Increasing the photovoltaic self-consumption and reducing peak loads in residential buildings with electric vehicle smart charging

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***Abstract*—This paper presents an electric vehicle (EV) smart charging scheme at residential buildings based on installed photovoltaic (PV) output and household electricity consumption. The proposed EV charging scheme is designed to determine the optimal EV charging schedules for the purpose of minimizing the load-variance or flattening the load profile. When the net-load is taken into account in the smart charging scheme, not only the peak load can be reduced, but also the PV self-consumption in the building can be increased.**

The charging scheduling problem is formulated and solved with a quadratic programming approach. The departure and arrival time and the distance covered by vehicle in each trip are specifically modelled based on available statistic data from Swedish travel survey. The scheme is applied on simulated typical Swedish detached houses without electric heating. The aggregation of distributed smart charging in multiple houses is conducted and compared to the smart charging in a single house. Numerical results are presented to show the effectiveness of the proposed smart charging scheme. Positive results on both the PV self-consumption and the peak load reduction are achieved.

***Index Terms*—electric vehicles, photovoltaic, electricity consumption, smart charging, self-consumption, peak load reduction, residential buildings**

I. Introduction

The environmental concerns in energy and transport sectors have increased the deployment of both electric vehicles (EVs) and renewable energy sources (RESs), such as photovoltaic (PV) power generation [1], [2]. However, the increasing penetration of EV charging load and PV power generation in the power grids can lead to several disadvantages such as voltage fluctuations, high load variances, high peak loads, power losses increases, and component overloadings [3], [4].

Besides in the power grids, PV power generation and EV charging can also meet on building level, such as at residential houses or workplaces where they will interact with other electrical loads. The integration of PV systems in buildings has increased in recent years due to the trend of net zero energy building (NZEB) [5]. In NZEB, the yearly energy consumption should be matched by local or on-site energy production [6]. With the addition of EV charging load in the building, the integration of on-site RES such as PV becomes more crucial in achieving the NZEB level.

However, NZEBs could have unfavourable mismatches between power production and power consumption since the NZEB concept only considers the yearly energy balance not the instantaneous power matching. The load mismatch between energy production and consumption are one of the main sources of problems in the distribution grid. Several techniques such as building energy management system and building energy storage have been addressed to improve the load matching and prevent potential problems in the distribution grid [7]. Self-consumption and self-sufficiency are two of the most common load matching indicators [7]. Self-consumption is defined as the total self-consumed local energy production divided by the total local energy production. Self-sufficiency is defined as the self-consumed local energy production divided by the total energy consumption.

Recent research has shown that the load matching or the synergies between PV power production and EV charging load could decrease the burden on power grids and increase benefits for users, building owners and grid operators [8]. These include increasing both the self-consumption and the self-sufficiency. While PV power production is naturally uncontrollable and cannot be shifted in time, the EV charging load potentially has a higher flexibility to be controlled and shifted in time due to the long parking duration. Thus, synergies between EV and PV could be improved with the so-called smart charging schemes.

Smart charging schemes could be divided into two categories based on their approaches: centralized and distributed. In the centralized charging approach, a central unit decides the charging time and rate of the EV fleet, while in the distributed charging approach, the charging of each EV is controlled on the user level [3]. The centralized charging approach utilizes the network capacity more efficiently, but it is more complex and requires an advanced communication infrastructure. The distributed charging approach is simpler, has low communication requirements and low privacy violations [9].

In this study, a distributed smart charging approach is used to minimize the load variance or flattening the load profile of individual households instead of considering higher level conditions such as distribution and regional network. Minimizing the load variance in each individual household can contribute to the decrease in the load variance of the distribution grid or even regional grid [10]. The decrease in load variance will lead to lower peak loads, lower power losses and fewer voltage fluctuations [3]. When a local RES such as PV systems exist in a household, minimizing the net-load also implies increasing the self-consumption of RES and the self-sufficiency of the building. Results from the smart charging scheme are compared with the uncontrolled charging scheme in the results section. The simulations in this study are based on the conditions for Sweden.

II. Methods

This section describes the details of data, models and assumptions used in this study.

A. Residential load

In this study, the residential load is generated from Widén model for generating synthetic electricity consumption profiles [11], [12]. The model is a Markov-chain based model that generates the electricity use profile based on occupant activity patterns. It was trained on Swedish electricity use patterns and set to simulate a detached house without electric heating with two adult inhabitants per household. There are two different scenarios which are simulated in this study: a single household load and the aggregation of 200 households which represents a medium-sized community.

B. EV daily charging demands

The daily energy requirement of EVs is estimated with a Monte Carlo method using the mobility data provided in the Swedish travel survey in 2006 [13]. The arrival and departure times of trips made by cars, the distance travelled, the origin and destination locations of these trips were available in the survey.

The daily charging requirement E (kWh) is estimated by

$$E = \eta \times D, \tag{1}$$

where D is the daily driving distance, and η is the EVs specific consumption (kWh/km). In this study, η is assumed to be 0.15 kWh/km and the maximum usable energy in the battery is set to 30 kWh. This is assuming that the battery can provide enough energy for the trips within a city. The daily driving distance D is calculated by doubling the random trip distance sampled from the trip distances of the recorded trips arriving at home [13]. This is assuming that each EV performs two equally long trips a day, such as a trip from home to work and back to home again. The model differentiates between weekdays and weekends, since they have different mobility behaviours. Home-work-home distance travelled data is used to estimate the EV daily energy demands on weekdays. While for weekends, home-other-home distance travelled data is used.

C. Solar PV power production

The solar power profiles are based on the data of global horizontal irradiation (GHI) in 2018 in Stockholm with lattitude 59.3° N and longitude 18.0° E, recorded by Swedish Meteorological and Hydrological Institute (SMHI) [14]. The PV system here is not specifically sized with kWp metrics, instead it is scaled relative to the total yearly energy demands, as a conversion can be made when that is suitable. The yearly PV production to the yearly house energy demands R is defined as

$$R = P/L, \tag{2}$$

where P is the yearly solar energy production and L is the yearly house energy demand including EV charging for each house. $R = 1$ means that the houses produce the same amount of energy as they consume making them NZEBs. In this study, several scenarios with different R are conducted to see the impact from the amount of PV power production, i.e., R = 0.10, 0.25, 0.50, 0.75, 1.00 and 1.25.

D. EV charging schemes

In this section, both the uncontrolled and the smart charging schemes simulated in this study are described. The schemes assume that the EV will only charge once a day, and the charging will take place at the residential buildings. Each simulated house has one EV. The arrival and departure time is randomly sampled from the recorded trips from the travel survey data [13]. Home-work-home mobility patterns are used for the simulation on weekdays, while home-other-home patterns are used for the simulation on weekends. Fig. 1 and Fig. 2 show the histogram of the home-arrival and home-departure time and the fraction of vehicles parked at home in this study respectively.

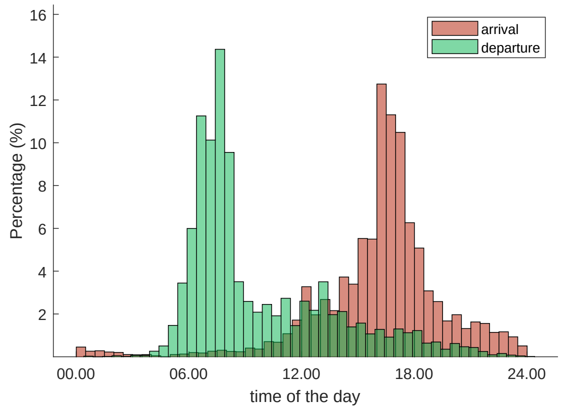

Fig. 1. A histogram of the time of home-arrival and home-departure of survey trips.

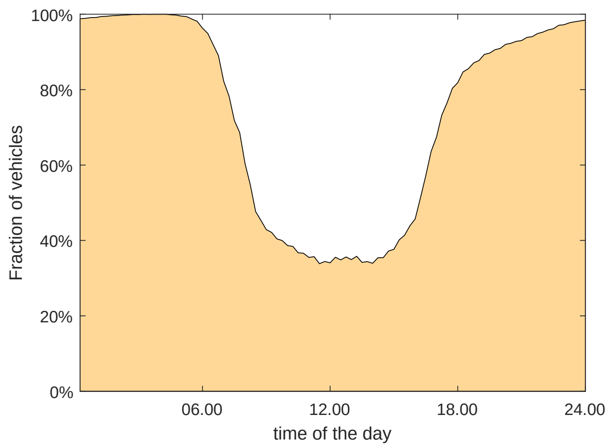

Fig. 2. The mean daily fraction of vehicles parked at home.

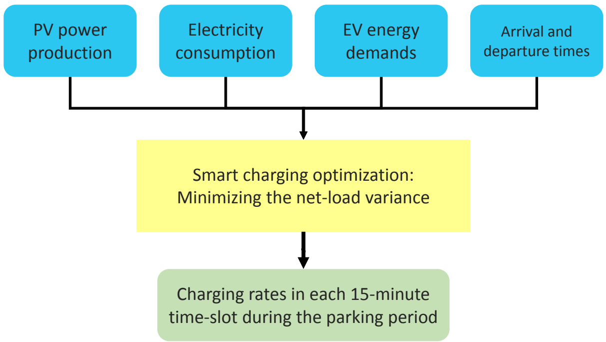

Fig. 3. Overview of the proposed smart charging scheme.

The maximum charging power is set to 3.7 kW, with 90% charging efficiency which refers to the average of level 2 charging efficiency [15]. It is assumed that the charging efficiency is constant regardless of the charging power. The simulations have a 15-minute resolution. Each simulated charging scheme in this study are presented in detail in the following subsections:

1) Uncontrolled charging: In the uncontrolled charging scheme, the charging always starts upon arrival with the maximum charging rate without considering the household electricity consumption and PV power production. The charging finishes when the battery state of charge (SoC) meets the targeted SoC.

2) Smart charging: In the smart charging scheme, the charging does not always start immediately upon arrival and with the maximum charging rate. The charging scheme considers the parking period duration, the targeted SoC or the EV energy demand, and the forecast of PV production and electricity consumption during the parking period. In this study, the historical data of the PV production and the model-generated data of the the electricity consumption are used, which means that they are assumed to be perfectly forecasted. From these data inputs, the smart charging scheme will minimize the household net-load variance with constraints of targeted energy in the battery and maximum charging rate. The smart charging scheme then will obtain the charging rate in each time-slot during the parking period. Fig. 3 shows the overview of the proposed smart charging scheme. The optimization problem of the smart charging scheme can be written as

$$\begin{aligned} \min \quad & \frac{1}{N}\sum_{t=t_{arr}}^{t_{dep}} (x_t + l_t - s_t - \mu_{tpark})^2, \\ \text{s.t.} \quad & \eta_x \sum_{t=t_{arr}}^{t_{dep}} x_t = E_{target} - E_{arr}, \\ & 0 \le x_t \le x_{max}, \end{aligned} \tag{3}$$

where t_{arr} and t_{dep} are the arrival and departure times of the car respectively, x_t is the charging power rate at time t, l_t is the household load at time t, s_t is the solar power production at time t, μ_{tpark} is the mean net-load during the parking period including EV charging load, η_x is the charging efficiency, E_{target} is the energy targeted in the battery, E_{arr} is the available energy in the battery on arrival, x_{max} is the maximum charging power rate.

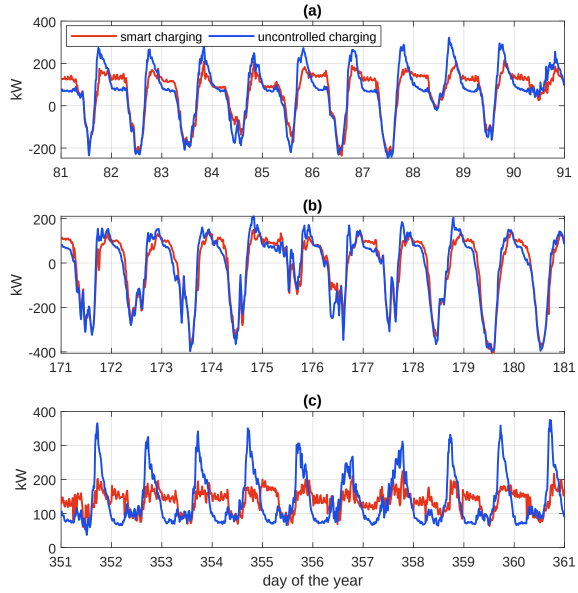

Fig. 4. Net load profile of aggregation of 200 houses with R = 0.5 in (a) spring, (b) summer, (c) winter.

III. Results

Fig. 4 shows the net-load profile in different seasons for a community with 200 houses and one EV in each house. Fig. 5 shows the mean daily load profile and solar power production. In both figures, the ratio of the yearly energy PV production to the yearly electricity consumption R is 0.50. It can be seen from Fig. 4 (c), the peak load reduction by the smart charging is clearly seen in the winter. During this period, the solar power production is very low, thus the smart charging scheme is significantly important in decreasing the peak loads. From Fig. 4 (b), it can be seen that the impact of the smart charging scheme in the summer is not as significant as it is in the winter. However, the net-load is still flatter with the smart charging scheme. The net load is often negative during the mid-day due to solar power production peaks. The smart charging scheme barely fixes the high negative net-load problems in the summer due to the low fraction of EVs at home during mid-day when the peak solar power production occurs as shown in Fig. 2. In the spring, shown in Fig. 4 (a), the peak load reduction by smart charging scheme is can be seen more clearly than in the summer but it has similar problems with negative net-loads.

From Fig. 5, based on daily average it can be seen that in the smart charging scheme the peak load is significantly lower. In this figure, the shaded area of both the household and the EV charging load by the PV power production is increased with smart charging scheme, even though it is not as clear as the peak load reduction. That means that the PV self-consumption actually increases.

A. Solar PV self-consumption

Fig. 6 (a) and (b) shows the PV self-consumption and self-sufficiency of the simulated scenarios. In this figure, black lines represent uncontrolled charging schemes, red lines represent smart charging schemes, thinner lines represent

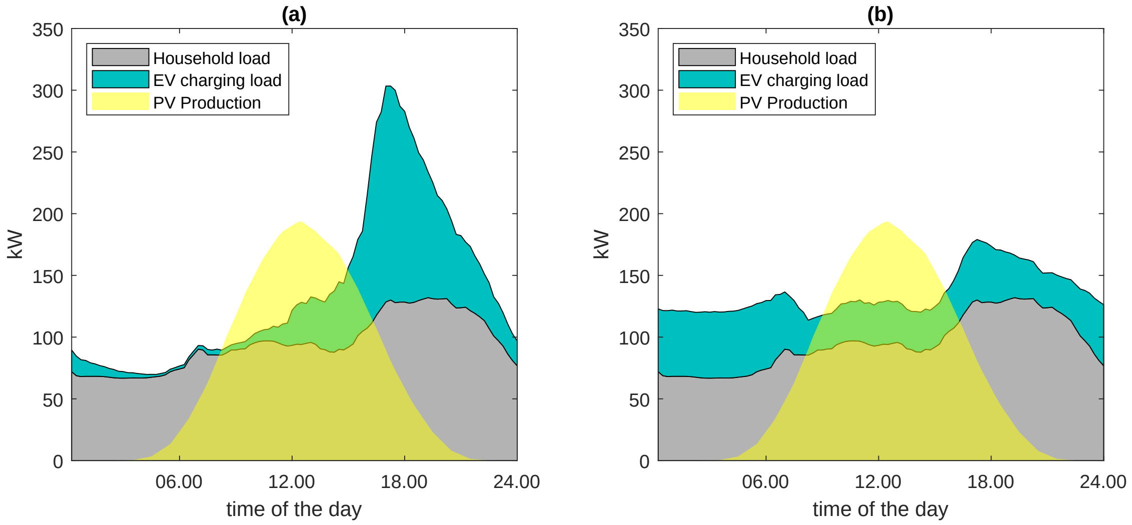

Fig. 5. Mean daily load profile with $R = 0.5$ with (a) uncontrolled charging scheme, and (b) smart charging scheme.

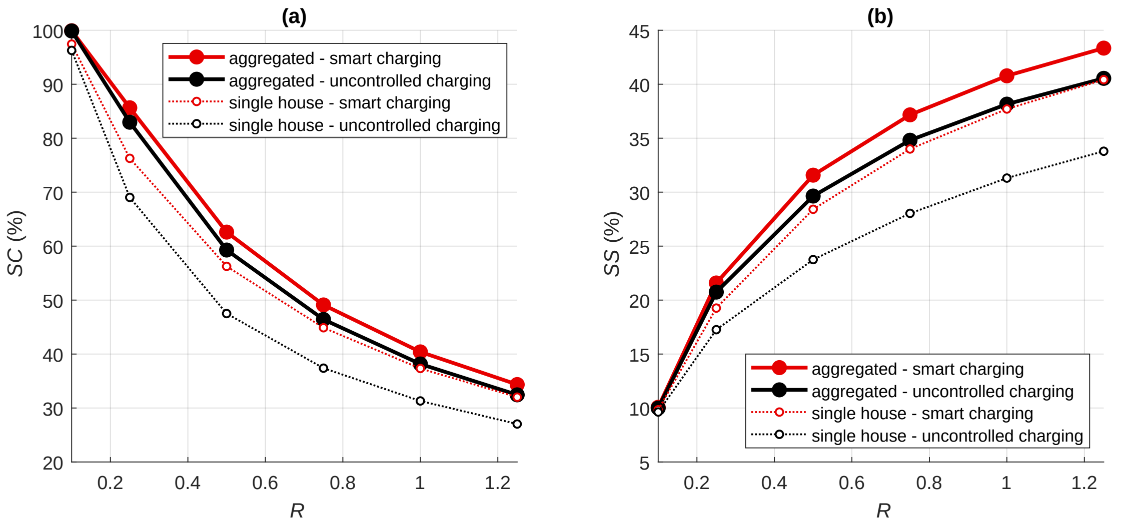

Fig. 6. Self-consumption (SC) and self-sufficiency (SS) against production per consumption ratio R for a single house and an aggregation of 200 houses with uncontrolled and smart charging schemes.

schemes with a single house, thicker lines represent schemes with 200 houses aggregated.

In general, the higher the share of PV production, the lower the self-consumption, and the higher the self-sufficiency. It can also be concluded that regardless of the charging scheme, the aggregation of multiple residential net-load profiles improves both the self-consumption and the self-sufficiency.

In terms of impact by the smart charging scheme, the improvements in both the self-consumption and the self-sufficiency are more significant in a single house than on the community level. This is because the net-load profile aggregation already improves the performance in both indicators, thus leaves only a little room for improvements for the proposed smart charging scheme. Table I shows the increases by the proposed smart charging scheme in both the self-consumption and the self-sufficiency.

Among the simulated scenarios, the scenario where the ratio of energy production to the consumption R is 0.50 has the most prominent self-consumption improvements with 8.8% increase on a single house level and 3.3% increase on the community level. While for the self-sufficiency, scenario with the highest R with 1.25, has the highest self-sufficiency improvements with with 6.6% increase on a single house level and 2.8% increase on the community level.

Ideally, the charging time is shifted to the time when the solar power peaks so that both the self-consumption and the self-sufficiency increase more significantly. However, that is not always possible. The improvements in both the self-consumption and the self-sufficiency by the smart charging scheme is limited by the low fraction of vehicles during the peaks of solar power production.

B. Peak load reduction

Table II provides the information on the peak load reduction by the smart charging scheme compared to the uncontrolled charging scheme in several scenarios. As it can be seen, the peak load reduction is significant. The reason is that in the uncontrolled charging scheme, the charging

TABLE I
SELF-CONSUMPTION AND SELF-SUFFICIENCY IMPROVEMENTS BY THE SMART CHARGING SCHEME.

R	Self-consumption increase		Self-sufficiency increase	
	single house	community	single house	community
0.10	1.2%	0.0%	0.2%	0.1%
0.25	7.2%	2.7%	2.0%	0.8%
0.50	8.8%	3.3%	4.7%	1.9%
0.75	7.5%	2.7%	6.0%	2.4%
1.00	6.0%	2.2%	6.4%	2.6%
1.25	5.0%	1.9%	6.6%	2.8%

TABLE II
PEAK LOAD REDUCTION WITH DIFFERENT R IN A SINGLE HOUSE AND A COMMUNITY WITH 200 HOUSES.

R	Peak load reduction	
	single house	community
0.10	53.2%	36.7%
0.25	54.0%	34.4%
0.50	54.0%	31.8%
0.75	52.4%	31.4%
1.00	49.1%	31.5%
1.25	46.4%	31.6%

loads often coincides with the household peak loads. Thus, by shifting and distributing the EV charging load to the time when the household electricity consumption is lower as long as it is still within the parking period, the peak loads will be reduced.

In general, the peak load reduction is better on the single house level than on the community level. This is because the peak load of each house does not always coincide with each other. So, when several load profiles are aggregated, the increase in the peak loads might not be linear with the number of the aggregated load profiles. Thus, the peak loads relative to the mean load are most probably lower on the community level than on the single house level which is actually good for the power grid. However, it leaves less room for the proposed smart charging scheme to improve the peak load problems on the community level.

IV. CONCLUSIONS

In this paper, a distributed EV smart charging scheme with an objective of minimizing the net-load variance of residential buildings are presented. The proposed smart charging scheme considers EV energy demands, arrival and departure times, forecasts of both PV power generations and electricity consumptions, which in the study are perfect forecasts. By minimizing the net-load variance, the PV self-consumption is increased and the peak loads are reduced.

Results shows that with smart charging scheme, the self-consumption and self-sufficiency could be increased up to 8.8% and 6.6% respectively depending on scenario. Increases in the self-consumption and the self-sufficiency are limited by the low fraction of vehicles during the peaks of solar power production. The achievement by the smart charging scheme on the peak load reduction is more significant for a single house with around 50% reduction than for a community with 200 houses with around 30% reduction.

Even though the smart charging has decreased the peak loads quite well, the solar power production excess which is not self-consumed will still be problematic if the share of solar power is high. The excess solar power will be transferred to the grid and if the grid is not strong enough to host a large amount of PV power excess, further actions such as PV power curtailment or installing home storage systems might be required to avoid further grid problems.

Future studies on comparisons between a centralized smart charging scheme and the proposed distributed smart charging scheme might be conducted. In addition, future studies could include realistic forecasts to the schemes and investigate how forecast errors will impact the performance of the schemes. Studies on the impacts of the proposed smart charging scheme on the distribution grids are also left for future work.

ACKNOWLEDGMENT

This project was funded by the Swedish Electromobility Centre Project “Modelling and implementation of smart-charging using the Annex D standard: Initial study”.

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