimated (red curve), given the estimated transformer voltage from Figure 6 for three different nodes in the grid. The right plots show the prediction errors.

5. Tariff Models

Today, household electricity costs in Sweden mainly vary with the spot price, but there are price models where the tariff is calculated based on the maximum active power P in the household each month. The maximum power for a month, $\max_{t \in T}(P(t))$, where T specifies the period, is multiplied by a parameter, c_p, which results in a power cost. The spot price tariff includes, when energy is purchased, energy price (spot price excluding VAT that is 25% in Sweden), $c_e(t)$; energy tax, c_t; electric grid transmission (the part that is proportional to the energy transmission volume), c_g; and surcharges from electricity trading companies, c_o. When energy is sold, there is a tax reduction, c_{red}, to compensate for the energy tax, transmission fee, and VAT when the energy later is bought back. Based on the average power consumed per hour, $P(t)$, the total cost for the period T (specified in the number of hours) can be calculated according to:

$$C_{\text{spot}} = \sum_{P(t) \geq 0, t \in T} \left[P(t) \cdot (c_e(t) \cdot 1.25 + c_t + c_g + c_o)\right] + \\ + \sum_{P(t) < 0, t \in T} \left[P(t) \cdot (c_e(t) + c_{red})\right] \tag{7}$$

The spot price can be seen in Figure 8: $c_t = 0.445$ SEK/kWh, $c_g = 0.245$ SEK/kWh, $c_o = 0.03$ SEK/kWh, and $c_{red} = 0.60$ SEK/kWh.

The end consumer in Linköping municipality has the opportunity to choose a peak power-based tariff instead of the one presented in (7). The parameter c_p is currently set to 50 SEK/kW and month during the winter period. All parts that are in the tariff based on the spot price in (7) are also included in the power tariff, but the proportional part, c_g, is lower in the power tariff, 0.10 SEK/kWh compared to 0.245 SEK/kWh.

$$C_{\text{peak}} = \sum_{P(t) \geq 0, t \in T} \left[P(t) \cdot (c_e(t) \cdot 1.25 + c_t + c_g + c_o)\right] + \left(\max_{t \in T} P(t)\right) \cdot c_p + \\ + \sum_{P(t) < 0, t \in T} \left[P(t) \cdot (c_e(t) + c_{red})\right] \tag{8}$$

The tax reduction based on households' sold electricity means that the compensation for the sale of electricity is in the same order of magnitude as the price for buying electricity.

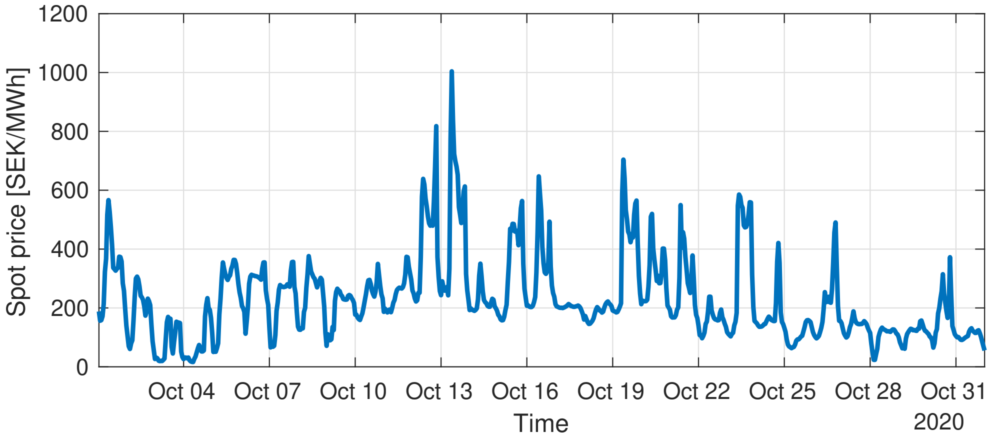

Figure 8. Spot price in Linköping during October 2020.

For households to be able to obtain an overview of their electricity costs, relatively simple pricing models are required. Therefore, a set of tariff models are here compared based on the existing spot and power tariffs for different scenarios where households have smart charging with or without V2G, the maximum charging power that is installed, and depending on when the vehicles are at home. The following factors are used to evaluate the resulting voltage variations in the low-voltage grid:

1. The time-of-use pricing model is mainly based on the spot price (7) or peak power (8).
2. The peak power used in the power-based tariff is either based on the maximum power consumption or the maximum absolute value of the power, i.e., both consumption and production.
3. The EV is at home and connected to the grid outside working hours (see Figure 5) or parked and connected at all times, i.e., it acts as stationary battery storage.
4. The EV charging can only be used to charge the EV or the vehicle's battery can also be used for household consumption (Vehicle-to-home V2H) or output electricity to the electricity grid (V2G).
5. When calculating compensation for the household's sold power, the tax reduction c_{red} on the household's sold power is or is not included.

The first two factors are related to the tariff model; factors three and four describe how the EV is used; and the final factor is the use of tax reduction on sold electric power. The set of candidate tariffs is summarized in Table 1.

Table 1. This table summarizes the tariffs that will be evaluated.

Tariff	1	2	3	4	5	6
Spot/peak power	Spot	Spot	Peak	Peak	Peak	Peak
Tax reduction	X		X	X		
Peak absolute power				X		X

As a reference, the results will be compared to a scenario without PVs and EVs, a scenario when all households only have PVs, and two scenarios with PVs and EVs with non-optimized charging with a maximum charging power of 5 kW and 11 kW. These cases are summarized in Table 2. The analysis compares the residential area's maximum voltage variation in the low-voltage grid and the total electricity cost for all households.

Table 2. This table summarizes the scenarios that will be used to compare the results from optimized charging profiles for different tariffs.

Scenario	Description
No PV + EV	Consumption (data)
PV only	Consumption + PV production, no EV
basic charging 5 kW	Consumption + PV + EV charging 5 kW
basic charging 11 kW	Consumption + PV + EV charging 11 kW

6. Evaluation of Different Tariffs

The effects of the different tariffs in Table 2 are evaluated by computing cost-optimal charging profiles, simulating smart chargers, for each household, and then analyzing the resulting voltage variations in the grid. The analysis focuses on how sensitive the voltage variations are to the available maximum charging power and how many EVs are home and connected to the grid.

6.1. Simulation of Voltage Variations for a Given Tariff

The simulation of the smart charging strategy is conducted by using dynamic programming to find the optimal charging profile for each household that minimizes the total electricity cost given a specific tariff. The analysis is performed for one month, October 2020. When the charging profiles for all households have been optimized, the resulting voltage variations in the electric grid are calculated given the households' total electricity consumption and production. Finally, the voltage variation is calculated by taking the difference between the maximum and minimum voltages in the grid throughout the month, since the extreme voltages are of most importance when evaluating the grid stability.

The optimal charging pattern for EVs when power tariffs are used depends on the peak power. The optimal charging pattern is computed by running dynamic programming with constraints on different maximum power and the cost function minimized in the suboptimization problem is based on (7). The optimal charging pattern to a given power tariff resulting in the lowest cost based on (8) is selected for the corresponding household in the evaluation of the grid stability. Note that the cost-optimal charging patterns for different households can have different peak power levels.

6.2. Monte Carlo Simulation of EV Usage

In practice, it is not likely that all vehicles will be home or away at the same time. Therefore, in the analysis, a subset of EVs will be parked at home during weekdays which can store energy from the PV systems. However, depending on which households that will keep their EVs at home, the impact on the voltage levels is likely to differ. A Monte Carlo study is used to analyze the impact on grid voltage when different percentages of the EVs are at home for each tariff. Different EVs are randomly selected to be at home and the resulting voltage variations are computed. For each tariff and selected rate of EVs staying at home, 1000 Monte Carlo samples are evaluated. The range of the voltage variations is shown in Figure 9 for the different tariffs and for different levels of allowed maximum EV charging power. Each figure shows the different quantiles {0%, 25%, 50%, 75%, 100%}, of the resulting voltage ranges which illustrates the variability in the voltage variations depending on which households have their EVs at home.

Figure 9 shows that higher maximum charging power significantly increases the voltage variations for the tariffs based on the spot price (tariffs 1 and 2) and does not include the peak power. Even for tariffs based on peak power (tariffs 3 and 5), the voltage variations increase with higher maximum charging power. This is explained by that even though there is peak shaving on consumption, there is no penalty on how much electricity is sold from the household, which also increases voltage variations. The smallest increase in voltage variations is for the tariffs penalizing the absolute peak power (tariffs 4 and 6) since this affects the maximum power flow both to and from each household. The figure also shows that tariffs 4 and 6 also have an almost linear voltage variation as a function of the rate of EVs at home. The other tariffs have a minimal voltage variation when a subset of EVs is at home.

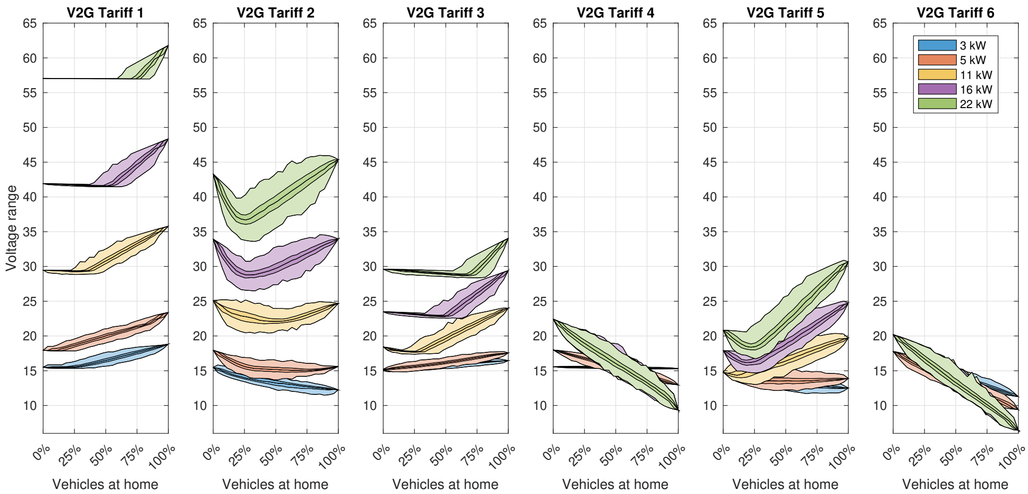

Figure 9. Monte Carlo study evaluating the impact of different rates of EV that are connected to the grid during the daytime on the voltage range, i.e., the difference between maximum and minimum rated voltage in the grid. The lines represent different quantiles {0%, 25%, 50%, 75%, 100%} when randomly selecting different combinations of households.

A comparison of the maximum and minimum voltages for the different tariffs shows that the "V" shape comes from the variations in the maximum voltage levels, i.e., when the batteries are discharged. As an example, Figure 10 shows the distribution of maximum and minimum voltages from the Monte Carlo study for the 11 kW case for each tariff. The deviation of the lower voltage level from the nominal 230 V improves with an increasing number of vehicles parked at home, while the maximum voltage levels diverge when there is no penalty on negative peak power. This can be explained by that these tariffs can result in more aggressive trading of electricity when solar power is produced to reduce the cost. Then, when only a subset of vehicles is parked at home, the total impact is less when those households can store the produced power in the residential grid during the daytime, which will reduce the voltage variations, even though some of the stored electricity is sold later when the spot price is higher. However, when the number of parked vehicles exceeds a certain rate, the peak voltage is not reduced but only moved to a different time when it is more economical to sell the stored electricity. For the tariffs penalizing the absolute value of the power, the voltage variations will dampen this effect, resulting in a general improvement in voltage variations when more vehicles are parked at home since the stored energy will be used to flatten out the power consumption.

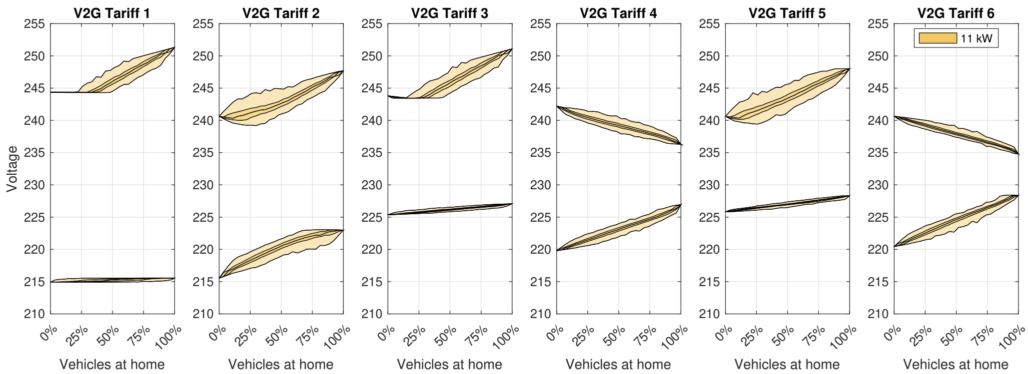

Figure 10. The curves show the distribution quantiles of the maximum and minimum voltage levels from the Monte Carlo evaluations for 11 kW.

Another observation in Figure 9 is that the median voltage range from the Monte Carlo study is largest when either all vehicles are at home or when all are away during the daytime. Thereby, the voltage range does not increase when only a subset of the households have their vehicles at home. When the tariff is based on the absolute value of the power, the voltage variations are less likely to exceed the voltage range when no EVs are at home during the daytime.

The use of tariffs based only on spot prices results in large voltage variations as there is no cost to limit electricity consumption at a certain point in time. Utilizing V2G, the EVs are used as energy storage that is charged when the electricity is cheap, and the electricity is used or sold when the price is high. The voltage variations vary with the installed maximum power of the charging of the EVs, where higher charging power results in greater variations. This is also visible when looking at the specific cases when either all EVs are at home the whole time or when all are away during the daytime on weekdays.

The left plot in Figure 11 shows the case when no EVs are home during working hours. The right plot in Figure 11 shows the case when all EVs are parked at home the whole day, which also corresponds to when a stationary battery is used instead of EVs. Each curve corresponds to a specific combination of tariff and scenario and each point on the curve corresponds to a maximum charging power for the EV of 3 kW, 5 kW, 11 kW, 16 kW, and 22 kW. In the left figure, the results from using tariffs 1 and 3, but without V2G, are also included. The least voltage variation is when no households have either PVs or EVs. As expected, if EVs are not at home during the daytime, smart charging cannot benefit from PV production, and the voltage variations cannot be improved as much.

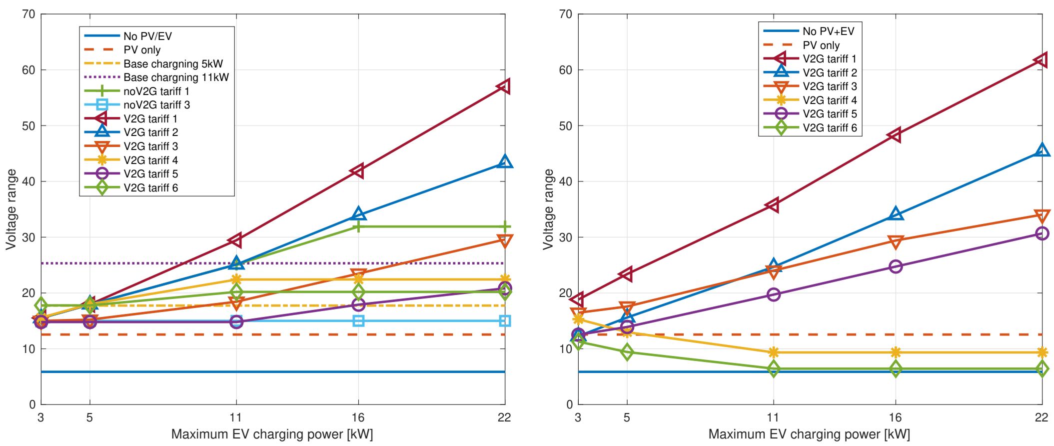

Figure 11. Comparison of different tariffs and charging scenarios with V2G when EVs are at home outside working hours in the left plot and when EVs are at home all day in the right plot. Note that base charging also includes PV. The maximum charging rate is compared with the maximum voltage variation.

6.3. Analysis of Household Power Consumption and EV Charging Pattern

The effects of the different tariffs are visible when analyzing the EV charging trajectory for different maximum charging power. An example of the charging profiles for EVs with V2G and a tariff based on the spot price and tax reduction on sold electricity (tariff 1) is shown in Figure 12 when EVs are away during daytime and in Figure 13 when EVs are at home. The figures show the power consumption for household 29 in the grid, the EV charging profile, the corresponding SOC in the EV, and the spot price. The figure zooms in on the results from the simulation for the period 10 October–18 October. Two cases are shown when the charging station has a maximum power of 5 kW (red curve) and 22 kW (blue curve), respectively. The power consumption and EV charging vary a lot when 22 kW is available. It is optimal for the end consumers to try to sell electricity when the price is high and charge when the price is low, which often happens at night and early in the morning. There are no incentives in this scenario to limit the power variations as long as the current is within the limit for the main fuses.

In Figures 14 and 15, tariff 4 is used. Compared with tariff 1 in Figures 12 and 13, the power variations in the upper graphs are much smaller. Since the cost is based on the absolute value of the peak power, some purchases and sales of electricity still take place, which can be seen when the power trajectory varies with the spot price, even if the levels are limited. The increase in voltage variations is much smaller in Figure 11 when the tariff is based on the absolute value of the peak power (blue diamonds) compared to if it is only based on the maximum power consumption (red triangles).

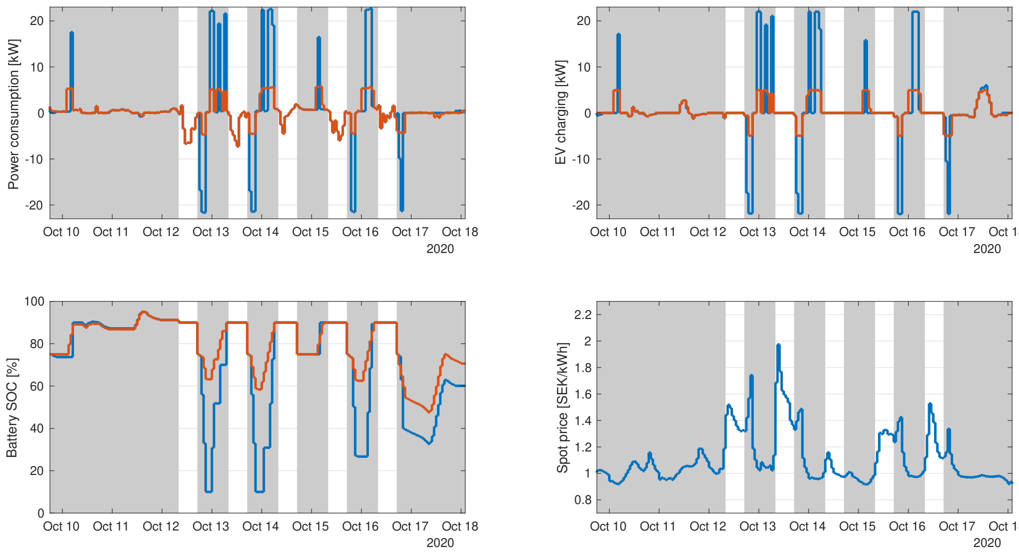

Figure 12. This figure shows the power consumption and charging power for household 29, where the blue curve corresponds to a maximum charging power of 22 kW and the red curve 5 kW. The charging profile has been optimized based on tariff 1 with V2G when the EV is connected to the grid outside of working hours. The intervals when the EV is connected to the charging station are marked in grey. The lower left figure shows the corresponding SOC for the EV. The bottom right figure shows the spot price.

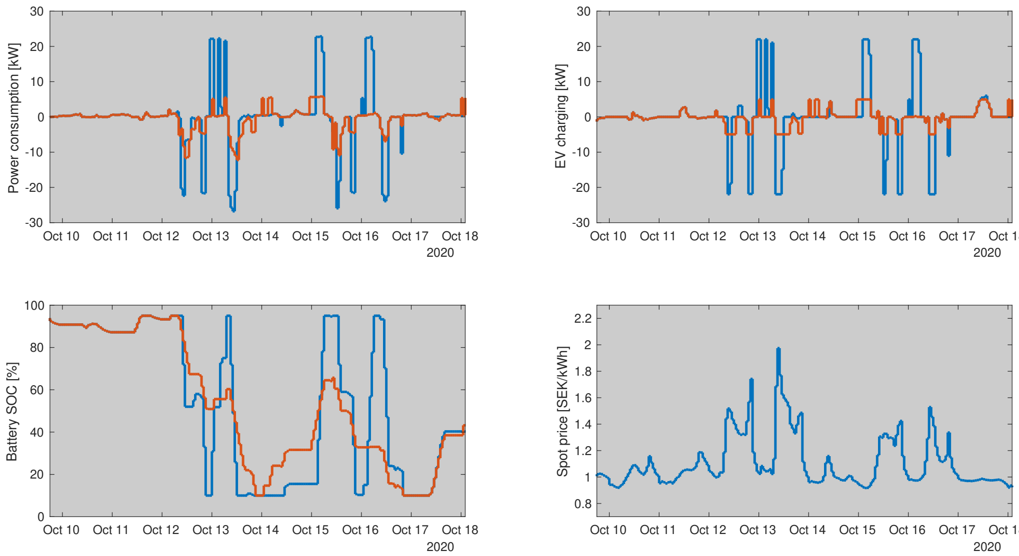

Figure 13. The figure shows the power consumption and charging power for household 29 when the EV is connected to the charging station at all times. The blue curve corresponds to a permitted maximum charging power of 22 kW and a red curve of 5 kW. The charging profile has been optimized based on tariff 1 with V2G.

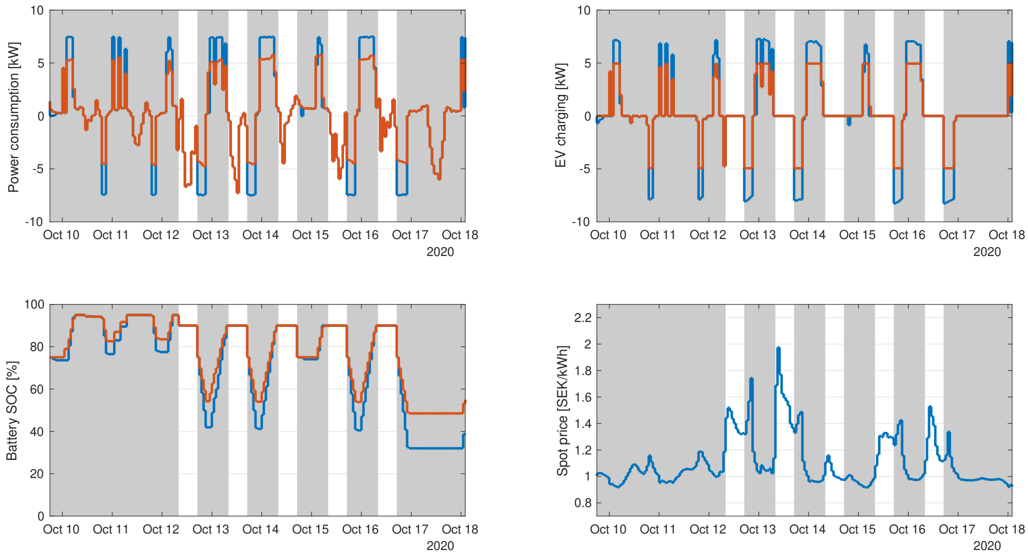

Figure 14. The figure shows the power consumption and charging power for household 19, where the blue curve corresponds to a maximum charging power of 22 kW and a red curve of 5 kW. The charging profile has been optimized based on tariff 4 with V2G.

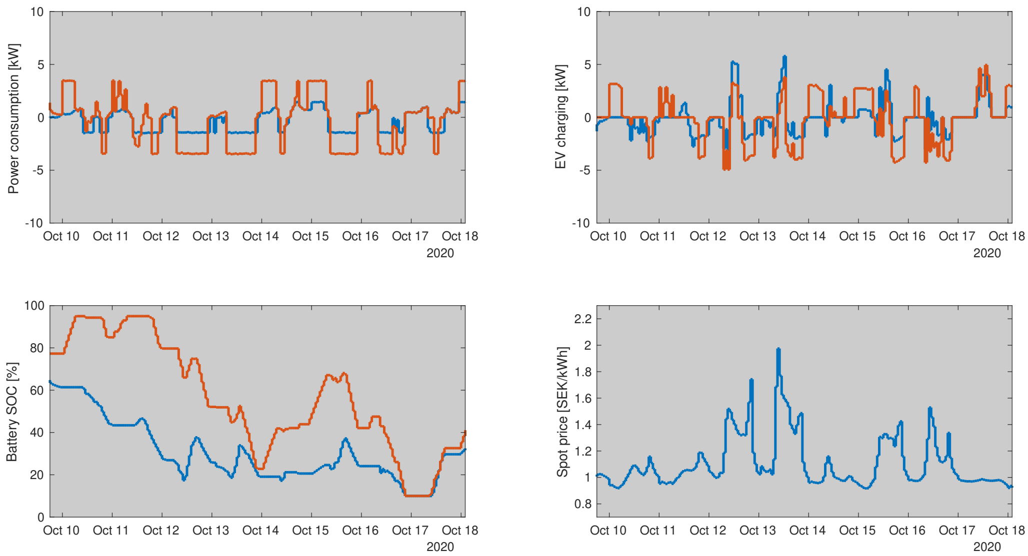

Figure 15. The figure shows the power consumption and charging power for household 29 when the EV is connected to the charging station at all times. The blue curve corresponds to a permitted maximum charging power of 22 kW and a red curve of 5 kW. The charging profile has been optimized based on tariff 4 with V2G.

In Figures 16 and 17, tariff 5 is used. Here, the tax reduction has been removed, and the optimal solution shows that it is less economically advantageous to sell electricity. Therefore, it is better to store and use electricity for the household's consumption, V2H, instead of V2G. As shown in Figure 11, the charging profile and the voltage variations do not vary significantly for different maximum powers but are the same.

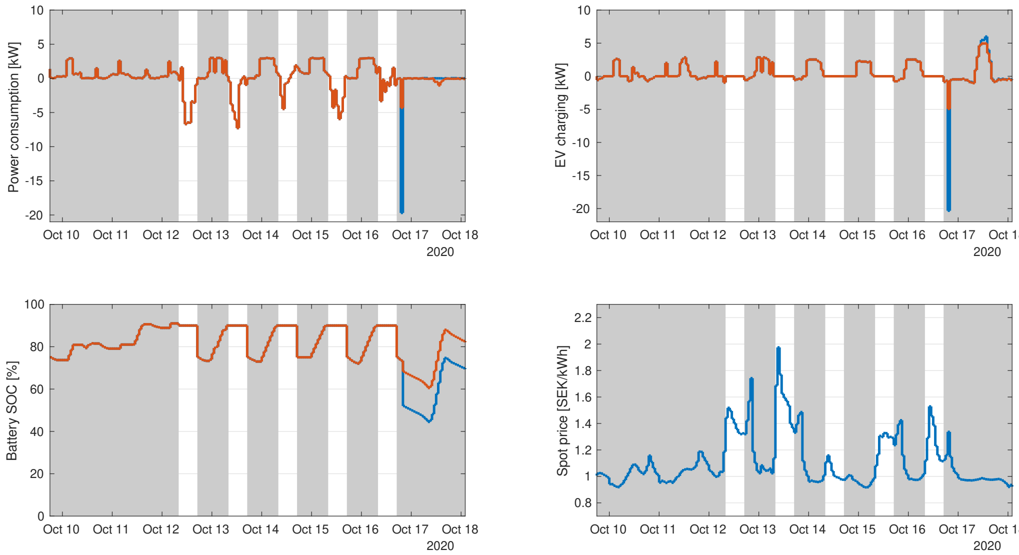

Figure 16. This figure shows the power consumption and charging power for household 19, where the blue curve corresponds to a maximum charging power of 22 kW and the red curve 5 kW. The charging profile has been optimized based on tariff 5 with V2G.

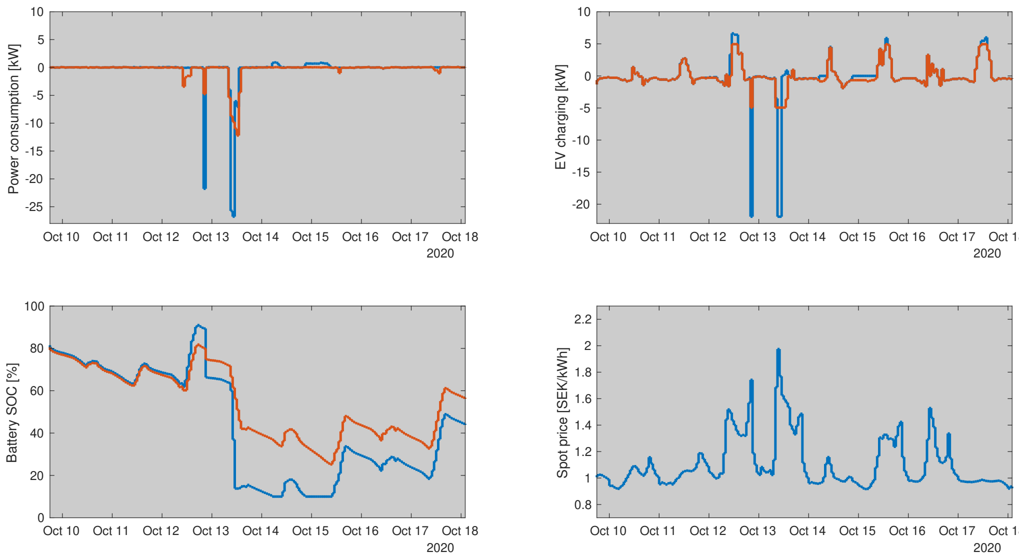

Figure 17. This figure shows the power consumption and charging power for household 19 when the EV is connected to the charging station at all times. The blue curve corresponds to a permitted maximum charging power of 22 kW and a red curve of 5 kW. The charging profile has been optimized based on tariff 5 with V2G.

7. Conclusions

In this study, the impact of different tariffs on EV charging patterns and voltage variations in a local low-voltage grid is evaluated when introducing PV and smart charging. Smart charging with V2G can reduce household electricity costs by buying and selling electricity. This study shows that the tariff will have a significant impact on the charging patterns and thus the voltage variations in the grid. Monte Carlo simulations using measured household power consumption data show that tariffs based on peak power distribute the power profiles to avoid large power flows in the grid, simultaneously as the power consumption patterns are affected by the spot price. The importance of reducing the peak power is even more important when V2G or stationary batteries are used since synchronized trading by multiple households could move the peaks to a different period and not flatten them. Results show that if the households have EVs charging at home during the day, or stationary batteries, buying and selling energy is important for the low-voltage grid stability to also reduce the peak power in the sold energy. The tariffs with the best effects are those that are less profitable to sell lots of electric power at the same time. This can be achieved by the design of the grid tariff, but it is also shown that reducing the existing tax reduction for sold electricity is a possible solution. Since the rate of households with BSS or EVs at home during the daytime has a significant impact on voltage stability, the tariff based on peak absolute power is shown to be robust to these uncertainties.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations and nomenclature are used in this manuscript:

BSS	Battery storage system
EV	Electric vehicle
FBS	Forward–backward sweep
PV	Photovoltaic
SEK	Swedish Krona
SOC	State-of-charge
SOE	State-of-energy
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
Nomenclature	
I_c	Complex cable current
P	Active power
P_{pv}	Produced power from photovoltaic
P_{ev}	Charging power by electric vehicle
S	Apparent power
U_n	Complex voltage in node n
U_{trafo}	Voltage in transformer's high-voltage side
Z_c	Cable impedance
$X_{\mathcal{N}}$	Vector $[X_1, X_2, \ldots, X_N]$ for the N household nodes in the low-voltage grid
X^*	Conjugate transpose of complex quantity X
$\hat{X}$	Simulation or estimation of X
$X(t)$	The value of X at time t

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