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Comparison of Smart Charging and Battery Energy Storage System for a PV Prosumer with an EV

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Abstract—Battery energy storage systems (BESSs) for residential photovoltaic (PV) prosumers are becoming more popular with the reduction of battery prices, as a means of increasing self-consumption. When considering prosumers that also own an electric vehicle (EV), smart charging can also fulfill the same objective. This paper assesses the benefits of a PV prosumer with an EV under two options: installing a BESS or applying smart charging. Smart charging is applied with the goal of reducing energy imports by charging the EV when there is excess of production. The effect of using a BESS of varying inverter and storage size is also investigated, when operated under a simple energy import minimization logic. We use a yearly dataset of real 5-min measurements collected from a Danish household with a 6 kWp PV plant. The prosumer also owns a 62 kWh Nissan LEAF. We find that smart charging increases self-consumption from 29% to 54%, leading to yearly savings of 220 €. Through a sensitivity analysis we find that a BESS of 8 kWh / 2 kW yields similar yearly results. Given the approximately 20 times higher payback period of the BESS, we conclude that smart charging is economically much more attractive.

Index Terms—battery energy storage system, electric vehicle, photovoltaic, prosumer, smart charging.

I. INTRODUCTION

In the effort of reducing carbon emissions and transforming the electricity system into a fully sustainable one, the increase of the share of renewable energy and the electrification of the transportation sector are key factors. Flexibility plays a major role in this development, and can be provided by battery energy storage systems (BESSs) [1] or via demand response, primarily through electric vehicles (EVs) [2]. Nevertheless, EVs are part of both the problem and the solution [3], as their large storage capacity offers flexibility, but the associated charging needs can potentially stress local grids [4].

The decrease of battery prices during the last decade is making EVs and BESSs more economically attractive. Among others, the rise of electricity prices due to policy implementations, together with the decrease of photovoltaic (PV) system costs, are motivating private households to become prosumers and to increase their self-consumption. The possibility to become more independent from the grid is also an opportunity for customers to reduce their risk exposure to increases of electricity prices or tariffs/taxes. However, given that PV production is predominant during the day time, whereas household consumption is mostly concentrated during the evening, a large part of the PV production is sold to

the grid, instead of directly being used by the household. In countries such as Denmark, where tariffs and taxes account for approximately 80% of the final residential electricity price, the import price per kWh can be several times larger than the price being paid for exporting electricity [5]. Therefore, in the absence of a dedicated premium tariff, it is logical that prosumers prioritize the use of electricity locally. In general, this can be done by shifting as much consumption as possible during the day time.

PV production often does not coincide with the bulk of a household's inflexible consumption or an EV's uncontrolled charging demand, leading to relatively low self-consumption. In order to increase the self-consumption of the PV prosumer, there are two main options: the modulation of EV consumption and the usage of a BESS.

On the one hand, researchers investigate the use of EVs to provide flexibility by considering smart (i.e., unidirectional) charging [6] and vehicle-to-X [7]. Smart charging analyses are often investigated for non-residential parking areas, where multiple chargers can be controlled and provide flexibility [8]. When future vehicles will be equipped with on-board bidirectional chargers, the investigation of a V2X case becomes more interesting. Few studies investigate the residential smart charging possibility, as in [9], [10] where a distributed and a centralized EV scheme are implemented to minimize grid export from residential customers. In [11], a demonstration test of EV smart charging controlling the energy production and consumption of an energy community is described.

On the other hand, there is a large interest in PV prosumers with BESSs, with regards to scheduling and optimization [12]–[14]. In [15], the authors investigate the self-consumption of Swedish single-family households/dwellings, providing a sensitivity analysis of PV installation and battery of different sizes. In [16], an optimal storage system sizing based on equivalent circuit modeling is proposed, where the main goal is to balance solar production and load demand. In [17], a technical approach based on the optimization of the self-sufficiency is proposed to size PV-battery systems. In [18], a Romanian study case with a PV plant and different BESSs are compared, showing that despite the higher self-consumption with larger batteries, the smaller ones are, for the time being, more economically viable.

In this article we focus on the increase of self-consumption,

also referred to self-sufficiency, and associated prosumer savings comparing two options: EV smart charging and BESS operation. Both cases are based on the consideration of real-data from a Danish PV prosumer, where an EV with fixed idle time and distance driven is introduced. The main contributions of the manuscript can be summarized as follows:

- Investigation of the effect of EV smart charging and BESSs in terms of self-consumption and savings, using real data with 5 minute resolution for both consumption and production.
- Self-consumption and savings sensitivity analysis of different BESSs sizes.
- Assessment and comparison of the two options, with a focus on economic viability.

The rest of the paper is structured as follows. Section II focuses on the methodology formulation of the EV smart charging and BESS control logic. Section III provides an overview of the study case. Section IV analyses the results and Section V concludes the manuscript with the main outcomes.

II. METHODOLOGY

Our goal is to evaluate and compare the increase in self-consumption when smart charging or a BESS are included on a residential prosumer equipped with a PV and an EV. The prosumer is represented by an inflexible household consumption (HC), a rooftop PV production and an EV under *dumb charging*, where the vehicle charges with the maximum possible charging power as soon as it is plugged-in at home. For the HC and the PV production we rely on the use of historical data, whereas EV consumption is derived from vehicle usage and needs in Denmark. We analyse the increase in self-consumption first in relation to the implemented smart charging logic, and second as a sensitivity analysis on the energy and power capacity of an added BESS.

We first present the EV and BESS formulations in subsection II-A. In subsection II-B we present generic controllers for the EV and the BESS that can be easily implemented in practice. To make the controllers more robust and friendlier for implementation, no optimization, considerations for hourly energy price variations or forecasting are employed. The goal of the smart charging logic and the BESS controller are to maximize self-consumption, which is an objective closely linked to prosumer cost minimization due to the high ratio of import/export prices. Given these components, and a yearly prosumer dataset with 5-min HC and PV measurements, in subsection II-C we show how we can conduct the aforementioned sensitivity analysis to derive the yearly self-consumption and the related savings.

A. Electric vehicle and BESS formulation

1) *EV*: We consider unidirectional EV charging, characterized by charging power P_t^{EVc} and state-of-charge (SOC) SOC_t^{EV} in each time step t . The charging power is subject to energy losses, according to a charger efficiency η_c , which is

a function of the charging power. SOC evolution is described by

$$SOC_t^{\text{EV}} = SOC_{t-1}^{\text{EV}} + \eta_c(P_{t-1}^{\text{EVc}})P_{t-1}^{\text{EVc}}\Delta t, \quad (1)$$

where Δt is the time step's duration in normalized terms, i.e., $\Delta t = 1/12$ for a 5-min time step. In this work we are only interested in accounting for the overall energy usage of the vehicle. To account for EV driving needs we subtract half of the equivalent total energy usage from the SOC as soon as the EV plugs out and half when the EV plugs in. For ease of notation, this SOC reduction is not included in the formulation (1), but it is accounted in the model.

2) *BESS*: The BESS is composed of a battery pack and an inverter, and is characterized by the charging P_t^{Bc} and discharging P_t^{Bd} power and SOC_t^{B} . The power values correspond to the AC side of the BESS. Since inverter losses are dominant, we neglect battery losses and only account for inverter charging η_{Bc} and discharging η_{Bd} efficiency, which are functions of the corresponding power values. The SOC evolution is described by

$$SOC_t^{\text{B}} = SOC_{t-1}^{\text{B}} + P_{t-1}^{\text{Bc}}\eta_{\text{Bc}}(P_{t-1}^{\text{Bc}})\Delta t - P_{t-1}^{\text{Bd}}/\eta_{\text{Bd}}(P_{t-1}^{\text{Bd}})\Delta t. \quad (2)$$

B. Controllers design

Two controllers are designed in this section: one for the EV smart charging logic and one for the BESS.

1) *Electric vehicle*: This section presents how the (unidirectional) EV charging power is derived. We propose a simple *smart charging* logic, characterized by three different windows of charging behaviour.

- *driving window*: the vehicle is not plugged-in and no charging occurs. During this window the vehicle could be driven or is parked on another location;
- *smart window*: the vehicle is plugged-in and smart charging is applied. The vehicle charges only if there is sufficient excess of net PV production P_t^{net} (PV generation minus HC) to allow charging by respecting the communication standard IEC 61851 [19]. According to the standard, the EV can charge with a minimum \underline{P} and a maximum \overline{P} power. Depending on P_t^{net} and IEC limitations, three charging regimes are defined:
 - if $\underline{P} < P_t^{\text{net}} < \overline{P}$, then $P_t^{\text{EVc}} = P_t^{\text{net}}$;
 - if $P_t^{\text{net}} < \underline{P}$, then $P_t^{\text{EVc}} = 0$;
 - if $P_t^{\text{net}} > \overline{P}$, then $P_t^{\text{EVc}} = \overline{P}$.

To avoid accelerated degradation, the battery is charged to a maximum SOC ($\overline{SOC}^{\text{EV}}$);

- *urgent window*: the vehicle is plugged-in and charges with P^{set} . This control mode ensures that the EV will have a SOC of at least SOC^{set} upon departure and $P^{\text{set}} < \overline{P}$ is chosen to avoid unnecessarily loading the grid.

We consider that the EV charger is capable of stopping the charging process when the available power drops below the minimum rate, and start it again when this limit is exceeded. Fig. 1 provides the flowchart of the smart charging logic.

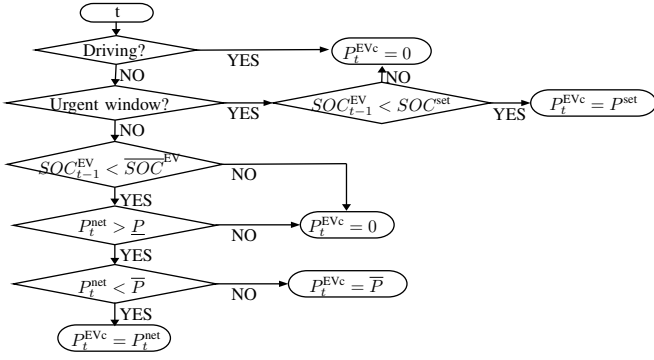


Fig. 1: Flowchart of the smart charging logic.

During the days that the vehicle is not driven, the smart window can be constantly applied, whereas when the vehicle is driven, the EV may enter both control modes.

2) *BESS*: The EV dumb charging power is given as input to the BESS controller, together with PV production and HC. The controller first stores any excess available power to the BESS and then exports the remainder to the grid. Similarly, any deficit is first covered by the BESS, and if this is not enough then energy is also imported from the grid. Fig. 2 presents the flowchart to derive the charging and discharging power of the BESS for each time step t . The available power P_t^{av} , i.e. the difference between the net demand and the charging power of the EV, is first determined

$$P_t^{av} = P_t^{net} - P_t^{EVc} = P_t^{PV} - P_t^{HC} - P_t^{EVc}. \quad (3)$$

If $P_t^{av} \geq 0$, this excess power should be stored in the BESS, if possible. First, the corresponding energy $P_t^{av} \Delta t$ is compared with the upward (U) energy charging potential

$$U = \overline{SOC}^B - SOC_{t-1}^B. \quad (4)$$

U is the energy that can be stored in the battery until the maximum SOC \overline{SOC}^B is reached. In a similar way, the downward (D) energy potential is defined as the energy that can be withdrawn from the battery so as not to reduce the SOC below \underline{SOC}^B

$$D = SOC_{t-1}^B - \underline{SOC}^B. \quad (5)$$

If U is large enough to store $P_t^{av} \Delta t$, an additional check is needed to ensure that power P_t^{av} does not exceed inverter power capacity P^{inv} . If this capacity is smaller, the BESS will be charged with P^{inv} and the remainder power will be fed to the grid. Finally, if U is not large enough, then only a part of the excess production can flow into the BESS. P^{inv} is compared with the corresponding power $U/\Delta t$, and if it is larger then the BESS can charge at a rate $U/\Delta t$, otherwise it can only charge by P^{inv} . Similar considerations apply when there is a deficit ($P_t^{av} < 0$). Note that charging and discharging are mutually exclusive quantities, so only the non-zero value is shown in Fig. 2. Furthermore, import P_t^{im} and export power P_t^{ex} from/to the grid (which are also mutually exclusive) are omitted from the flowchart and are calculated as follows

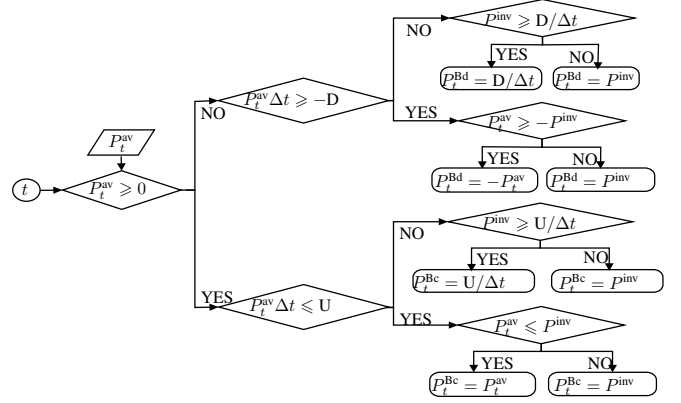


Fig. 2: Flowchart charging/discharging power BESS derivation.

$$P_t^{im} = \max(-P_t^{av} + P_t^{Bc} - P_t^{Bd}, 0), \quad (6a)$$

$$P_t^{ex} = \max(P_t^{av} - P_t^{Bc} + P_t^{Bd}, 0). \quad (6b)$$

C. Self-consumption, savings and losses

To compare the benefits of smart charging with those of the BESS, we determine the self-consumption and the savings that the two solutions can provide. Self-consumption (SC) is defined as the ratio of the consumed energy covered by local production divided by the total consumption.

$$SC = \frac{\sum_{t=1}^T \frac{P_t^{HC} + P_t^{EVc} - P_t^{im}}{P_t^{HC} + P_t^{EVc}}}{\sum_{t=1}^T \frac{P_t^{HC} + P_t^{EVc} - P_t^{im}}{P_t^{HC} + P_t^{EVc}}}, \quad (7)$$

where T is the investigated period of time. Costs (C) are given in both cases of using smart charging or a BESS by

$$C = \sum_{t=1}^T (c_t^b P_t^{im} \Delta t) - \sum_{t=1}^T (c_t^s P_t^{ex} \Delta t), \quad (8)$$

where c^s and c^b are the selling and buying prices per kWh of energy, respectively. Eq. (8) is also used to calculate the baseline cost, i.e., the cost without the addition of a smart charger or a BESS. Savings are calculated by subtracting the resulting costs in each case from the baseline cost. When smart charging is considered, there is a single C value to determine. When a BESS is used, we need to consider different sizes of the storage system. A sensitivity analysis is thus conducted, which allows us to calculate prosumer costs (and thus savings) under different combinations of battery and inverter sizes.

Another important aspect to consider is the increased amount of losses due to smart charging or the use of a BESS. Dumb charging happens at the charger's nominal capacity with maximum efficiency, whereas smart charging increases charging losses due to operation in lower-efficiency regions. The charging losses L^{EV} are derived by using (9), whereas inverter losses L^B are given by (10).

$$L^{EV} = \sum_{t=1}^T (P_t^{EVc} - P_t^{EVc} \eta_c(P_t^{EVc})) \Delta t, \quad (9)$$

$$L^B = \sum_{t=1}^T \left(P_t^{Bc} - P_t^{Bc} \eta_{Bc}(P_t^{Bc}) + P_t^{Bd} - \frac{P_t^{Bd}}{\eta_{Bd}(P_t^{Bd})} \right) \Delta t. \quad (10)$$

III. CASE STUDY

A. Case study description

A Danish prosumer, characterized by a number of domestic appliances, a 6 kWp PV plant and a Nissan LEAF 62 kWh EV is considered in this paper. The EV charger is single-phase, with maximum charging power of 3.68 kW and the possibility to provide unidirectional smart charging, in the range of 6-16A [19]. A simplified system configuration is provided in Fig. 3. The figure provides both the power and communication flows and the location of the energy and smart meters used for the data collection. It should be noted that the energy supplier meter, although measuring values every second, stores data with an hourly resolution [5]. Therefore, an additional meter (Fronius smart meter) was installed to save data with a finer resolution (five minutes). The smart meter sends the data to the PV inverter data logger (via RS-485). Also, the figure shows the smart charger, BESS components (red squares), and their behind the meter location.

B. Investigated scenarios

The following three scenarios will be investigated:

- 1) *Base case*: this scenario is the initial situation, where PV production, HC and EV dumb charging are considered;
- 2) *Smart charging*: in this scenario the PV production and HC remain the same, whereas the smart charging logic is considered for charging the EV;
- 3) *BESS*: similar to the base case (EV dumb charging), but different BESS sizes are introduced.

For simplicity, c^b and c^s are considered constant and equal to 0.25 €/kWh and 0.03 €/kWh, respectively, which are the current (2020) average prices for a residential customer with a net billing scheme [5]. Furthermore, we are considering summation metering at the point of common coupling. In this regard, single- and three- phase loads are not differentiated, and the same goes for the EV charger and BESS inverter.

C. Data analysis

1) *PV and base consumption*: Data is provided for a one year period (Sep 1 2019 to Aug 31 2020) with 5 minutes resolution. An in-depth analysis of the data is provided in [5].

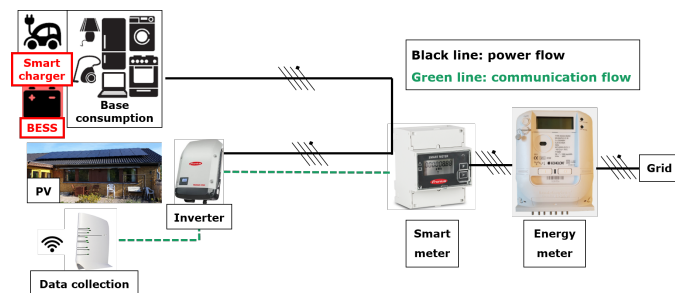


Fig. 3: System configuration including power and communication flows. Modified from [5].

TABLE I: 3.68 kW charger efficiency.

P^{EVc} [kW]	1.38	2.30	2.99	3.68
$\eta_c(P^{EVc})$ [%]	80	86	88	90

TABLE II: Charging efficiency of the Fronius inverter [21].

P^{Bc} [%]	5	10	20	25	30	50	75	100
$\eta_{Bc}(P^{Bc})$ [%]	92.6	95.6	97.1	97.5	97.7	98.0	98.0	97.9

2) *EV data*: For the EV driving/charging profile it is assumed that a 62 kWh Nissan LEAF is driven on Wednesday, Thursday and Sunday, with respectively 40, 40 and 80 km, and the user leaves home at 8.00 and returns at 18.00. During the remaining time the vehicle is plugged-in at home, charging or available for smart charging. This driving behaviour takes into consideration a lower amount of km driven than the average Danish in 2019 of 45 km/day [20]. This decrease reflects the increased home-working due to the Covid-19 effect, which led to a significant reduction in commuting [3], [20].

The considered charger has a charging range of 6 – 16A, which follows the communication standard IEC 61851 [19]. When dumb charging is considered, the EV charges when it is plugged-in with a maximum charging power of 3.68 kW ($16A \cdot 230V$, considering a power factor of 1) and until $\overline{SOC}^{EV} = 90\%$ is reached. The internal charger efficiency of the vehicle ($\eta_c(P_t^{EVc})$) is 0.8 at the minimum and 0.9 at the maximum charging power with an almost linear increase. These values were obtained by the authors after conducting measurements. When smart charging is considered, constraints on the start/end charging time and charging power are included, as described in Section II-B1. The vehicle can charge with smart logic during the entire day for the days when it is not driven, whereas it can smart charge only few hours during the remaining days. During smart charging the vehicle charges if there is an excess of PV production above the minimum $\overline{P} = 1.38$ kW ($6A \cdot 230V$) up to $\overline{P} = 3.68$ kW, until $\overline{SOC}^{EV} = 90\%$ is reached. To avoid having a fully discharged vehicle when the user needs to drive, if the vehicle has a SOC lower than 50% (SOC^{set}) at midnight of the driving day, the urgent charging mode takes over and can charge the vehicle up to 50% until 8.00 with offset charging power: $P^{set} = 2.53$ kW ($11A \cdot 230V$).

3) *BESS data*: To avoid accelerated degradation, the battery is operated between $SOC^B = 10\%$ and $\overline{SOC}^B = 90\%$. The inverter is considered to have a power-dependent efficiency. The inverter is assumed to be a Fronius type [21], as the one of the PV in Fig. 3. Therefore, the efficiency data of this inverter is considered and is provided in Table II for the charging case. Since only some operating points are provided, the remaining points are derived with linear interpolation. The discharging efficiency is the inverse of the charging one.

IV. RESULTS

In this section first we visualize the effect of employing smart charging and the use of a BESS over a week, and discuss the increase in self-consumption and the obtained savings over

one year. Next, we assess and compare the performance of the two solutions, both in technical and economic terms.

A. Smart charging

Fig. 4 provides the profiles of the PV production, HC and EV charging profile during week 11 (9th-15th of March) of 2020. When dumb charging is considered (top plot), the vehicle starts charging at 18:00 when it is plugged-in, with 3.68 kW and up to the maximum SOC of 55.8 kWh. When smart charging is considered (bottom plot), the vehicle charges if there is net generation, and this is large enough to reach the minimum charging limit of 1.38 kW (Monday, Tuesday, Friday and Saturday); the user drives on Wednesday, Thursday and Sunday, thus the vehicle will enter on urgent window at midnight of the same days to cover the missing energy until the minimum SOC of 31.0 kWh is reached.

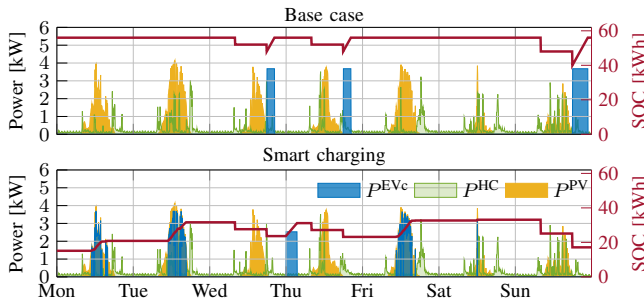


Fig. 4: Comparison charging behaviour with normal (top plot) and smart charging (bottom plot).

On a yearly basis, self-consumption is increased from 29% to 54% when smart charging is applied, resulting in savings equal to 221 €/year.

B. BESS

Different combinations of BESS sizes are here investigated. The power of the inverter (P^{inv}) varies from 1 to 6 kW with 1 kW steps, whereas the battery capacity (C^B) varies from 2 to 16 kWh with 2 kWh steps. Fig. 5 compares week 11 of 2020 in the case of the smallest BESS (P_s^B) with $P^{inv} = 1$ kW and $C^B = 2$ kWh, and of the largest BESS (P_1^B) with $P^{inv} = 6$ kW and $C^B = 16$ kWh. HC, PV and EV profiles are the same in both cases. P^B is the difference between discharging (P^{Bd}) and charging (P^{Bc}) power.

In Fig. 6 the different BESS sets are compared in terms of self-consumption and savings per year. On a yearly basis, self-consumption is increased from 29% to 41-66% depending on

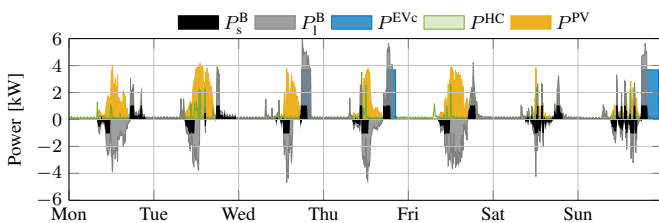


Fig. 5: Comparison of BESS profiles during week 11 of 2020.

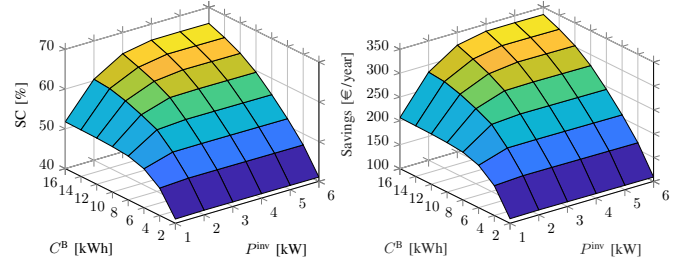


Fig. 6: Comparison of self-consumption and yearly savings of the different battery-inverter sets.

the BESS size, resulting in savings equal to 110–335 €/year. It is interesting to note that the increase on self-consumption and savings by using an inverter larger than 3 kW is not significant.

C. Comparison and discussion

Both solutions increase self-consumption and savings compared to the base case. Table III summarizes the main outputs, comparing the base case with smart charging and three BESSs: the smallest (2kWh/1kW), the largest (16kWh/6kW) and the one whose savings and self-consumption are comparable with smart charging (8kWh/2kW).

Smart charging and BESS operation introduce additional losses. The former due to the modulation of the charging power and the latter primarily due to the inverter. These additional losses are 85 kWh for smart charging and 27–105 kWh for the BESS. With smart charging the average SOC of the EV battery is also decreased to 57% (compared to 88% with dumb charging, which is also applied when the BESS is used), which may have a positive effect on the battery lifetime. Differently, when introducing a BESS the number of cycles is deemed more relevant for the battery lifetime. Increasing the inverter size with the same battery capacity, the number of cycles increases, whereas the opposite happens when increasing the battery size with the same inverter.

One of the most important aspects from the prosumer's point of view is the economic viability of the solution. A smart charging infrastructure of 3.68 kW may cost twice as much

TABLE III: Yearly results comparison of base case with smart charging and three different BESS sizes.

	Base case	Smart charging	2kWh 1kW	8kWh 2kW	16kWh 6kW
SC [%]	29.01	54.33	41.06	55.51	65.96
Energy to grid [kWh]	4798	3699	4269	3626	3149
Energy from grid [kWh]	2954	1938	2453	1851	1416
Energy to EV [kWh]	1851	1934	1851	1851	1851
Energy in EV [kWh]	1666	1661	1666	1666	1666
L^{EV} [kWh]	185.1	272.3	185.1	185.1	185.1
L^B [kWh]	-	-	26.56	65.82	105.5
$L^{EV} + L^B$ [kWh]	185.1	272.3	211.7	250.9	290.6
Average SO^{EV} [%]	88.14	57.43	88.14	88.14	88.14
Average SO^{CB} [%]	-	-	40.57	45.05	44.25
Cycles number BESS	-	-	257.5	142.1	99.59
C [€]	594.7	373.6	485.1	354.0	259.7
Savings [€]	-	221.0	109.5	240.6	335.0

as a 'dumb' charger of the same size, e.g. 400 € for a dumb charger [22] against 900 € for a smart one [21], [23]. The price of a BESS is a function of the battery size, with larger batteries costing more, but with a lower price per kWh of capacity. Considering that the price of a 8kWh/2kW BESS, which yields similar savings to the prosumer, is approximately 10000 € [24], the payback time would be approximately 20 times higher than that of the smart charger. Even if a higher smart charger cost with more advanced capabilities is considered, a BESS is clearly less attractive economically. With the current prices, the payback period in our case study is around 2 years for a smart charger (compared to installing a 'dumb' charger) and 40 for a BESS, far exceeding system lifetime. It is possible that a more sophisticated use of the battery, e.g., for spot price optimization, could increase savings, but the 20 to 1 payback ratio makes smart charging much more attractive under the current circumstances.

V. CONCLUSION

This article compares the increase in self-consumption and the obtained savings of a PV prosumer with an EV, when smart charging and a BESS operated under a simple energy import minimization logic are considered. We find that in a typical Danish household smart charging increases self-consumption from 29% to 54% and results in yearly savings of 220 €, with a payback time of approximately 2 years. A BESS that yields similar results was found to be sized to 8kWh/2kW, but has a payback time of approximately 40 years. It should be stressed that these results may depend on the prosumer's characteristics, such as inflexible consumption, PV size and EV usage, and savings could to some extent improve by more sophisticated control logics. However, the obtained 20 to 1 ratio indicates that with the current prices smart charging is a much more attractive option economically for typical PV/EV prosumers. In our future work we will conduct a more thorough analysis by employing more advanced controllers that consider variables prices, and also consider different prosumer characteristics, driving patterns and retail prices. This will allow us to obtain more accurate and generalized results regarding the economic viability of the two solutions.

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