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Battery Storage Integration in EV Fast Charging Station for Increasing its Revenues and Reducing the Grid Impact

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Abstract—This paper discusses the design and optimization of electric vehicles' fast-charging stations with on-site photovoltaic energy production and a battery energy storage system. Three scenarios, varying the number of chargers, distance from the main grid, and on-site photovoltaic generation potential, are investigated. Such scenarios are benchmarked in investment, operating costs, and grid connection requirements. The addition of a battery storage system is also evaluated to reduce the operating cost and, therefore, boost the system's economic parameters, such as the net present value, and increase the grid independence.

The analysis shows that the addition of the battery system can be effective in both performance metrics, the reduction of the grid connection, which can be reduced up to 80% by the addition of a large size battery, and the increase of the net present value, which can be even doubled with respect to the case when the battery storage system is not installed.

Index Terms—Battery energy storage system, electric vehicle station design, multi objective optimization, net present value.

I. INTRODUCTION

Electric vehicles (EVs) are a prominent technology for the decarbonization of the transportation sector since they do not rely on internal combustion engines, and they can be powered by electrical energy produced through renewable energy sources. The widespread deployment of EVs requires several technological developments to allow long driving ranges and fast charging, which are some of the main concerns that users have about EVs [1]. These can be achieved both by improvements in the onboard power electronics, i.e., by the traction inverter efficiency and power density [2], and by creating an extended fast-charging infrastructure network [3]. However, the deployment of EV fast-charging stations does not come without a cost.

Fast charging stations (FCSs) are characterized by a high power demand [3], which needs to be supplied by the distribution grid. When several FCSs are introduced in the same area, the local grid might suffer from overloading [4], therefore investments are necessary so to reinforce the grid. As a result, FCS are subject to high demand charges by the distribution system operators (DSOs). These demand charges can therefore account for a significant portion, up to 90%, of an FCSs electric bill [5]. Under such circumstances, there is a clear incentive for FCS owners to limit their peak power.

Intelligent charging strategies, which aim to spread the maximum available charging power of the station among the

charging vehicles, instead of providing full power to all of them, can achieve this [6], [7]. The charging power allocation depends on several factors, e.g., the EV battery state of charge or the applied charging fee. Implementing such methods does not require significant investment costs; however, they foresee the reduction of the charging power of one or multiple vehicles, which might be undesirable.

Alternatively, to avoid the power curtailment of the charging vehicles, a Battery Energy Storage System (BESS) can be installed on the EV FCS premises. BESSs can shift the energy consumption, flattening the power profiles at the grid connection point [8], and therefore are a suitable solution for reducing the peak power demands and demand charges at FCSs.

The coupling of a photovoltaic plant with an electric vehicle charging station can also reduce the FCS peak demand power [9]. However, the effectiveness of the coupling depends on the time of use of the charging station, the solar irradiance, and weather condition. In this context, a BESS may help match the daily charging profile with the photovoltaic generator to increase self-consumption and reduce the station peak power [9]. Therefore, adding both a BESS and a PV plant to the FCS premises may allow for a lower power demand. Nonetheless, BESSs also add extra investment costs, so their deployment has to be adequately investigated to find the right compromise between the project's economic feasibility and the reduction in grid connection.

This paper discusses the design and optimization of EV FCS employing a BESS to reduce the grid connection size and boost the system's economic performance. Three scenarios, provided by Stedin, a Dutch DSO, varying the number of chargers, distance from the main grid, and photovoltaic generation potential are investigated. The net present value (NPV) indicator is used to benchmark the economic impact of adding a BESS to the EV FCS. Additionally, it is also evaluated the grid connection reduction due to the BESS deployment.

The paper is organized as follows, Section II describes the considered EV FCS scenarios, Section III presents the analysis and results of the BESS integration in the considered EV FCSs, and Section IV concludes the paper.

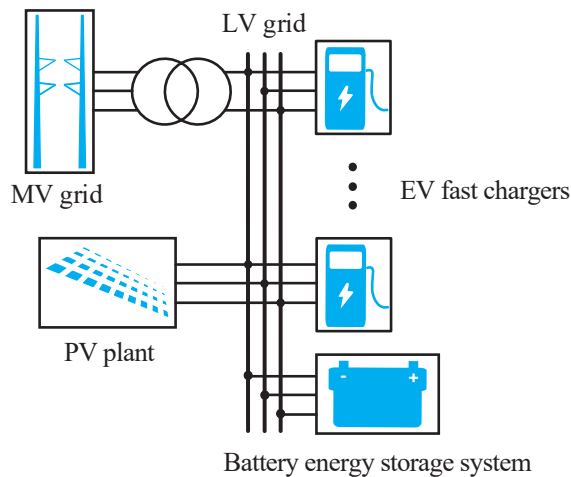


Fig. 1. Layout of a EV FCS connected to the MV grid and supported by PV generation and a battery storage system.

II. FAST CHARGING STATION DESIGN SCENARIOS IN THE NETHERLANDS

The layout of an FCS equipped with a BESS is shown in Fig. 1. Three example configurations have been considered in this study. These differ in the number of EV chargers installed, distance from the main distribution grid, and on-site photovoltaic generation potential. The details about the three FCS configurations are given in Table I. Stedin, a Dutch DSO, has provided the station layouts. These station layouts are seen as possible common layouts in the future electric distribution network. Furthermore, Stedin provided measured power profiles with a time step of 5 minutes for two FCSs located in the Netherlands. The power profiles are shown in Fig. 2. Fig. 2 (a) shows the per-unit PV production over one year for a plant located in the Netherlands. Fig. 2 (b) and (c), instead, show the power profiles of the two high-power chargers. The two chargers profile have a high utilization rate, opposite the PV profile, which reaches high peak power only during the central months of the year, as expected. These power profiles have been used as a reference for generating the power demand of the FCS configurations of Table I.

The three FCS configurations are analyzed in terms of their impact on the distribution grid by calculating the power of the grid connection and their Net Present Value (NPV), an economic indicator used to analyze the profitability of a project. The NPV can be calculated over a time horizon of n years as:

$$NPV = \sum_{t=1}^n \frac{R_t}{(1+r)^t} \quad (1)$$

where r is the discount rate of the project, fixed to 5%, and R_t are the yearly revenues.

Regarding the energy costs, the value of 0.1€/kWh, 0.05€/kWh, and 0.6€/kWh [10] are used as reference respectively for the purchase of energy from the grid, the selling of PV energy to the grid, and the selling of energy for the fast charging of EVs. In terms of initial investments, the cost of a single 120 kW fast charger is considered to be 75k€

TABLE I
SPECIFICATIONS OF THE THREE FCS CONFIGURATIONS WHICH ARE CONSIDERED FOR THE STUDY.

Parameter	Case 1	Case 2	Case 3
Chargers [n-kW]	20-120	20-120	16-120
Distance from substation [km]	12	12	12
PV possibility [MWp]	0.5	24	1

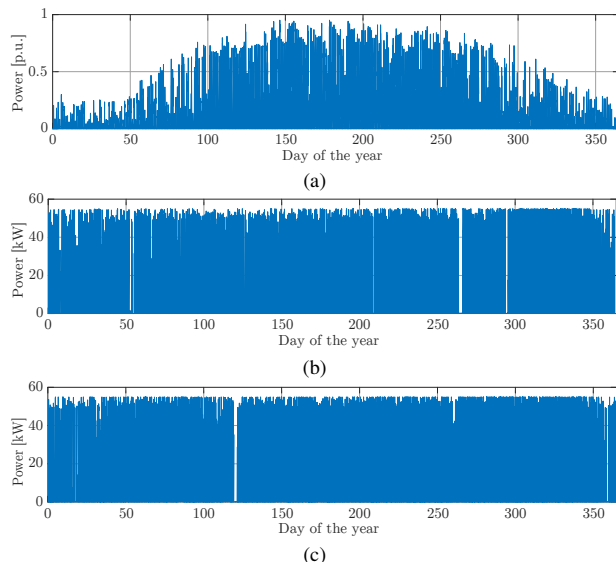


Fig. 2. Measured power profiles of (a) a PV plant located in the Netherlands, in per unit, and (b) and (c) of two high power 50 kW electric vehicles chargers.

[11], the PV installation cost used is 700€/kW [12], and the underground cable installation to connect the FCS to the substation 150€/m [13]. The underground cable installation costs include both the cable material costs and the costs of the civil works for the digging and laying of the cable. Additionally, the DSO tariffs for the grid connection are taken from Stedin website [14]. The DSO tariffs comprehend several parts. The first fee is a one-time connection fee to be paid by the user at the time of connection. This depends on the installed connection power and ranges from 38k€ to 198k€ for systems rated from 630 kVa to 3000 kVa, which is the power range of interest in this study. Secondly, the Dutch DSO charges a periodic fee with a fixed part, depending on the rated connection power, and a variable part. The variable part is paid monthly. It is determined based on the highest requested monthly power, and the total energy exchanged between the plant and the grid. Also, the rates for the variable part of the DSO fee are related to the rated connection power. The detailed tariffs are given on Stedin website [14].

Given the economic parameters and the power profiles of the EV chargers and the PV generators, it is possible to calculate the investment costs and the yearly cash flow of the various case scenarios. These are shown in Fig. 3, considering that the maximum PV potential is installed in the FCS premises. From Fig. 3(a), it can be seen that for Case 2, the main investment cost is related to the PV installation. For the other two cases, the main investment costs are the cable installation and the EV

TABLE II
SUMMARY OF THE ANALYSIS OF THE THREE CONSIDERED SCENARIOS
WHEN NO BESS IS CONSIDERED.

Parameters		Case 1	Case 2	Case 3
EV charger power	[MW]	2.4	1.9	1.9
PV rated power	[MW]	0.5	24	1
Grid connection	[MW]	2.3	27.5	1.8
Investment Costs	[M€]	3.85	20.07	2.85
Yearly Costs	[k€]	194	1134	143
Yearly Revenues	[k€]	623	1383	438
Yearly Profits	[k€]	429	249	295
NPV	[M€]	0.60	-17.48	0.21
NPV without PV	[M€]	2.17	1.24	2.37

chargers. Overall, the DSO one-time fees represent a marginal investment cost compared to the other factors. Regarding the yearly revenues and expenses, shown in Fig. 3(b), it is seen that the revenues from the charging of vehicles are the dominant revenue stream for Case 1 and Case 3, while it is the selling of PV energy to the grid in Case 2. In Fig. 3(b), the yearly profit or loss is calculated as the difference between the revenues and costs.

Furthermore, Table II, provides a summary of the three scenarios when the addition of a BESS is not considered. As it is possible to see, Case 1 and 3 are already profitable without adding a BESS, although a large grid connection is required. Case 2 is not profitable due to the large PV power installed. In this study, state incentives for PV energy are not considered; therefore, a large PV installation might not be economically profitable. State incentives are adopted in most countries, although their implementation might differ, and they generally aim at increasing the revenues of the PV plants. On the other hand, if no PV installation is considered, all three cases show a positive NPV, indicating that the deployment of EV FCS is a profitable investment in the considered scenarios.

III. BATTERY ENERGY STORAGE SYSTEM INTEGRATION IN THE FCS

BESSs can support a PV-FCS station in several ways, e.g., reducing its peak power demand, increasing the self-consumption of the locally produced PV energy, reducing the energy bill and the grid connection costs, etc. A multi-objective framework was used to evaluate the impact of introducing a BESS in the FCS. The BESS operation is focused on maximizing the system NPV and minimizing the size of the grid connection.

In this study, the BESS is deployed in an FCS with two objectives: to reduce the grid connection size, increase the FCS grid independence, and improve the NPV of the project. The investment costs for the BESS addition are considered to be 250€/kWh. A particle-swarm-optimization method is used to solve the optimization routine. The optimization variables x are the BESS power and energy ratings and the installed PV capacity. The objective function is expressed as:

$$\mathbf{max}\{NPV(x), -c(x)\} \quad (2)$$

where NPV is the project net present value, c is the size of the grid connection, and x is the optimization variables vector.

The NPV is determined as (1), considering a time horizon of 15 years, where the yearly revenues, $R(x)$ are calculated as sum of the revenues from the selling of PV energy, C_{pv} , and vehicle charging, C_{ch} , the costs of purchasing the energy from the grid, C_g , and the DSO fees, C_{dso} :

$$R(x) = C_{ch}(x) + C_{pv}(x) - C_g(x) - C_{dso}(x). \quad (3)$$

The various energy costs are calculated by evaluating the respective power flows and considering the tariffs detailed in Section II.

The grid connection size is calculated based on the power flow of the vehicles charging, PV panels, and of the the BESS, which result in the grid exchange power, P_g . Furthermore a 20% over-sizing coefficient is considered.

$$c(x) = \max\{P_g(x)\} \cdot 1.2. \quad (4)$$

The optimization problem's constraints are typical to the BESS operation, such as limiting the state of charge between 0 and 100%, not charging and discharging at the same time, and the power limits.

Fig. 4 shows the Pareto front of the multi-objective optimization for the three case scenarios. Higher grid independence will result in a lower NPV due to the investment costs of the larger BESS size required. The red star indicates the NPV without any added BESS, as specified in Table II. Fig. 4 clearly shows that a BESS can be beneficial in both objectives. A small rated battery can strongly boost revenues due to its peak shaving and the increased self PV energy self-consumption. On the other hand, a large battery can help the FCS achieve higher grid independence, reducing the grid connection size by 80%. However, this comes at the cost of a sub-optimal NPV. These solutions with small grid connection sizes may be practical in areas where a strong grid is not easily available, and the high power demand of the FCS might be detrimental to the grid stability.

The lifetime of BESSs is an important indicator when deploying such systems. Various methods have been proposed to evaluate the BESS lifetime based on empirical, analytical, or physical models. In this article, the model proposed by [15] is used to estimate the lifetime of the electrochemical storage. This model is derived empirically for LiFePO₄ cells through accelerated cycling. The model has already been applied to estimate the BESS degradation when deployed in various applications, such as wind power support [15], [16] and primary frequency regulation [17]–[19]. The calendar aging, C_{cal} , and the cycling aging, C_{cyc} , of the battery are evaluated separately as: (6) respectively [15]:

$$C_{cal} = 0.1723 \cdot e^{0.007388 \cdot SoC_1} \cdot t^{0.8} \quad (5)$$

$$C_{cyc} = 0.021 \cdot e^{-0.01943 \cdot SoC_{avg}} \cdot cd^{0.7612} \cdot nc^{0.5}. \quad (6)$$

where SoC_{avg} is the average SoC of a cycle, nc is the number of cycles of a certain cycle depth cd , and t is the idling time of the battery at a certain SoC level SoC_1 . These are derived from the BESS power flow calculated as a function of x through the particle swarm optimization.

The lifetime of the Pareto front points of Fig. 4 is shown in Fig. 5. The lifetime of the optimal solutions is in the range

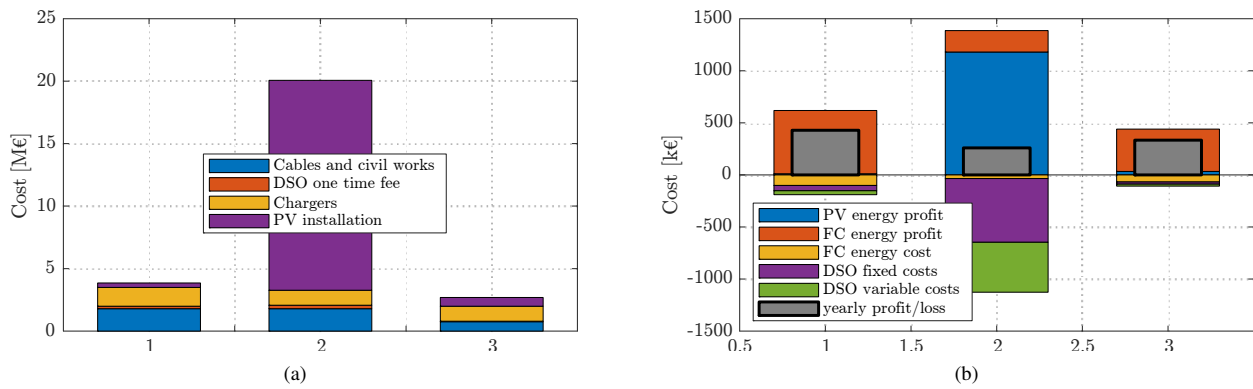


Fig. 3. (a) Investment costs for the deployment of the FCS stations of Table I, and (b) the respective yearly revenues and costs.

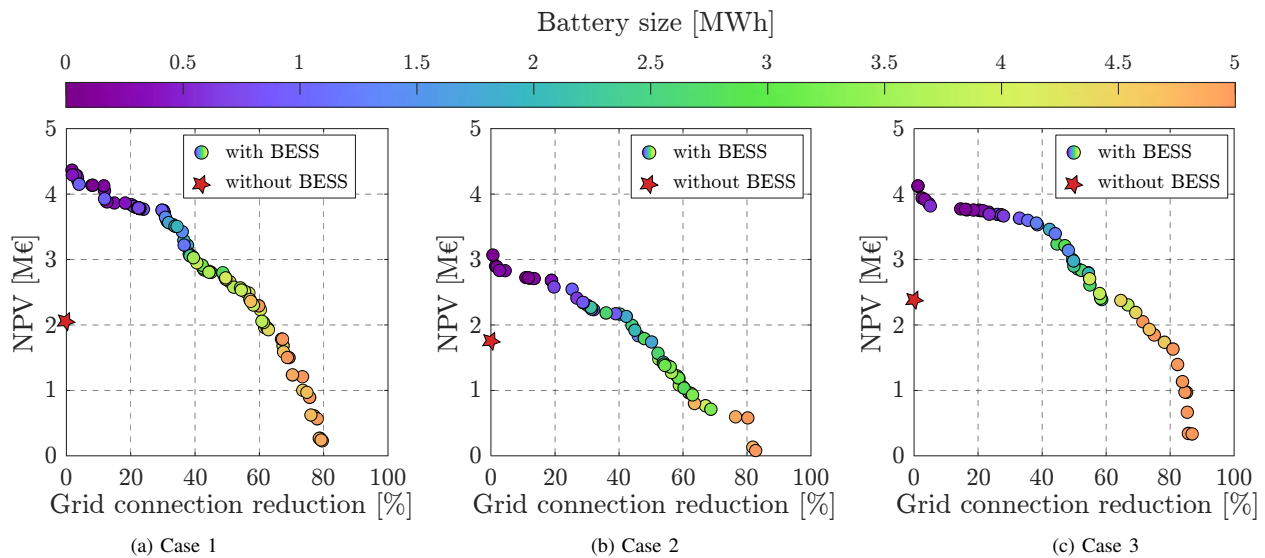


Fig. 4. NPV, grid connection reduction, and size of the added BESS of the three case scenarios of Table I. The red star indicates the NPV without any added BESS, as specified in Table II.

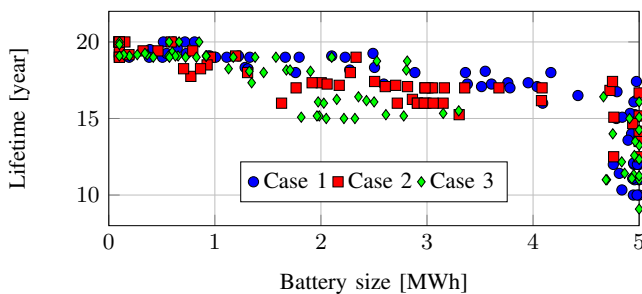


Fig. 5. Lifetime of the Pareto front points of Fig. 4.

between 10 and 20 years. The lifetime information is included in the calculation of the NPV, considering the replacement costs in case of end of life lower than the time frame of the NPV calculation. The highest lifetime values are found for low grid connection reduction, therefore for small-size BESSs. Furthermore, Fig. 5 shows that there is a similar trend in terms of lifetime between the three cases.

IV. CONCLUSION AND FUTURE WORK

This paper investigated the design and optimization of battery-aided electric vehicles' fast-charging stations. Three scenarios based on measured data and layouts provided by Stedin, a Dutch DSO, were considered, where the number of fast chargers, the distance from the main distribution grids, and the on-site photovoltaic generation potential considered differ. The grid impact and economic performance of such FCS have been analyzed when PV generators and BESS were added to the FCSs.

The analysis shows that the addition of the battery system can be effective in both performance metrics, the reduction of the grid connection, and the increase of the net present value. The charging station's net present value can be strongly boosted, even doubled, with a small rated battery. On the other hand, a large battery can help the FCS achieve higher grid independence, reducing the grid connection size even by 80%. Small rated batteries are also subjected to lower degradation than larger rated ones. To conclude, adding a battery storage system to a fast-charging station is advantageous for both the

charging station owner and the distribution system operation.

In future work, a sensitivity analysis of the station layout and number of components will be performed to investigate the effect of BESS integration in FCS from a more general perspective.

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