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PV-Powered Public Smart EV Charging in Denmark: A Feasibility Assessment

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Executive Summary

The emission reduction targets for the transportation sector set by the European Commission require a conversion of the existing fleet of internal combustion engine cars to electric vehicles (EVs). For EV charging stations in public locations, the charging point operator (CPO) gets paid by the EV owners who charge their vehicles, and sustains the costs for electricity provision (including grid tariffs). Those costs could be reduced by making use of the energy produced by a photovoltaic (PV) system, one of the cheapest types of renewable energy sources. In this paper, we analyse the economic feasibility of installing a PV system to supply 1-4 parking lots in Denmark, adopting the perspective of the CPO. We analyse both the scenarios where the EV charging processes are controllable (smart charging - SC) or not (uncontrolled charging - UC). The deployed SC algorithm is a centralised one, aimed at minimising the EV charging costs. We find that, with the analysed pricing scheme and without taking a loan for the PV system, it takes 6-10 years to reach payback if smart charging (SC) is applied. The payback time increases to 9-12 years without SC, showing that a cost reduction for the EV owners also means a reduced payback time for the CPO. Considering more than one parking lot is beneficial in reducing the PV system payback time, as a higher self-consumption means lower electricity provision costs. Additionally, the suggested SC strategy reduces the equivalent CO_2 emissions by 5-25%, contributing to the EU commission CO_2 emission reduction targets.

Keywords: electric vehicles, smart charging, charging business models, energy management, modelling & simulation

1 Introduction

In 2024, 13.6% of the new car registrations in the EU were electric[1], hinting at a continuous upward trend in the adoption of electric vehicles (EVs). The European Commission's fit-for-55 action plan requires the EU countries to reduce their greenhouse gas emissions by at least 55% by 2030 (compared to 1990

[1]ACEA Auto, "New car registrations: +0.8% in 2024; battery-electric 13.6% market share, `https://www.acea.auto/pc-registrations/new-car-registrations-0-8-in-2024-battery-electric-13-6-market-share/`

levels), and achieve a 100% reduction by 2050[2]. To meet these goals, decarbonizing the transportation sector is essential, as it contributed to 11% of Europe's total greenhouse gas emissions by the end of 2022[3]. Given that passenger cars cover a significant portion of the current vehicle fleet, replacing older internal combustion engine vehicles (ICVs) with EVs is crucial to reduce their carbon footprint, since EVs are, at least in Europe, significantly less CO_2 intensive than ICVs [1]. A further reduction could be attained by making use of PV systems to power the EVs [2, 3], realising i) a cost reduction, if the levelised cost of electricity (LCOE) of the PV system is low enough, ii) an emissions reduction, if the national energy mix still relies to a large extent on fossil fuels, and iii) a reduction of the grid impact, due to the coincidence of PV generation and EV charging demand in public stations. Furthermore, EVs can also be "smart charged", i.e. charged when the electricity costs or equivalent CO_2 emissions are lowest. In this article, we analyse the business case of a PV system used to power a parking lot located in Denmark, assuming the perspective of a charging point operator (CPO), installing the PV system and aiming at reaching the payback as fast as possible. We make use of a centralised V1G smart charging algorithm to charge the EVs with the PV production as much as possible, increasing the self-sufficiency of the system and reducing the payback period at the same time.
The topic of smart unidirectional (V1G) charging in parking lots with a cost-minimal solution is formulated using a deterministic approach (i.e., MILP), and what follows in Table 1 is a collection of similar works found in the scientific literature.

Objective	Formulation	PV Profitability Analysis	Real EV Charging Dataset	Source
Maximising EV Charging Revenues	MILP	NO	NO	[4]
Maximising EV Owners' Revenues	MILP	NO	NO	[5]
Minimising EV Charging Costs	MIQP	NO	NO	[6]
	LP	NO	NO	[7]
	NLP	NO	NO	[8]
	MILP	NO	NO	[9]
	MILP	YES	YES	This paper
Minimising System Costs	MILP	NO	NO	[10]
	MILP	YES	NO	[11]
	NLP	YES	NO	[12]

Table 1: Relevant literature overview on smart EV charging techniques in parking lots for costs minimisation/PV usage maximisation. QP=Quadratic Programming, LP=Linear Programming, MI=Mixed-Integer, NLP=Non-Linear Prograrmming.

It is evident that, for this specific type of optimisation problem, there is a gap concerning the use of metered data for both the EV charging and PV production, which only our paper covers. Moreover, a complete and detailed profitability analysis for the installation of a PV system to supply the EVs is only analysed in this work, and in [12], where the authors found that the payback period for a PV-flywheel or PV-battery storage system is around 11-12.5 years in France and Morocco, respectively. As such, we

[2]Council of the European Union, "Climate Change: What is the EU Doing?", `https://www.consilium.europa.eu/en/policies/climate-change`

[3]Eurostat, "EU Economy Greenhouse Gas Emissions" (2023), `https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230515-2`

think it is interesting to investigate the feasibility of a PV-EV charging system in Denmark, a country where the solar resource is available with a comparably low intensity throughout the year, but charging tariffs are already dynamic and the end-user exposed to spot price fluctuations.
The paper is structured as follows: section 2 formulates the mathematical optimisation problem, and the reasoning behind the choice of the cost for the energy consumed from the PV system in relation to the payback period (PP). section 3 thoroughly describes the electric features of the parking lot and the EV charging dataset. Finally, section 4 presents the results of the analysis, and section 5 draws the conclusions of the work.

2 Methodology

This section presents the centralised smart charging algorithm and the formalised methodology for calculating the payback period for different investigated cases.

2.1 Centralised Smart Charging Algorithm

The V1G smart charging algorithm used for this analysis is a simplified version of the one introduced in [3], and optimally schedules the EV operation to minimise both the EV charging cost for their owners, and the electricity provisions cost for the CPO. The scheduling algorithm is executed in real time, and runs every time an EV is either connected or disconnected. The optimisation is formulated as a mixed-integer linear programming (MILP) problem, as summarised below:

$$\min_{\substack{\mathbf{P^{EV}};\mathbf{P^{EV}_{PV}}\\ \mathbf{P^{PV}_{surp}};\mathbf{Y}}} \quad \Delta t \cdot \sum_{n=1}^{N(t^*)} \sum_{\tau=1}^{\mathcal{T}} \left(P^{EV}_{\tau,n} \cdot (c_\tau + c^{prov}_\tau) - P^{PV}_{surp,\tau} \cdot c^{spot}_\tau \right) \tag{1}$$

$$\text{subject to:} \quad \Delta t \cdot \sum_{\tau=1}^{\mathcal{T}} \left(P^{EV}_{\tau,n} + P^{EV}_{PV,\tau,n} \right) = \Delta E_{s,n} \tag{2}$$

$$Y_\tau \cdot P^{EV}_{min} \leq P^{EV}_{\tau,n} + P^{EV}_{PV,\tau,n} \leq P^{EV}_{max,n} \cdot Y_\tau \tag{3}$$

$$0 \leq P^{EV}_{PV,\tau,n} \leq P^{PV}_\tau \cdot Y_\tau \tag{4}$$

$$P^{EV}_{\tau,n} \geq 0 \tag{5}$$

$$\sum_{n=1}^{N(t)} P^{EV}_{\tau,n} \leq P_{fuse} \cdot N_{lots} \tag{6}$$

$$\mathcal{T} = \max \begin{pmatrix} t_{dc,1} - t^* \\ t_{dc,2} - t^* \\ \vdots \\ t_{dc,N(t^*)} - t^* \end{pmatrix} \tag{7}$$

$$\text{where:} \quad n = 1, ..., N(t^*)$$

$$\tau = 1, ..., \mathcal{T}$$

where:

- $P_{\tau,n}^{EV}$ is the power absorbed by the n-th EV from the power system at time τ and price c_τ €/kWh.
- c_τ is the dynamic electricity cost for charging the EV, defined as the day-ahead (spot market) price c_τ^{spot} plus a CPO markup fee, as described in Section 3.
- c_τ is the dynamic electricity provision cost for the CPO, considered as a C-type customer in Denmark. As described in Section 3, this tariff includes network costs and taxes.
- $P_{PV,\tau,n}^{EV}$ is the power absorbed by the n-th EV from the PV system at time τ and price c_τ^{PV} €/kWh.
- c_τ^{PV} is the cost of charging from the PV system, which is equal to the cost of electricity minus a discount applied by the CPO $c_\tau \cdot (1 - disc)$ to push the EV owners to use the PV energy first, and the grid second.
- $P_{surp,\tau}^{PV}$ is the PV production which is sold to the power grid because it is not utilised to feed the EVs.
- $\Delta E_{s,n}$ is the energy to be charged in the n-th connected EV during session s.
- Y_τ is a binary variable which is 0 when an EV is connected, and 1 when no EV is connected to a charging outlet.
- $P_{max,n}^{EV}$, P_{min}^{EV} are the max. and min. charging power values for the n-th connected EV.
- P_τ^{PV} is the PV power production at time τ.
- P_{fuse} is the maximum parking lot (fuse) capacity.
- $N(t)$ is the number of EVs connected at time t.
- t^* is the time at which the algorithm is run, i.e. when an EV is connected or disconnected [3].
- $\mathcal{T}$ is the optimisation period, defined as the duration of the session for the EV which stays the longest, between the ones connected at t^*.

In short, the algorithm is run every time an EV connects or disconnects, and aims at minimising the total charging cost for the EV owners, while still charging the required amount of energy, without triggering penalties due to high concurrent charging power values.

2.2 Payback Period Calculation

The cash flow logic is represented in Figure 1, note how the dynamic tariffs are represented by average costs for the sake of clarity.
The CPO receives 0.274 €/kWh from the EV owners for charging their EVs, and applies a small discount for the energy purchased from the PV system ($disc = 1\%$), to push them to consume the PV production first. Since the tariffs were not updated after the EV chargers were installed (in 2019), the average electricity provision costs for 2024 (0.279 €/kWh) are slightly higher than the average revenues. The installation of a PV system would help the CPO to get back on track, avoiding a renegotiation of the electricity provision contract, or an increase of the EV charging costs.

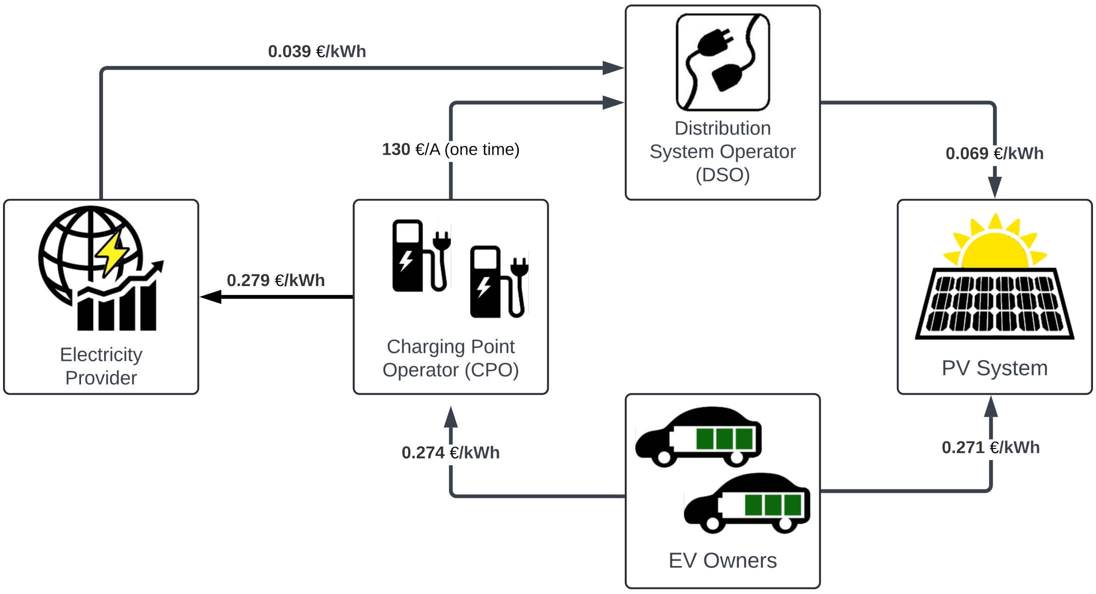


Figure 1: Cash flows and average costs for the purchased/sold electricity in the parking lot under study for 2024.

The CPO will reach payback for the PV system before its end of life if the yearly average cash flow with the PV system CF_y^{PV} is higher than the one without CF_y, or, equivalently, if the average yearly margin is positive: $MS_y = CF_y^{PV} - CF_y \geq 0$. This calculation is repeated for one or more adjacent parking lots, to assess whether increasing the total load brings any benefit to the payback time of the PV system. In mathematical terms, considering average costs:

$$CF_y = (\overline{c} - \overline{c}^{prov}) \cdot EV_{load} \cdot N_{lots} \tag{8}$$

$$CF_y^{PV} = [(\overline{c} - \overline{c}^{prov}) \cdot (1 - SS) + (\overline{c}^{PV} - LCOE) \cdot SS] \cdot EV_{load} \cdot N_{lots} - OPEX \tag{9}$$

$$MS_y = (\overline{c}^{prov} + \overline{c}^{PV} - LCOE - \overline{c}) \cdot SS \cdot EV_{load} \cdot N_{lots} - OPEX \geq 0 \tag{10}$$

where:

- EV_{load} is the total annual EV load of one parking lot, while N_{lots} is the number of parking lots the PV system is supposed to power up.
- SS is the PV system self-sufficiency, i.e., the share of EV_{load} covered by the PV system [13].
- $\overline{c}$ is the average cost of the electricity the EV owners purchase from the CPO.
- $\overline{c}^{prov}$ is the average cost for the CPO to purchase the electricity from the electricity provider.
- $\overline{c}^{PV}$ is the average cost for the energy purchased by the EV owners from the PV system.
- $LCOE$ is the levelised cost of electricity for the PV system in Denmark.
- $OPEX$ is the yearly cost for operation and maintenance of the PV system.

Considering the payback period PP is the year at which the sum of the discounted margins becomes zero, if PP must be kept under 10 years (current industry standard in Denmark), then MS_y needs to be high enough to justify the investment. Eq. (11) defines PP as a function of MS_y and the discount rate DR:

$$PP = Y \mid CAPEX + \sum_{y=1}^{Y} \frac{MS_y}{(1+DR)^y} = 0 \tag{11}$$

By combining eqs. (10) and (11), if we assume $DR = 0$ and MS_y to be the same each year $y > 0$, PP becomes as:

$$PP = \frac{CAPEX}{MS_y} = \frac{CAPEX}{(\overline{c}^{prov} + \overline{c}^{PV} - \overline{c} - LCOE) \cdot SS \cdot EV_{load} \cdot N_{lots} - OPEX} \tag{12}$$

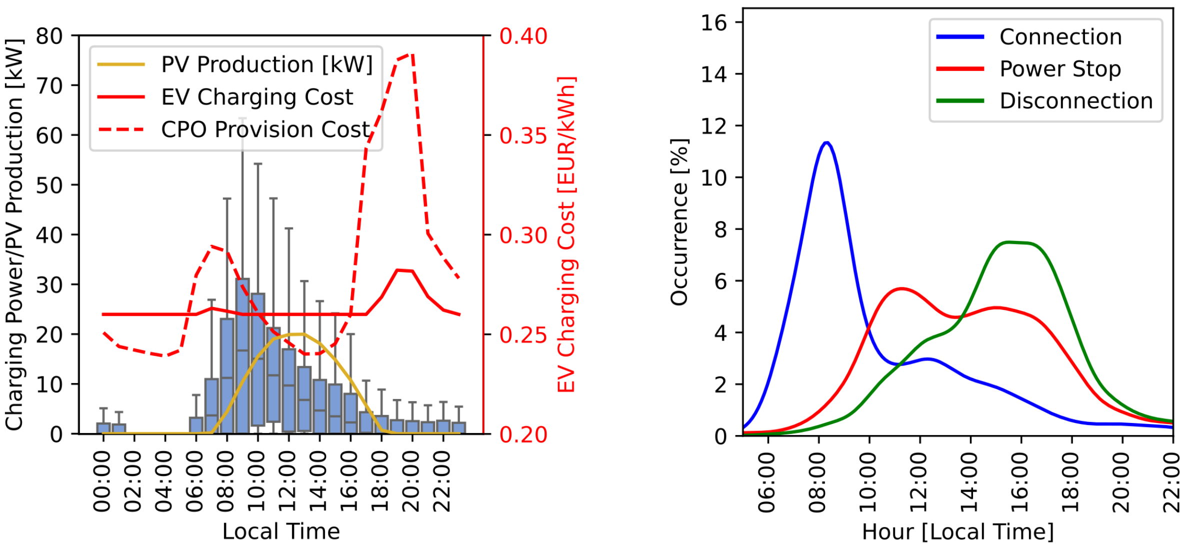
which reasonably tell us that PP is inversely proportional to $SS \cdot EV_{load} \cdot N_{lots}$, $\overline{c}^{prov}$, and $\overline{c}^{PV}$, and directly proportional to the $LCOE$ and $\overline{c}$.
If the EV owners pay the LCOE when charging from the PV system, then $\overline{c}^{PV} = LCOE$. Since $\overline{c}^{prov} \leq \overline{c}$, then $MS_y < 0$. This means that, if the EV owners pay the cost of producing the PV energy only, then the margin is negative and the CPO loses money in the investment. The higher the difference between $\overline{c}^{PV}$ and $LCOE$, the higher the margin for the CPO, and the lower the PP. When the EV owners pay as much as they would if they purchase from the power system, i.e. $\overline{c}^{PV} = \overline{c}$, then the optimiser would never choose to consume the PV production, because it is too expensive and it does not produce any cost savings for the users. Hence, the value of $\overline{c}^{PV}$ needs to be set by the CPO as close as possible to $\overline{c}$, but not too low, considering that $LCOE \leq \overline{c}^{PV} \leq \overline{c}$. This is why the formulation of $\overline{c}^{PV} = \overline{c} \cdot disc$ was adopted.

3 Case Study

This section describes the analysed parking lot and utilised PV production profiles, the applied tariff system, and the different simulation parameters for both the optimisation model and the economic feasibility analysis.

3.1 Parking Lot Features

The parking lot under study is located in the Greater Copenhagen Area, in the municipality of Kgs. Lyngby, at DTU's (Technical University of Denmark) premises. It includes 12 outlets, each limited to 13.8 kW, distributed over 6 charging stations with a max. capacity of 22 kW. No smart energy management system is currently used in the parking lot. The nominal parking lot charging capacity is 68.3 kW (99 A, 3ph, 230 V), so approximately 6 EVs can charge at 11 kW at the same time. The parking lot capacity utilisation, as well as the production of an optimally oriented PV system (42° tilt, 0° azimuth) located on a nearby rooftop, and connected under the same metering point, are shown in Figure 2a, together with the charging cost for the EV owners. Note that the shaded areas represent the 25th-75th quantiles interval of the different represented distributions.
It is immediately noticeable how the EV owners tend to charge in the early morning (07:00-09:00), after arriving at work, so the EVs are fully charged around 10:00-11:00, while the disconnection time is around



(a) PV production and EV charging consumption patterns in the parking lot.

(b) Statistical distribution of connection, charge completed, and disconnection instants.

16:00-17:00, when the working day is over. This allows for a good potential to shift the consumption from the morning to the central hours of the day, when the PV production is also higher. Note how a PV system in Denmark produces around 950 kWh/kWp, and that the median of the hourly production along the year is around 40% of the installed capacity, even for an optimally installed PV system.

3.2 EV charging costs

The tariff applied by the CPO at the parking lot follows the mathematical relation expressed in (13).

$$c_\tau = \max(c^{min}, c_\tau^{spot} + \Delta c^{CPO}) \tag{13}$$

In short, the final price for the EV owner is either c^{min} = 0.26 €/kWh, or the sum of the spot (day-ahead) market price c_τ^{spot} and a CPO surcharge Δc^{CPO} of 0.175 €/kWh. The minimum cap is set to avoid negative prices and have a constant income from the charging services, while the surcharge should cover DSO and TSO tariffs, and taxes. The "floor" cost value does not allow the EV owners to charge when the spot market price is very low, severely reducing the SC cost reduction potential, as shown in [3]. The PV overproduction which is sold to the grid is assumed to be priced at the spot market cost of electricity, i.e. c_τ^{spot}.

Since the parking lot is connected to the 400 V LV network and doesn't have its own substation, considering the total consumption per year, the DSO who is managing the area prescribes that the CPO is a "C-level" customer. In Denmark, the grid tariffs dynamically change based on three different loading levels (low/high/peak), to disincentivise consumption in peak loading hours. Figure 3 shows on the left, a breakdown of the electricity provision tariffs for a typical day, and on the right, how much the EV owners pay for charging their EVs at the parking lot on the same day.

It is evident that the tariff structure imposed by the CPO is not profitable, hence the installation of a PV system becomes a viable option to avoid increasing the EV charging costs, with the additional value of not losing competitiveness against other CPOs in the area.

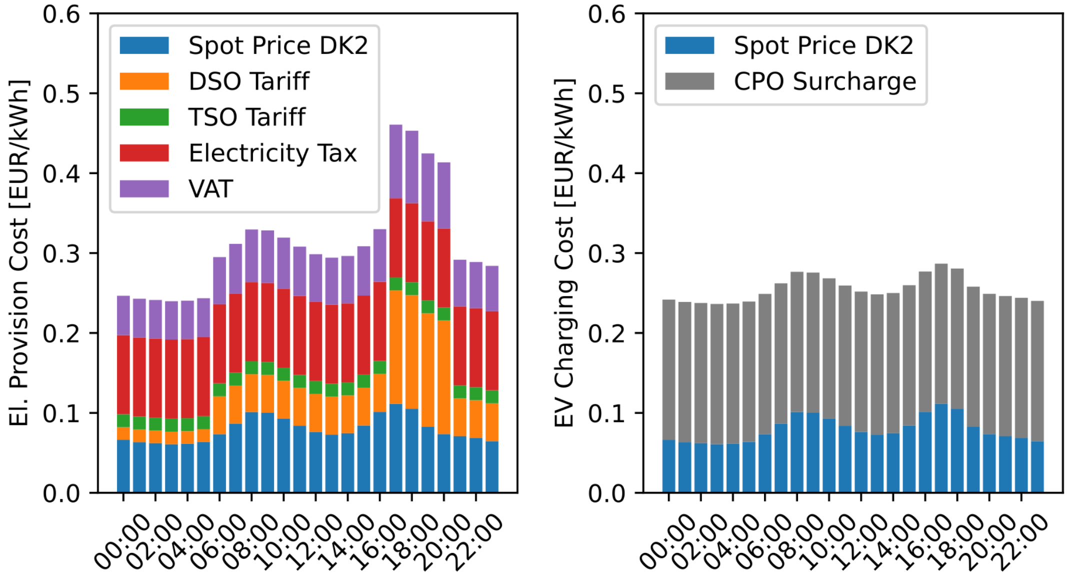


Figure 3: Average electricity costs breakdown for the CPO (left), and for the EV owners (right).

3.3 Simulation Parameters

The different parameters and assumptions for the economic analysis are:

- **PV System Costs**: CAPEX: 1250 €/kWp, for utility scale (in 2022 [14]), OPEX: 2% of the CAPEX per year [15], expected lifetime of 30 years [16]. This yields a $LCOE$ = 0.08 €/kWh, in line with the values from [17], but the estimate is conservative since the cost of PV systems is slowly decreasing year by year.

- **Discount rate**: 3.4% when getting a loan from a bank in Denmark. This value is estimated as 50% more of the rate suggested by the Danish National bank[4]. When the money instead is coming from a private deposit, the chosen value $DR = -1.4\%$ is the 2024 inflation rate for Denmark (1.4%)[5] taken with a negative sign because purchasing the PV system with the money avoids the loss of value due to inflation.

- **Average costs of electricity**: $\overline{c}_{rev}$ = 0.274 EUR/kWh for the EV owners, $\overline{c}^{prov}$ = 0.279 €/kWh electricity provision costs for the CPO.

- **PV energy cost:** As explained above, since the objective is to minimise the PV payback period for the CPO, when the EV owner consumes electricity from the PV system, i.e. for the "self consumed" energy, there is a small discount of $disc = 1\%$ of the price per kWh. This small discount value is necessary to "force" the optimisation algorithm to consume from the PV system first, so $\overline{c}^{PV}$ = 0.271 €/kWh.

The values used for the optimisation algorithm instead, are:

[4]Danmarks Nationalbank, "Official Interest Rates", https://www.nationalbanken.dk/en/what-we-do/stable-prices-monetary-policy-and-the-danish-economy/official-interest-rates

[5]Danmarks Nationalbank, "Inflation is on track, but there is still some pressure", https://www.dst.dk/en/Statistik/emner/oekonomi/prisindeks/forbrugerprisindeks

- P^{EV}_{min} = 1.38 kW is the minimum power that can be absorbed by each EV, i.e. 6 A in single-phase, assuming a constant 230 V charging level [18].
- $P^{EV}_{max,s}$ ranges between 3.7 kW and 11 kW, depending on the recorded power levels for each session s.
- N_{lots} is the number of considered parking lots, ranging between 1 and 4 (12-48 charging stations).
- P_{fuse} = 79.1 kW, since the nominal capacity is 70 kW (101.5 A, 3ph, 230 V), but the installed parking fuse can withstand up to 113% of the nominal power [19].

Given an SS value of 37.5-78.0% for a 30-70 kWp PV system, a yearly EV_{load} of 21.82 MWh for N_{lots}=1, and $DR = 0\%$, the PP is over 25 years. This means that, even if the EV owners have basically no discount for consuming the PV production, i.e. the CPO does not lose money compared to selling them the electricity coming for the power system, installing the PV system for one parking lot is not enough for the investment to reach payback in the required time.

If N_{lots} increased instead, e.g. from the perspective of an aggregator who owns multiple parking lots, the investment could make sense, as shown in (12). It has to be noted that, in case more parking lots are considered, ($N_{lots} \geq 1$), then, unless they are under the same common metering point, the CPO would be operate a virtual power plant. Since this falls out of the scope of this analysis, we will assume, from here onwards, that the considered parking lots share a common metering point.

In this paper, we adopt the second option, and scale the P_{fuse} limit to the number of analysed lots N_{lots}, while increasing the EV load proportionally by having the EV charging data from the same lot repeated N_{lots} times. In order to add some variability to the generated dataset, a random delay with a 30 min average was added to the connection instant of each charging session.

4 PV System Profitability Analysis

The algorithm is able to efficiently schedule the EV consumption to consume as much PV production as possible, as shown in Figure 4. The average annual sources of revenue and expenditure are shown in Figure 5 for one or four parking lots, and different installed PV capacities.

Figure 5 firstly shows that the average total cash flows increase with the number of considered parking lots. The average total values are up to 10 k€/year both for SC and UC. If a single parking lot is considered, the main income source is of course the payment from the EV owners for charging the vehicles, while the extra PV production selling is not so profitable due to the low compensation rewarded for injecting power into the grid (spot market price). Increasing the PV installed capacity does not significantly decrease the electricity provision costs, because there is not enough consumption to efficiently exploit the increased generation (SS is almost constant when the installed PV capacity increases). When four parking lots are considered instead, the effect of increasing the installed PV capacity is more noticeable, given the increase in the revenue from the self-consumed energy. The investment payback periods are showed in Figure 6, for both the -1.4% and 3.4% DRs, and the two charging strategies (UC/SC).

From Figure 2a, it can be firstly noticed that, for both DR values, the payback time is lower than the lifetime of the PV system (25-30 years), but is lower than the industry standard (10 years) in some scenarios only. SC has definitively a positive impact for both the chosen DR values, reducing the payback

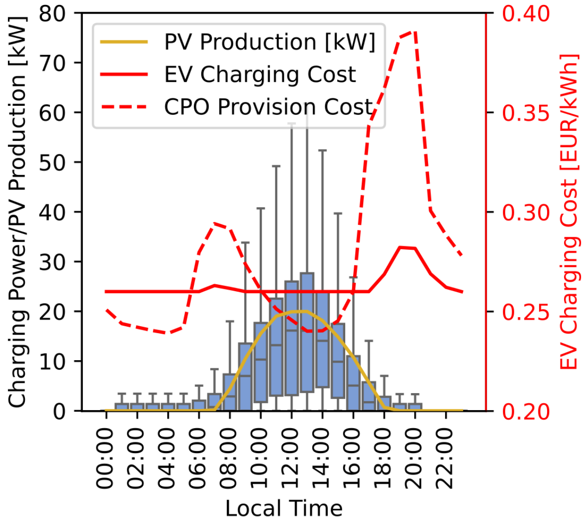


Figure 4: Normalised PV production and EV charging consumption patterns in the parking lot when SC is applied.

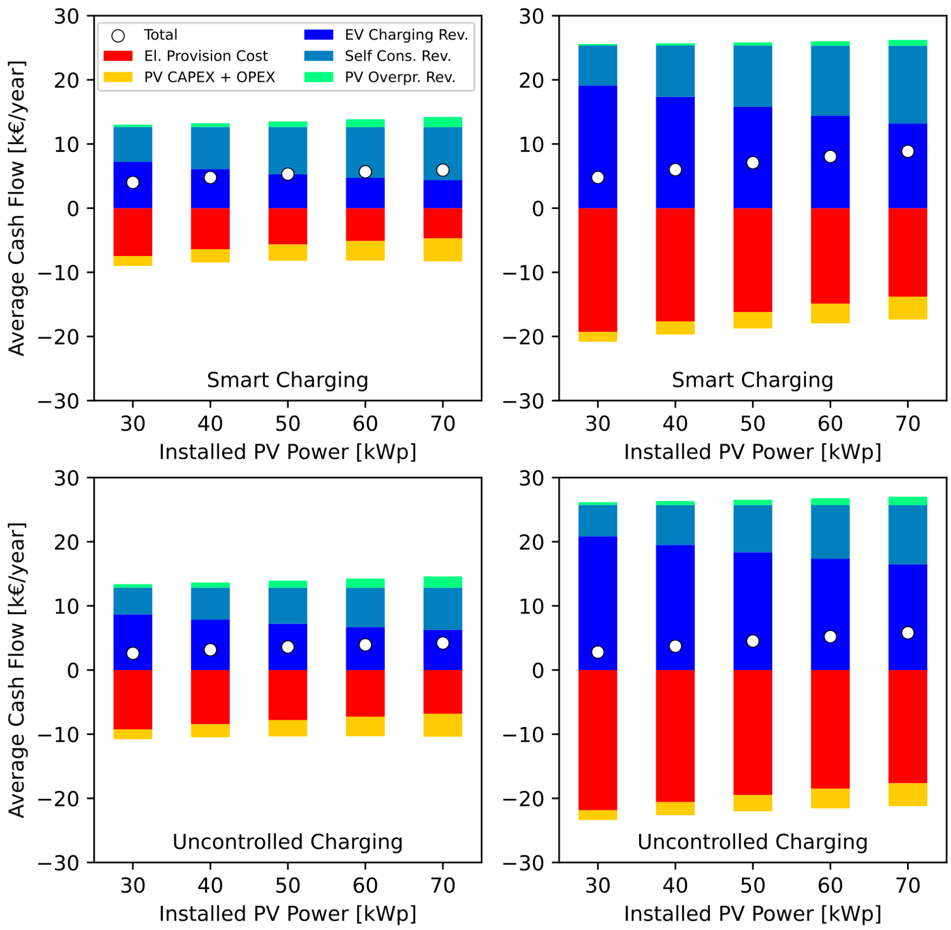


Figure 5: Average annual cash flows for the CPO w.r.t. the installed PV power and the number of considered parking lots when SC is not applied (lower row) and when it is applied (upper row). Values for one (left column) and four (right column) parking lots are presented.

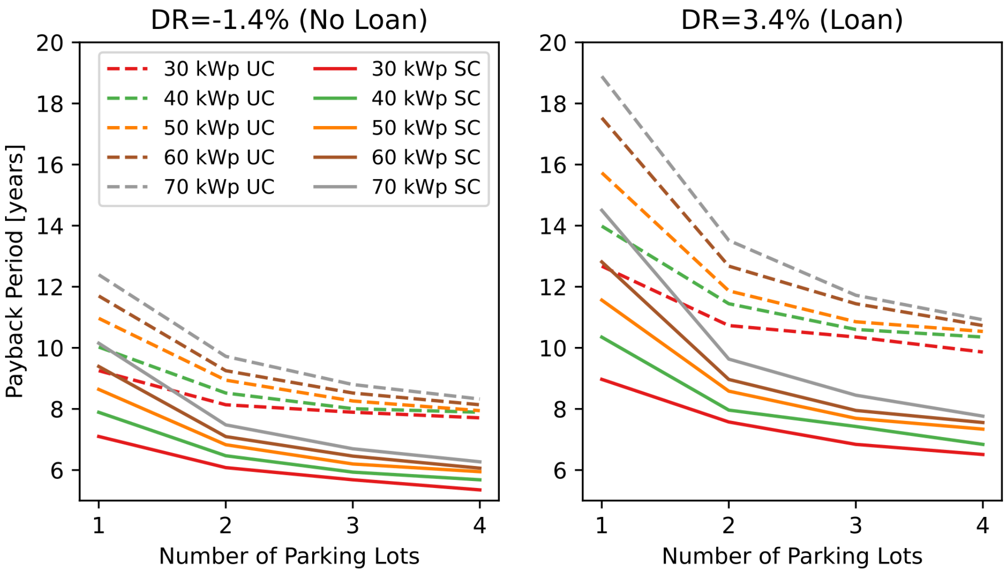


Figure 6: Payback period values for the PV system investment, considering negative (money from deposit) and positive (bank loan) discount rates.

period by around 2-4 years. Moreover, when one parking lot is considered only, the value of self-consumption is almost constant as the PV power increases, since the EV load is not enough to justify a higher installed PV capacity. This means that, the higher the number of considered parking lots, the lower the payback period, under the assumption that the parking lots are under the same metering point. The situation is quite different for the two DRs, with the negative one (inflation) naturally providing a better outcome. The application of SC does not only benefit the CPO, but also saves some money for the EV owners, and reduces the overall equivalent CO_2 emissions, as shown in Figure 7.

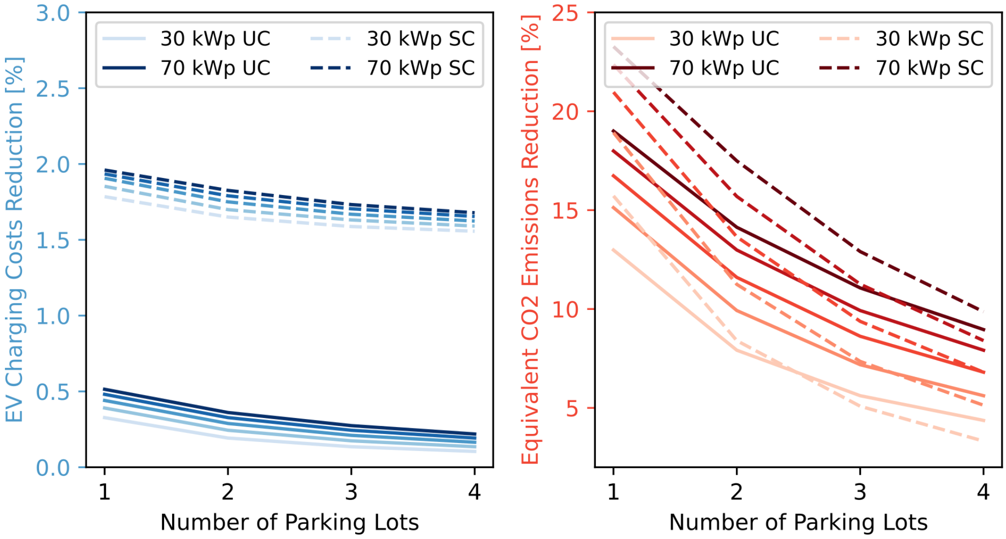


Figure 7: EV charging costs and equivalent CO_2 emissions reduction due to the application of SC.

Figure 7 shows that the EV charging cost reduction is, on average, quite low (1.75-2% with SC), due to the aforementioned floor tariff of 0.26 €/kWh imposed by the CPO and to the low discount applied when charging from the PV system ($disc = 1\%$). The equivalent CO_2 emissions reduction is instead quite relevant (5-25%), and increasing as the installed PV capacity does. Since the installed PV capacity is not scaled to the number of served parking lots, both the emissions and EV charging costs reduction are lower when increasing the EVs load.

5 Conclusions

In this paper, we analysed the economic feasibility of powering one or more EV parking lots in Denmark with a common behind-the-meter PV system. We analysed both the cases when cost-based V1G smart charging is applied or not. Results show that, even if the PV system payback period is lower than its lifetime, PV-following smart charging is an effective way to reduce the payback time under 10 years (industry standard) if the PV system size is under 70 kWp (without loan) or 40 kWp (with a loan). If more parking lots are considered instead, the payback period is greatly reduced, highlighting the importance of self-consumption. Indeed, results that do not consider taking a loan show that the payback lowers to 6-7 years with four parking lots if smart charging is applied, and to 9 years if not. If a loan is taken to purchase the PV system, the payback period is between 7-9 years with four parking lots with SC, and 11-12 without SC. In both cases, the EV owners do not have a discount to purchase energy coming from the PV system, so the EV charging cost reduction is minimal, while a 5-25% reduction in equivalent CO_2 emissions can be achieved in the same conditions. It needs to be underlined that this study is conditioned both by the EV charging scheme in the parking lot, and the productivity of a PV system (around 900-1000 kWh/kWp/year). The situation would be very different at lower latitudes.
Future research directions should include the analysis of i) parking lots with different usage and pricing schemes, ii) parking lots located in different geographical areas with higher solar irradiation, iii) the benefits from energy arbitrage via vehicle-to-grid (V2G).

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