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Battery Energy Storage System Optimal Sizing in a Battery Electric Vehicle Fast Charging Infrastructure

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Abstract

The growing number of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) brings the need of more fast charging stations across cities and highway stops. This charging stations toned to be connected to the electrical grid via existent facilities, causing constraints such as power availability.

This study brings an approach for the planning and operation of such energy hubs by coping with this challenge by deploying a Battery-based Energy Storage System (BESS). With the BESS integration, it is expected to minimize utilization and overall energy costs, preventing infrastructure upgrades, and enhancing the integration of renewable energy resources.

This approach sizes a stationary energy storage system with lithium-ion technology batteries through a co-optimization of the planning and operation stages, integrated in an electrical installation that will implement fast charging stations. This sizing is a result of an optimization based on the interior point algorithm, where the objective is to minimize the costs of maintenance, operation, and installation of a BESS, while properly modelling the different resources such as the BESS, the charging station and EV charging and PV generation.

Author Keywords. Battery Energy Storage System; Fast Charging Stations; Battery Electric Vehicle

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1. Introduction

The efforts made to decrease the greenhouse emissions, through the world, are increasing and the reduction of the consumption of fossil fuels is one of the main focus of the environmental policy. One of the main consumers of fossil fuels is transportation, therefore governments are giving incentives to buy vehicles that are powered by electric energy (European Automobile Manufacturers Association 2020). This diminishes the usage of petroleum derivatives because people opt to buy electric vehicles.

The argument for the adoption of EVs is that they mitigate CO2 emissions in opposition of their counter part, the internal combustion vehicle (ICV). It is expected that by 2030 there will be a reduction of 1 giga ton of CO2 emission (Rodge and Joshi 2018), resulting from the exchange of internal combustion vehicles by electric vehicles.

Although EVs bring a new and greener perspective to the transport sector, they bring new challenges to the electrical grid. Electric power systems are designed to respond to instantaneous consumer demand (heat, light, etc) (Denholm and Short 2006). Therefore, the implementation of new electric loads will cause constraints of power and voltage congestion on these systems. (Sundstrom and Binding 2012)

The growing number of battery electric vehicles and plug-in hybrid electric vehicles entails the need of fast charging stations across cities and highway stops. This charging stations toned to be connected to the electrical grid via existent facilities, causing constraints such as power availability, power losses, power quality, grid reliability, etc.

The charging of BEVs causes an increase of load demand and may be uncontrolled, meaning that the charging can occur during peak hours. Because of the multiple and simultaneous charging, the electrical grid components, sized for the previous load demand, have to handle the extra loads which can cause overloading and diminish in the lifespan of such equipment.

Energy storage systems are an approach to mitigate the peak power demands of electric vehicles charging, acting as a buffer. The future of EVs is devoted to increase its range and reduce charging time, which implies to increase the increasing power availability at the charging points. (de Simone and Piegari 2019) This strategy can prevent upgrades to the distribution grid and if coupled with renewable energy sources potentialize its generation, charging the ESS with energy produced by RES and then discharge it when needed to the EV. (Calise et al. 2019; Forrest et al. 2016)

In (Datta, Kalam, and Shi 2020; Affonso and Kezunovic 2019), a coordinated smart charging control scheme in a PV-BESS integrated EV charging station to regulate BESS operation in order to avoid transformer overload. The BESS is regulated for smoothing PV power output depending on the loading of transformer and PV availability. Grid services are also provided in these two articles. These grid services are also comprised in (Kim et al. 2012), where BESS is coupled in an EV charging station, comprised in a microgrid, to analyze power quality and load demand variations, paired with vehicle to grid (V2G) technology.

A grid connected PV and BESS in a charging station optimization is proposed in (Dai, Liu, and Wei 2019) to determine the optimal sizing and energy management strategy with the objective of minimizing the cost of electricity. Also, in (Richard and Petit 2018) a BESS is proposed to be coupled in a fast charging station to reduce connection fees and grid reinforcements costs. This paper uses a method for the energy management of charging station that delivers grid services in off peak EV charging demand, sizing method that takes into account its ageing and an economic analysis for the trade-off between the BESS investment and contracted power.

This paper brings an approach for the planning and operation of such energy hubs by coping with this challenge by deploying a Battery-based Energy Storage System (BESS). With the BESS integration, it is expected to minimize utilization and overall energy costs, preventing infrastructure upgrades, and enhancing the integration of renewable energy resources.

This approach sizes a stationary energy storage system with lithium-ion technology batteries through a co-optimization of the planning and operation stages, integrated into an electrical installation that will implement fast charging stations. This sizing is a result of an optimization based on the interior point algorithm, where the objective is to minimize the costs of maintenance, operation, and installation of a BESS, while properly modelling the different resources such as the BESS, the charging station and EV charging and PV generation.

2. Methodology

The optimization process is done by using the Interior Point Algorithm from the solver fmincon in MatLab 2020b. This solver is a method of the Optimization Toolbox and are based on trust regions. The choice to use such method was to find a solution on constrained nonlinear problem.

2.1. Electric Vehicle charging Modelling Approach

In this section, a modelling approach for electric vehicle charging is proposed. In (Negarestani et al. 2016), is purposed a probabilistic approach taking into the distance travelled by the EV and the probability of being a car with a particular set of characteristics. In this study, a similar approach was implemented.

The characteristics of the vehicles presented in Table 1 allow classifying EV into five types. The chosen vehicle is defined in the beginning, and it takes into consideration the probability associated with them, Pr^k (Pontes 2020). The other characteristics such as power P^k, energy E^k and range d^k_{max} were based on ("EV Database" 2020).

$\boldsymbol{Vc^k}$	$\boldsymbol{P^k}$**(kW)**	$\boldsymbol{E^k}$**(kWh)**	$\boldsymbol{d^k_{max}}$**(miles)**	$\boldsymbol{Pr^k}$
Vc^1	150	72,5	276	0,300
Vc^2	45	52	195	0,295
Vc^3	40	32	118	0,150
Vc^4	75	46	118	0,135
Vc^5	45	36	136	0,120

Table 1: Electric Vehicle characterization

In (Shiau, Peterson, and Michalek 2010) is defined that a vehicle day mileage has an exponential distribution, expressed by the equation (1) , where x is the daily driving miles.

$$f(x) = 0{,}0296^{(-0.0296x)}, x \geq 0 \tag{1}$$

The average mileage of such vehicles is going to be considered instead of considering every short trip defined by the previous equation. The average mileage (da) is defined in equation (2). The variable d^k_{max} is the maximum possible miles by vehicle k.

$$da = \frac{d^k_{max}}{2} \tag{2}$$

Equation (3) is the expression that gives the probability for the vehicle k going through the da trip.

$$F(da) = \int_0^{d^k_{max}} f(x).dx \tag{3}$$

The expected mileage at each time instant, $d^k_a(t)$, is computed based on the probability of driving at any time instant for each day, $g(t)$. This can be obtained in (Negarestani et al. 2016) that gives the vehicle trip distribution on weekdays and weekends in the United States. Therefore, by multiplying this probability by the probability obtained in (3), it is achieved the probability of driving at any time instant for each day, equation (4).

$$d_a^k(t) = g(t) \times F(da) \tag{4}$$

The vehicle state of charge is calculated by equation (5), taking into account the previous state of charge and subtract the distance that the car covered in its trip. Assuming that in the beginning of every trip a SoC is always 100%.

$$SoC_i^k(t) = SoC_i^k(t-1) - \left(\frac{\int_{t-1}^{t} d_a^k . dt}{d_{max}^k} \times 100 \right) \tag{5}$$

The energy that the vehicle has left, in its batteries, is calculated in equation (6). It is obtained assuming a direct proportion between the state of charge and the energy capacity of the EV.

$$E_{EV} = \frac{E^k \times SoC_i^k(t)}{SoC(0)} \tag{6}$$

The energy that is needed to fully charge the vehicle is calculated in equation (7).

$$E_{EVC} = E^k - E_{EV} \tag{7}$$

Assuming that the charging power, supported by the electric vehicle, stays the same through the charging, the time it takes to charge the vehicle can be calculated by equation (8).

$$\Delta t = \frac{P_{EVC}}{E_{EV}} \tag{8}$$

The charging power has a very simple restriction, translated by the system of equations (9). If the charging power limit of the EV is lower than the maximum power output of the charger, the power considered should be equal to the vehicle power limit, otherwise, the charging power must be equal to the power output of the charger.

$$\begin{cases} P_{EVC} = P^k & se\ P^k \leq P_{ch} \\ P_{EVC} = P_{ch} & se\ P^k \geq P_{ch} \end{cases} \tag{9}$$

2.2. Photovoltaic Energy Generation Modelling Approach

The photovoltaic energy generation is modelized by equations (10) and (11). Equation (10) refers to the power generated by the photovoltaic panels in the moment t, $P_{pv}(t)$. $G(t)$, is the solar radiance at the time period t, given by the Photovoltaic Geographical Information System (PVGIS) interactive tool. The dataset has the hourly solar radiation for the year 2015, with optimize slope and azimuth, and for a fixed mounting type. The localization was set to the north of Portugal. A is the total area covered by the PV panels, in square meters (m^2) and μ_{pv} is the system efficiency.

$$P_{pv}(t) = G(t) \times A \times \eta_{pv} \tag{10}$$

Equation (11) refers to the energy obtained from the photovoltaic panels, $E_{pv}(t)$, in the moment t, that can be used to feed the electric vehicle charging station, sold to the connected electrical grid or to store in the energy storage system.

$$E_{pv}(t) = \int_{t_1}^{t_2} P_{pv}(t).\,dt \tag{11}$$

2.3. Energy, Implementation and Maintenance costs of BESS

The energy prices are the ones defined by ERSE that respect their time periods and costs difference between low voltage and medium voltage delivery.

The efficiency of the system is translated in equation (12). Followed by the limits on the efficiency variables in (13).

$$\eta_{ESS} = \eta_{ST} \times \eta_{PCS} \tag{12}$$

$$0 \leq \eta_{ESS} \wedge \eta_{ST} \wedge \eta_{PCS} \leq 1 \tag{13}$$

The cost for the installation of the BESS is defined in (14). It is the summation between the costs of the power conversion system (15) and costs associated with the energy storage technology (16).

The latter two equations take into consideration the power of the system, P_{ESS}, and its nominal energy, E_{nESS}. The costs per unit of energy and power, $C€/_{kWh}$ and $C€/_{kW}$, will have fixed values, as well as for the efficiency of the storage technology, η_{ST}.

$$c_{IESS} = c_{PCS} + c_{ST} \tag{14}$$

$$c_{PCS} = P_{nESS} \times \eta_{PCS} \times c€/_{kW} \tag{15}$$

$$c_{ST} = c€/_{kWh} \times \eta_{ESS} \times E_{nESS} \tag{16}$$

The maintenance cost, Mc, of the BESS is presented in (17). This approach is similar to described in (Domínguez-Navarro et al. 2019). It considers costs of installation (defined in the equations above, within this section) and the annual degradation defined by the variable d_{ESS}.

$$Mc = c_{IESS} \times d_{ESS} \tag{17}$$

2.4. Energy Storage System Modelling Approach

This section describes the modelling approach for the energy storage system.
The charging power, $P_{CESS}(t)$, is given by equation (18), for time periods of one hour. The variable $E_{ESS}(t)$ can assume positive and negative values, as it represents the charge and discharge energy values. This variable must have a lower or equal value when compared to the constant P_{nESS} (19).

$$P_{CESS}(t) = E_{ESS}(t), \rightarrow E_{ESS}(t) \geq 0 \tag{18}$$

$$P_{CESS} \leq P_{nESS} \tag{19}$$

Equation (20) defines the energy level of the energy storage system at each period, where the energy level of the next period is the summation between the energy level of the current period and the energy charged between those periods. This equation is valid for the charging process.

$$El_{ESS}(t+1) = El_{ESS}(t) + \eta_{ESS} \times \int_{t_1}^{t_2} P_{CESS}(t).\,dt \tag{20}$$

The discharging process is defined in equations (21) and (22). First, it is necessary to define the discharging power at each given moment, $P_{DESS}(t)$. The discharging power is given by equation (22), as this equality can be assumed when periods of one hour are being considered. The variable $E_{ESS}(t)$ can assume positive and negative values, as it represents the charge and discharge energy values. This variable must have a lower or equal value when compared to the constant P_{nESS} (22).

$$P_{DESS}(t) = -E_{ESS}(t), \rightarrow E_{ESS}(t) \leq 0 \tag{21}$$

$$P_{DESS} \leq P_{nESS} \tag{22}$$

Equation (23) defines the energy level of the energy storage system at each time period, where the energy level of the next period is the summation between the energy level of the current period and the energy discharged between those periods. This equation is valid for the discharging process.

$$El_{ESS}(t+1) = El_{ESS}(t) + \frac{\int_{t_1}^{t_2} P_{DESS}(t).\,dt}{\eta_{ESS}} \tag{23}$$

Equations (24) and (25) represent the limits of the energy level of ESS. These limits are defined between 10% ($Elmin$) and 90% ($Elmax$) of the nominal energy of the energy storage system.

$$El_{ESS} \geq Elmax \times E_{nESS} \tag{24}$$

$$El_{ESS} \leq Elmin \times E_{nESS} \tag{25}$$

2.5. Objective function and Problem Constraints

The objective function of this optimization is to minimize the total operational costs, including the implementation of an energy storage system in an electric vehicle charging station. Equation (26) represents the objective function taking in consideration the costs with energy transactions, BESS investment costs and its life cycle.

$$\min cost = \sum_{t=1}^{T} \left(c_{PEG}(t) \times E_G(t)\right) + c_{IESS} + Mc \tag{26}$$

Equation (27) translates the energy balance in this study. It contemplates the ESS charge/discharge process, the energy purchased from the electricity supplier and demanded by the EV chargers as well as the energy produced by photovoltaic panels.

$$E_G(t) = E_{EVC}(t) + E_{ESS}(t) - E_{PV}(t) \tag{27}$$

Equation (28) defines the nominal power of the energy storage system, given by maximum absolute value of E_{ESS}.

$$P_{nESS} = max|E_{ESS}| \tag{28}$$

Equation (29) limits the number of cycles of the ESS. This condition is to maximize the longevity of the batteries.

$$\sum_{t=1}^{T} (Pdess\ (t) \leq N(n^{\underline{o}}ciclos) \times \eta_{ESS} \times E_{nESS}) \tag{29}$$

3. Case Study on the integration of BESS in a Fast Charging Station

The case study is composed by four different fast charging stations infrastructures. The variations between the four of them dwell on the assets that are connected to the infrastructure.

One depends exclusively on the electrical grid, a medium voltage connection to the distribution system. The second one has a photovoltaic generation. The last two have a Battery Energy Storage System connected to the same electrical connection point of the distribution system and of the PV generation. The difference between the two BESS integration scenarios is the photovoltaic generation. One of them has it and the other does not.

The scope of the case studies is to compare the energy cost savings between the four scenarios and the operation costs of the fast charging infrastructure. This approach sizes a stationary energy storage system with lithium-ion technology batteries through a co-optimization of the planning and operation stages

The simulations were performed taking into consideration the methodologies presented in section II. The time series is presents an hourly resolution and the optimization is done for each week of the year.

3.1. Summary Comparison of the scenarios

This section gives a summary comparison between the main results of the scenarios, focusing on comparing the three scenarios with the baseline scenario. Table 2 summarizes the results of the baseline scenario and the differences between this baseline and the others scenarios.

The negative values represent the savings and the positive values represent the increased costs. Also in this table, it is represented the sizing of the BESS for each scenario where the implementation of the energy storage system is applicable.

Scenario	Cost of Operation (€)	Cost of Energy (€)	Contracted Power (kW)	BESS Annual Investment (€)	BESS Annual Maintenance (€)
Baseline Scenario	46,919.11	46,585.60	580	-	-
RES Integration Scenario (PV:95kW)	-6,651.65	-11,012.56	-13	-	-
BESS Integration Scenario (BESS:438kW/438kWh)	21,616.60	-5,379.53	-36	27,329.64	6,306.84
BESS with RES Integration Scenario (BESS:250kW/303kWh PV:95kWp)	-2,105.53	-20,280.95	-75	18,313.93	4,226.29

Table 2: Scenario comparison with the baseline scenario

The BESS sizing is, in both scenarios that have BESS integration, an application in power. For instance, in the scenario that only has the BESS the batteries have to be able to charge/discharge at 1C and in the scenario with RES the batteries must be able to charge/discharge at 0.8C.

The higher costs of operation for the third scenario is explained by the bigger sizing (comparing to the last scenario) and by the time shifting capability that it is not enough to justify the investment due to the higher costs of investment compared to energy costs savings.

3.2. Battery Energy Storgae System with Renewable Energy Source Integration Secenario

The fourth scenario adds a battery storage system to a renewable energy source coupled to the distribution operator. The BESS is restricted to seven discharge cycles per week to balance battery degradation.

For the analysis, three days are focused: one that represents the summer, one the winter and the last one the spring/autumn. The reason for this choice is based on the electric energy price that is divided in two periods. This could translate in more pronounced time shift in one period instead of the other.

The BESS contributes in the periods for which the energy price is higher, and the power demand is greater. The BESS provides peak shaving to the electrical load using the energy charged during the night period (valley hours), when it is cheaper (time shifting).

During summer, when the power generated by the photovoltaic panels is considerably higher, the afternoon is very different. On the day shown in Figure 1, the power generated by the PV is sufficient to cope with the demand and to charge the batteries. This condition demands lower power from the electrical grid and, therefore, lower energy costs.

The optimal sizing for the BESS, in this case study, is 250kW of power and 303 kWh of energy. This translates in a charge/discharge at 0,8C, so a power application of the battery energy storage system must be considered for this scenario.

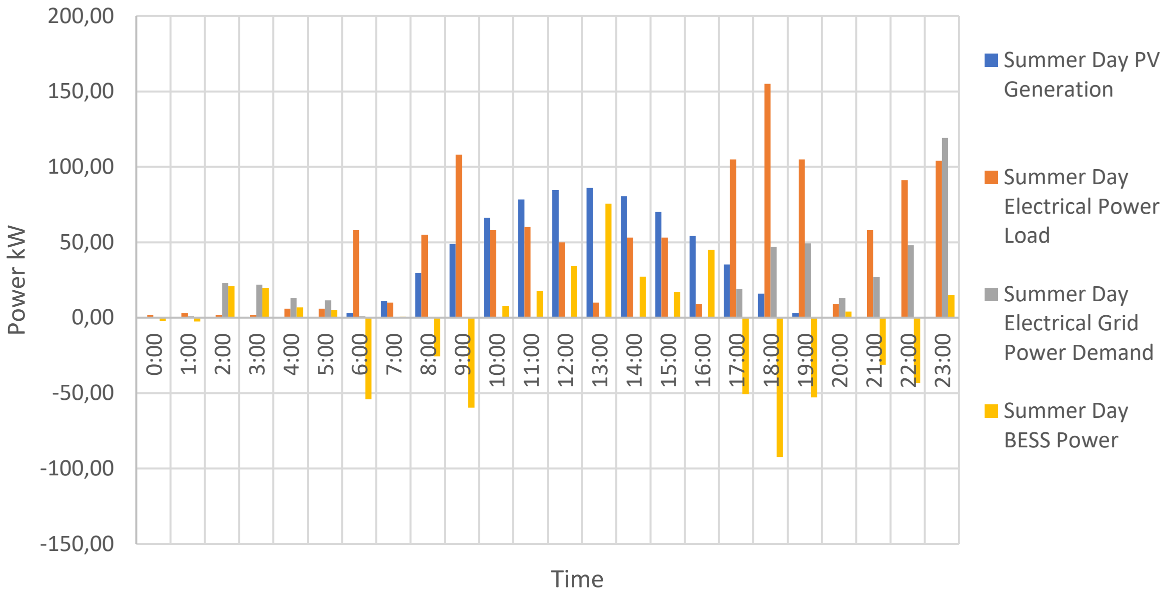

Figure 1: Summer Day load diagram, power demand, PV generation and BESS charge/discharge power

3.3. BESS implementation costs Sensibility Analysis

The analysis of the implementation costs is comparable to the baseline scenario in Table 3. The objective of this table is to easily identify the future perspective of implement energy storage systems in a way that is economically viable.

In these scenarios, the implementation of the BESS is not viable even with lower implementation costs. With the lower implementation costs, the scenarios with RES enables a different sizing for the rate of charge/discharge, lowering the C rate from 0.8 to 0.6.

Scenario	Cost of Operation (€)	Cost of Energy (€)	Contracted Power (kW)	BESS Annual Investment (€)	BESS Annual Maintenance (€)
Baseline Scenario	46,919.11	46,585.60	580	-	-
BESS Integration Scenario (BESS:461kW/461kWh 60€/kW-200€/kWh)	8,200.34	-5,654.51	-34	14,188.36	3,274.24
BESS Integration Scenario (BESS:438kW/438kWh 30€/kW-100€/kWh)	3,212.29	-3,856.31	-12	7,402.10	1,708.18
BESS with RES Integration Scenario (BESS:289kW/450kWh PV:95kWp 60€/kW-200€/kWh)	-8,816.50	-21,366.55	-34	12,883.56	2,147.26
BESS with RES Integration Scenario (BESS:379kW/585kWh 30€/kW-100€/kWh)	-13,865.37	-21,916.37	-46	8,384.52	1,397.42

Table 3: BESS Implementation Costs comparison

4. Conclusions and Future Work

This paper presents an optimization tool that minimizes the operational costs of a battery electric vehicle fast charging station with an optimal sizing of a battery energy storage system. The optimization takes into consideration the costs with energy, contracted power, BESS integration and maintenance. This tool allows the owner of a fast charging station to evaluate the economic and technical benefits of integrating an energy storage system.

The analysis of the case study verifies that the costs of operation of the fast charging station with the BESS integration with renewable energy source decrease. The Battery Energy Storage System enables the infrastructure to store surplus energy of the RES and time shifts the energy at off peak hours and uses it when the energy is more expensive. This brings savings in cost of operation and helps mitigate technical grid constraints (triggered by the BEV charging) such as voltage deviation, harmonic distortion, increase in power and energy demand at peak hours and the overloading of the distribution network equipment such as transformers, feeders, switchgear, etc., demonstrating that a BESS can tackle the challenges posed by BEV fast charging stations.

For future work, smart charging scenarios and vehicle to grid operation should be considered. In this case we should have a more controllable load and sizing of the BESS will be different.

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