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Behind-the-meter residential electric vehicle smart charging strategies: Danish cases

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Abstract—**This paper presents and compares electric vehicle (EV) smart charging (SC) strategies for residential customers with a photovoltaic (PV) system. Three SC strategies are designed with a focus on user interests, the vehicle charges depending on (1) spot price and time-of-use (ToU) tariffs, (2) prognosis for grams of emission per kWh, and (3) own PV production. All strategies consider a local virtual aggregator, which collects information regarding price and emission prognosis, power flow at the household meter, EV connection time, time availability, and EV-user charging needs. Based on a survey of EV Danish owners, three charging patterns are identified and used to compare the effect of varying the charging flexibility within the aforementioned SC strategies. The results show that strategies with regard to price and emission signals are able not only to provide a positive impact on their own specific goal but also to reduce both costs and CO2 emissions. However, this is highly dependent on the connection time of EVs, where overnight charging and more frequent EV connection increase the strategies effect. Charging based on own PV production requires greater user awareness with respect to connection times to have a noticeable effect. However, when the EV is connected during sunny hours, there is good potential for self-consumption increase.**

Index Terms—**electric vehicle, smart charging, residential flexibility, electricity tariffs, photovoltaic prosumer, CO2 emissions.**

I. INTRODUCTION

Denmark has established a stoppage in sales of diesel and oil vehicles by 2030 to reduce CO2 emissions [1]. However, electric vehicles (EVs) can double the average household electricity consumption [2] and the successful implementation of Denmark's goals can put great pressure on the Danish power system [3]. This, together with the expected increase of intermittent renewable sources will create challenges on the power system stability [4]. Such power system challenges seem to be related more to the power delivery, rather than energy terms [5]. In fact, simultaneous charging, especially during peak hours, is a major issue [6]. Uncontrolled charging can easily overload the distribution grid [7]. smart charging (SC) presents a solution where EV becomes a flexible load [8], [9]. The charging flexibility, as defined in [10], can modulate and/or shift the charging power by controlling the current. This can be achieved through centralized, decentralized, or distributed control architectures [11]. This paper considers only one charger, however it is based on the distributed control architecture, as the one that merges decentralized with centralized control for distributed energy resource (DER) coordination [12]. SC strategies are often created with one specific goal, such as: lessen charging costs [8], increase EV owners' rates of renewable power self-consumption [13], reduce load impact [9], [14], or provide ancillary services [10].

This study focuses on flexible residential SC using a virtual aggregator [15], where a distributed autonomous charging control architecture is considered. Three goals of SC are considered: (i) charge during hours with the lowest electricity price, (ii) lower emission footprint and thus lessen the demand for carbon-intensive generating units, or (iii) increase self-consumption by charging during photovoltaic (PV) production and therefore reduce demand from the grid. The first two consider external parameters, that is, electricity price and CO2 emissions, while the last strategy only focuses on the residential system behind the meter. Furthermore, in contrast to other similar studies [8], [14], all SC strategies are tested considering real EV user behavior in terms of plug-in/out times and varying energy demands.

The contributions of this study are as follows:

- Proposal and comparison of SC strategies based on price, self-consumption and C02 emissions.
- Comparison of SC strategies for different user profiles, both in technical and economic terms.
- Guidelines regarding the most suitable strategy for different user connection behaviour.

The remaining of the paper is structured as follows. In Section II the methodology is presented, including the implementation of the model and the charging strategies. Case studies, with the charging patterns of EVs and the characteristics of the residential prosumer, are presented in Section III. The results are discussed in Section IV and the main conclusions are summarized in Section V.

II. METHODOLOGY

This section presents the methodology, where the system model is first described in Section II-A and then the three charging strategies are presented in Section II-B.

A. System model

The system accounts for a residential household with a rooftop PV system, and an EV with possibility to be controlled with a virtual aggregator (VA). More information on VA can be found in [15]. The VA retrieves signals of total power flow for the entire system at the metering point, download price and emission prognosis data, while the initial battery level, the energy requested at plug-out time, and EV plug-in/out times are provided from the EV owner.

The entire system is modeled in Matlab Simulink. The base model is divided into four main subsystems that can be viewed in Figure 1. Relevant inputs to the model are the aforementioned signals given to the VA and signals from the charging equipment for EV connection. The system uses a load convention, and thus PV production is negative. The charging control occurs via a proportional integral (PI) controller inside the VA in the charging control subsystem. The input into the PI controller is the total power flow at the smart meter and the desired consumption as a reference. This reference is at the maximum allowed power import at point of common connection (PCC) for the first two strategies or zero when charging to optimize the PV own consumption. A zero as reference means that the smart charger attempts to minimize the import/export exchanges with the grid. Additionally, another step on the control logic, *force charge*, is implemented to ensure the EV reaching its desired battery level before plugging out. The model estimates the battery energy level at each step (each second) of the simulation, and if this dips below the minimum allowed limit, then charging at maximum available power is activated for the remainder of the connection period. To assess the impact of SC, a base dumb charging scenario is considered. Here, EV starts charging at maximum power when plugged in, until the charging goal level is reached.

B. Smart charging strategies

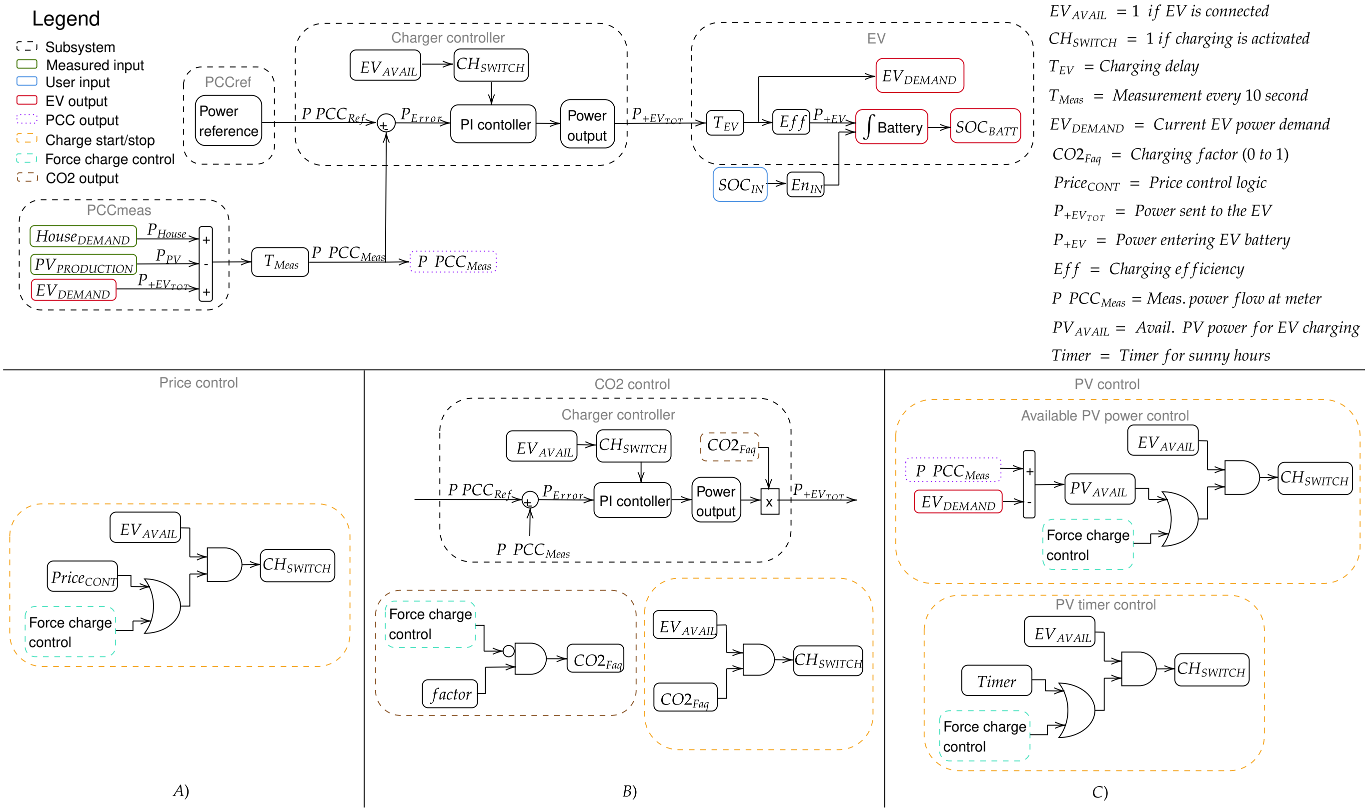
1) Price based: In the first strategy, EV charges according to an electricity price signal. This includes both the spot price based on the day-ahed market and the time-of-use (ToU) tariffs. As spot prices for the following day are published around 13.00 every day [16] and ToU tariffs are established beforehand, each hourly value is known for a maximum of 33 hours forward. When the EV is plugged-in, the necessary charging time is calculated. The hours with cheapest electricity within the connection period are selected to charge the vehicle. From these hours, a threshold is created, and this value is compared with the cost value for each hour during the connected time. If the charge cost is equal to or below this value, the EV will be charged at full capacity, whereas during the remaining time it is idle. The additional logic from the base scenario can be seen in Figure 1 box A).

2) Emission based: This strategy aims to minimize the carbon footprint by charging during periods of lower carbon levels in the grid. The prognosis of the CO2 levels delivered per kWh to the distribution system is based on the day-ahead and intraday market for spot prices, which again predicts the generation mix in the system and the subsequent emissions. However, for this study only the day-ahead market is assumed for the prediction. As actual emission can vary from its prognosis, two methods are considered: 1) charge only during periods of lowest predicted emission levels, and 2) vary charging power according to predicted emission level. The first method is equal to on the price strategy only with emission as a control signal. The latter is a more dynamic charge control, where the charging power varies with the predicted emission level. The charging power depends on the predicted CO2 g/kWh, with only the very lowest amount resulting in the maximum charging power. This method reduces the chance of charging at maximum power for a few hours. The emission control signal is a number between 0 and 1, which is then multiplied with the PI controller output. Positive (1) results in charging at maximum power, while neutral (0) proceeds in no charge. The logic implementation can be seen in Figure 1 box B). For more details on the actual modeling of all strategies, please refer to [2].

3) Self-consumption based: The last strategy is to increase self-consumption, usage of owner PV production, by charging according to the available PV production. Two different methods are designed and compared: 1) charge according to a present threshold of available production surplus, PV production minus house consumption, and 2) charge according to daylight hours. In the first method, PV production is calculated by subtracting the PI controller power output to the vehicle from total power flow at the meter. Two thresholds are investigated, -1 kW and -2 kW. If the available PV power is below (negative due to load convention) these thresholds, the charge is activated. Charging power is decided by the PI controller, while the reference power for PCC is set to zero kW. The charging power is saturated between the maximum and minimum levels of charging current. When there is not enough available PV power, charging is stopped. In the second method, the charging strategy schedules charging for sunny hours during the day. Charging power control is similar to the former method, with the only difference that charging is not stopped within its active period. The logic implementation is shown in Figure 1 box C).

III. CASE STUDY

1) EV data: A survey for 14 EV owners residing in Denmark was performed during November and December of 2019 to understand their charging behavior [2]. The information included are: battery size, state-of-charge (SOC) in plug-in and plug-out, plug-in / plug-out times, and charging location, namely: home, work or elsewhere. The charging patterns were classified into three groups of similar behavior with regards to energy demand versus connection time, charging frequency, and battery SOC at plug-in (SOC_{IN}). A representative pattern is chosen from each group and named G1, G2, and G3. These groups represent EV owners with different connection times. In G1, EV owners use the vehicle everyday, and plug-in once arrive at home, independently from battery level, and they do not disconnect until the EV is used again. In G2, EV is connected one / two nights a week, and thus is charged less frequently. In this group, users connect and charge their vehicles only if the SOC is below 20 - 30% (value selected from the user). G2 vehicles on average have a higher demand



A)

B)

C)

Fig. 1: Simplified schematic overview of the model with charging strategies: self-consumption in A, price in B and emission charging case 2 in C.

per charging event than G1. Lastly, G3 represents the inflexible group, where vehicles are charged at maximum once a week and connected to the charger only for a limited amount of time. A graphical example of charging times for one arbitrarily week and each representative pattern is provided in Figure 2. For simplicity, the three groups are considered to have the same battery size of 75 kWh and a charging power of 11.1 kW (6-16 A as limiting currents) with 80% charging efficiency at 6A and 90% at 16A. As the case study is for the entire year of 2020, charging connection times are considered to be the same for the 12 months. However, seasonal variations that affect energy consumption are incorporated by varying SOC_{IN} from vehicle efficiency data [17]. More details of the relevant study of EV charging behaviour is given in [2].

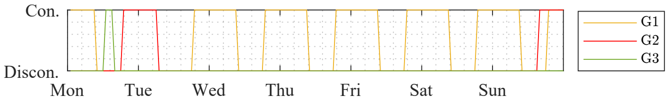


Fig. 2: EV plug-in/ plug-out patterns groups G1 (average distance driven between charging events 80 km), G2 (218 km) and G3 (75 km).

2) System data: Data for household consumption and PV production of a 6 kWp PV plant are taken from a representative household in Denmark for the year 2020. Data are provided with a 5-minute resolution; more details are given in [18]. The hourly spot-prices are retrieved from NordPool [16]. The ToU tariffs are extracted from the largest distribution system operator (DSO) in Denmark, Radius, and its price scheme for residential homes [19]. Emission prognosis data are collected from Energinet [20], [21] for East Denmark grid region (DK2) and have a 5-minute resolution. Sunny hours are defined based on data from the Danmark Meteorologiske Institut [22] and PV production data from the house system with respect to sunrise, sunset and production hours.

The investigated scenarios are summarized in Table I, with names given for each specific scenarios for further reference. Electricity prices broke old records during the year 2021 and therefore represent an interesting case for studying the effect on SC compared to 2020. Therefore, the price-based strategy will be studied with electricity prices from 2021 as a standalone case and analyzed with the original price strategy case in its own subsection. The system layout, production, and consumption data from 2020 are used.

TABLE I: Overview of scenarios including charging pattern groups and charging strategies.

Smart charging	Dumb charging	Electricity price	CO2 low emissions	CO2 varying emissions	PV with threshold	PV with timer
Group 1	G1-Base	G1-Price based	G1-CO2 Case 1	G1-CO2 Case 2	G1-Thr	G1-Timer
Group 2	G2-Base	G2-Price based	G2-CO2 Case 1	G2-CO2 Case 2	G2-Thr	G2-Timer
Group 3	G3-Base	G3-Price based	G3-CO2 Case 1	G3-CO2 Case 2	G3-Thr	G3-Timer

IV. RESULTS

This section presents the results of the SC strategies by comparing the three groups. First, an example of a price-based strategy is given. Then, the annual results are described with a focus on energy consumption, total electricity cost, and CO2 emissions. Finally, to highlight the importance of electricity spot prices, a comparison between the years 2020 and 2021 is considered.

1) Price based: Figure 3 shows the price-based charging strategy for an arbitrary winter week for G1. The upper plot shows household consumption (HC), PV production, export, and import. The charging power and EV SOC are displayed in the middle plot. The lower plot displays the electricity price with the threshold created from the charging strategy. Charging occurs every time the price level is equal to or below the threshold value, and this usually happens during the night. The import of power is clearly higher for EV charging than for other HC loads, indicating the importance of SC for the households total electricity cost. The remaining strategies have similar behavior, but in the following we will only focus on the main results. Annual results are provided in Figure 4, together with emission-based strategies. If focusing on G1- to G3 price based, all groups have a reduction compared to the base case, albeit with varying degrees. G1 has a cost cut of 20% (334 euros), G2 of 10% (63 euros) and G3 of 3% (4 euros).

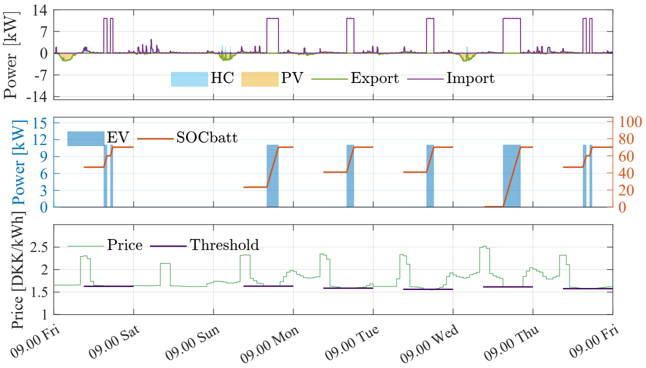


Fig. 3: (upper plot) Power [kW] exchange at the metering point, (middle plot) EV charging (power [kW] and SoC) and (lower plot) electricity price and the price threshold activation for one winter week with G1.

Lowest electricity price in 2020 usually occurred between 02.00-05.00, as it can be observed in Figure 3, indicating the benefit of overnight connection. The comparison between groups hints towards the advantage of more frequent EV connection with lower demand, versus waiting to charge until the battery has a low SOC. G2 has on average double energy demand as G1 per charging event and has half of the cost reduction percentage.

2) Emission based: Total CO2 g/kWh is analyzed for the base case using both emission strategy methods and compared between groups. However, only EV emissions levels are considered, meaning that the household emissions are disregarded. The main result can be observed in Figure 4 B) with a reduction in total emission from charging for both strategy methods and for all groups. Here, CO2 case 1 has the highest decrease. This indicates a good correlation between the emission prognosis values and the actual emission levels. The benefit of connecting the vehicle more often is also shown for this strategy. The largest reduction in emissions is G1-CO2 case 1 and G1-CO2 case 2 with 21% and 16%, each. G2 has 12% and 3% reductions, and G3 has 6% and 5% reductions in emissions, respectively.

3) Comparison of price and emission based strategies: Figure 4 gives details for the cost of charging with the emission-based strategies and the resulting CO2 levels after charging according to electricity cost. The results indicate a correlation between low-emission hours and low electricity prices, where the use of a control signal following the prediction of the emission has the ability to reduce the charging cost and vice versa. For the first emission strategy method (CO2 case 1), all groups have a reduction in cost, the highest being 253 euros for G1. The second case for the emission-based strategy has a smaller decline for all groups. Furthermore, G1-Price based and G2-Price based have a lower total CO2 level than their CO2 case 2 scenarios, which further points to the correlation between cost of electricity and CO2 levels in today's power system.

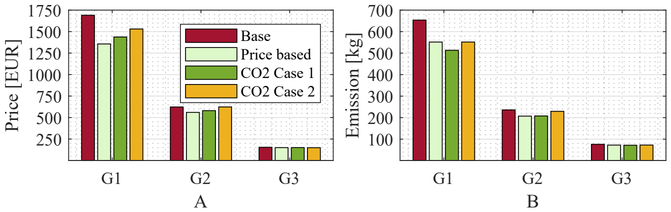


Fig. 4: (A) Cost and (B) emission for one year of charging for all groups when using different smart charging strategies.

4) Self-consumption based: Figure 5 compares the energy used for charging, for all groups in the case of SC with PV self-consumption increase. The share of energy is split between energy from PV entering the EV, PV energy lost, and similar for energy from the grid to the EV. G1 charges every night, therefore it is not possible to utilize the full benefit of the PV system. This group has a modest increase in self-consumption of 125 kWh from the PV system for the most successful case (G1-Thr with -1kW), and only small differences in PV consumption between the subcases. Also, the yearly 125 kWh is negligible compared to the groups total demand of around 6400 kWh, including losses. G2 has greater potential to increase PV consumption, since it is connected more hours during the day. However, the increase in self-consumption is limited, due to other influencing factors, such as the possibility of having cloudy days and the PV consumption is always prioritized first for the household and then for the EV charging. As a result, there is also little difference between any of the methods and dumb charging. In conclusion, we can say that this strategy demands a longer connection time than the minimum charging time. Additionally, a more active behavior is required from the EV owner with connecting the EV when necessary. The third group shows a larger benefit, despite the rare and limited connection periods. The day charging has increased PV utilization from 4.8% to 16.6% for the most successful case (G3-Thr of -1kW). "Thr - 1kW" is the most successful case for all groups with the timer, giving the smallest amount of PV energy to EV.

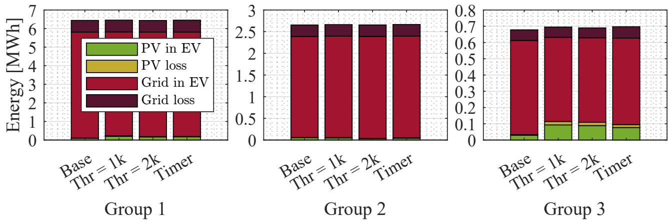


Fig. 5: Charging energy for all groups, coming from PV and grid, and split between the actual energy going to the EV and energy lost during charging.

5) 2020-2021 comparison: For the dumb charging and price based case, the annual costs are compared in Table II by considering both 2020 and 2021 electricity prices. With dumb charging, costs increase by 31%, 36%, and 33% for G1, G2, and G3, respectively. With the price based strategy costs decreased by 25% for G1, 15% for G2 and 5% for G3. In this case also, regular charging yields the highest savings.

TABLE II: Charging costs with price based strategy for 2020 and 2021.

Group	20 Base [€]	20 Cost[€]	21 Base [€]	21 Cost [€]
G1	1692	1358	2219	1670
G2	624	561	849	723
G3	155	150	207	196

V. CONCLUSION

This paper assesses and compares smart charging strategies with self-consumption, lowering costs and CO2 emissions goals. Each strategy was simulated for a prosumer case with three different real-life charging patterns to gain a wider perspective of the benefit of specific smart charging controls. The most suitable strategy for different user charging behaviors is investigated. For the price based strategy, G1 (EV users that plug-in every night) and G2 (EV users that plug-in once/twice per week overnight) have a noticeable reduction in costs, with a 20% cut for G1. The emission based strategy has a similar maximum drop, 21% for G1 being the largest. The use of price or emission SC strategies reduces both costs and emissions. Most importantly, both strategies point to the benefit of a longer overnight connection and more frequent charging events. The results are opposite for the self-consumption based strategy. There is only a negligible change in the results for vehicles that connect more often and during night. However, a 12% growth could be achieved by connecting the vehicle once a week during daytime hours. This suggests the success of the strategy for consumers who ensure that EV is connected during the day. Lastly, higher electricity costs in 2021 resulted in an increase of 30-35 % in the cost of dumb charging. Price based charging lowered the cost more for 2021 compared to dumb charging than for 2020, with 25% and 20% for G1, group with largest savings. However, in Nordic countries, during a summer day, sunny hours correspond in time with higher electricity prices (for example, during 16:00-20:00), making PV based charging more viable.

Future work on charging designs should focus on revenue from selling excess PV power to the power system, considering weather forecast in self-consumption strategies and introduction of emission taxes as a control signal.

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