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Methodology for BESS Design Assisted by Choice Matrix Approach

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ABSTRACT Battery Energy Storage Systems (BESS) can provide several ancillary services to renewable energy-dominated power systems. However, the choice of the battery employed in the projects is not a straightforward task, since there are several criteria that should be taken into account. Thus, six criteria are considered in this work: the system dc-link voltage, battery lifetime, battery bank volume, battery bank power losses, battery bank price and storage capacity index. The last criterion is related to the BESS energy storage capacity during one-year mission profile operation, which depends on the battery selected for the project. The Multiple Criteria Decision Making (MCDM) is used to choose the best battery based on the relative importance between the Operational Expenditure (OPEX) and Capital Expenditure (CAPEX) concepts. The methodology proposed in this work was applied to 27 batteries composed by lead-acid and Li-ion batteries aiming to select the best solution for a Photovoltaic (PV) system with storage energy based on the peak shaving operation mode. Considering the CAPEX with more relative importance, a lead-acid battery bank was found to be the best solution. On the other hand, when the OPEX is considered more important, a Li-ion battery bank was selected as the best solution.

KEYWORDS Battery Selection, BESS Design, CAPEX, Decision Matrix, OPEX.

I. INTRODUCTION

In recent decades, a high penetration of renewable energies has been verified, especially the commissioning of photovoltaic and wind power plants [1]. Despite the operational advantages of these sources, some operational challenges are addressed for their integration in the power system [2]. Due to the intermittent generation of these renewable energy sources, common grid problems arise, such as voltage and frequency disturbances, instabilities during faults, power quality, harmonic resonances and others [1]. Thus, the use of the so-called Battery Energy Storage System (BESS) is considered great solution in this field of study. The BESS can provide several ancillary services, including: peak shaving, load leveling, black start capability and time shift, among others [3].

Battery bank sizing is a challenging step in the project, since the battery is one of the most expensive components of BESS [4]. The battery market deals with several technologies. Lead-acid and lithium-ion chemistries are consolidated in the rechargeable battery market, with maturity and better cost/benefit ratio [5]. Currently, hundreds of manufacturers have several catalogs with numerous types of batteries [6]. In addition, each battery available on the market has different price, lifetime and electrical characteristics which affects BESS sizing, especially due to rounding, when considering whole numbers of batteries. Thus, the challenge of a designer for a battery bank is related to a multiple criteria decision [7], [8].

Figure 1 presents a typical connection of a PV system and BESS connected into the grid, emphasizing the Power Conversion System (PCS) topology, Battery Management System (BMS) and Energy Management System (EMS). Basically, two main system configurations are available DC- and AC-coupled configurations. The main difference between two lies in the point of connection for the battery unit which can either be connected in the DC-link or at the point of common coupling. The system connected in the AC-coupled configuration is presented in Figure 1.a. As observed, the EMS plays a crucial role in optimizing the performance, efficiency, and reliability of battery systems, thereby maximizing their economic and environmental benefits. The system connected in the AC-coupled configuration is presented in Figure 1.b.

Based on the BESS characteristics such as output voltage, converter energy and power requirements, the arrangement of the battery bank can be defined, consisting of series arrays of batteries and parallel arrays of battery strings [9]. In the same direction, after the definition of BESS configuration, the battery to be used in the energy storage system is defined. The chemistry of the chosen battery and its electrical char-

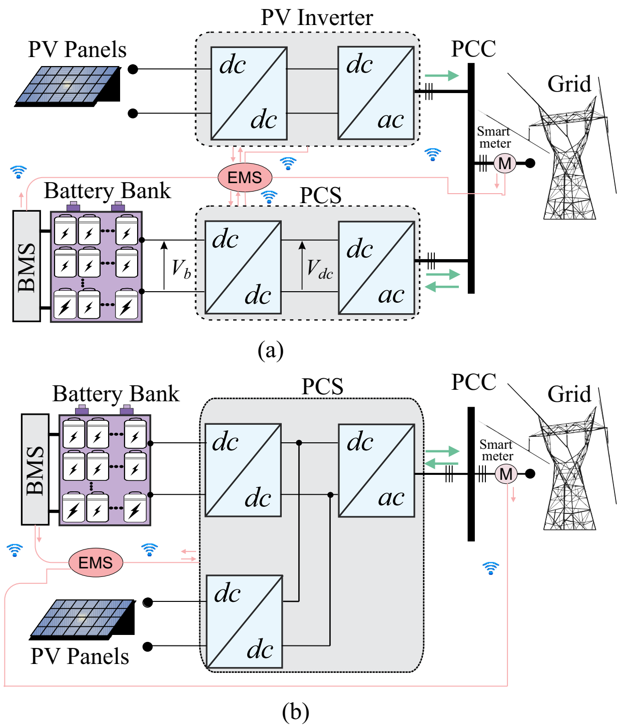

FIGURE 1. A typical PV system with BEES connected in: (a) the AC-coupled configuration (b) the DC-coupled configuration.

acteristics determine BESS volume/weight, power losses, battery lifetime and total cost [8], [9].

Thus, based on the main selection criteria presented, this manuscript proposes to classify the different metrics used in BESS design by relating them to Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) concepts [1]. The first one is related with BESS footprint and the battery bank cost. On the other hand, OPEX is related to the battery power losses [10], which depends on the number of batteries in series per string and the battery strings in parallel. In addition, the OPEX costs depend on the total storage capacity and the lifetime. Based on the costs assessed for CAPEX and OPEX, it is possible to apply Multiple Criteria Decision Making (MCDM) [11], [12]. The MCDM method is applied to different areas of knowledge, such as industries, material selection, investment decision and economics [9], [11].

Reference [13] presents a method for selecting materials in different industry applications. According to Ashby's approach, the desired objective function is minimized/maximized to optimize performance under the influence of restrictions. References [14], [15] proposed a Technique for Ordering Preferences Similar to an Ideal Solution (TOPSIS), which is an instrument to measure the relative efficiency of possible solutions. In this case, the best alternative must have the shortest distance to an ideal solution. The proposed methodology assumed that if each attribute had a monotonic increase or decrease in the variation between possible solutions, then it would be easy to obtain the best solution.

In this sense, based on the optimization methods discussed, the main contribution of this work is to provide a methodology to help engineers in decision making regarding the selection of the battery bank to be used in the BESS. The main variables of the MCDM method is based on the dc-link voltage, volume, power losses, battery lifetime, energy capacity index and battery price. Thus, compared to previous works, this methodology is able to select the best battery for the system based on the importance level assigned to CAPEX and OPEX relevance. In addition, the proposed method is able to consider several part numbers for the selection process.

This paper is outlined as follows: Section 2 describes the battery bank sizing. Section 3 presents the battery selection criteria. The MCDM technique is presented in Section 4. In addition, the study case is presented in Section 5 and the obtained results are discussed in Section 6. Finally, the conclusions are stated in Section 7.

II. STORAGE SYSTEM DESIGN

In this study, the peak shaving application is used as an example. The storage system design should be firstly performed and it is divided into three steps, as presented in the next subsections.

A. Step 1: Minimum Number of Batteries

The first step determines the minimum number of batteries (N_{min}) required for the BESS application. The N_{min} value is obtained based on the criterion of the energy and power requirements. The minimum number of batteries based only on the energy requirement (N_{En}) is calculated by:

$$N_{En} = \text{ceil}\left(\frac{100E_n}{E_{bat}(SOC_{max} - SOC_{min})}\right) \quad (1)$$

where E_n is the energy requirement for the BESS application and E_{bat} is the energy stored by a single battery. In addition, the operation limits of the SOC (State of Charge) are also taken into account and this variable should be used in percentage. Thus, the interval between the maximum and minimum SOC values (SOC_{max} - SOC_{min}) is used.

Similarly, the minimum number of battery based on the power requirement (N_{P_n}) is calculated by:

$$N_{P_n} = \text{ceil}\left(\frac{P_n}{V_{batmin}C_nC_r}\right) \quad (2)$$

where P_n is the power required by the BESS application and V_{batmin} is the minimum voltage of a single battery considering the SOC_{min}. In addition, the C-rate (C_r) and the nominal battery capacity are also taking into account (C_n). Depending on the BESS application, different strategies can be performed to find the parameters of E_n and P_n.

Thus, based on the results obtained from (1) and (2), the minimum number of batteries based on the energy and power requirements is selected by the maximum value between N_{En} and N_{P_n}.

B. Step 2: Voltage Limits of the Battery Bank

Since N_{min} is calculated, the maximum (V_{bmax}) and minimum voltages (V_{bmin}) of the battery bank are estimated. In this context, the voltage range of the battery bank and the dc-link voltage of the BESS dc/ac stage (V_{dc}) are presented in Figure 2 for the sake of clarity.

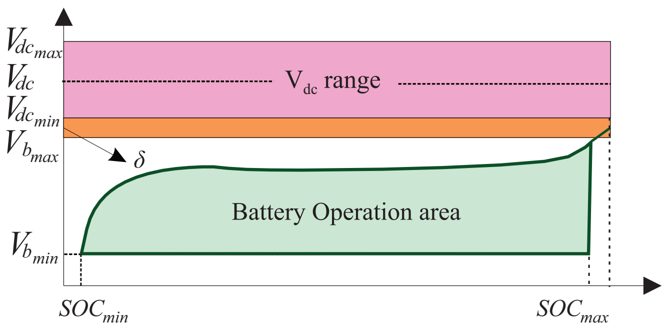

FIGURE 2. Voltage representation of the BESS inverter dc-link and voltage limits of the battery bank.

As observed, the battery bank has a range voltage between the minimum and maximum voltage (V_{bmin} - V_{bmax}), which is defined by the voltage at the maximum and minimum SOC specification. In addition, the dc-link voltage of the BESS dc/ac stage also presents a range of operation, which is defined by the maximum and minimum dc-link voltage (V_{dcmax} - V_{dcmin}). This voltage range is obtained based on the inverter limits and this interval is used to obtain the dc-link voltage which will be used in the number of batteries in series. The V_{dcmax} is chosen based on the safe voltage supported by the semiconductor device. Generally, in terms of project, the maximum value used is around 75% of the blocking voltage provided by the semiconductor device manufacture. On the other hand, the V_{dcmin} voltage is chosen based on the methodology proposed by [16], in which the minimum voltage necessary to inject reactive power into the grid parameters is calculated based on the grid parameters, as follows:

$$V_{dcmin} = 1.05\hat{V}_g(1 + \Delta V_g + x_{pu}) \quad (3)$$

where $\hat{V}_g$ is the peak of the line-to-line, ΔV_g is the maximum ac grid voltage variation (in pu) and x_{pu} is the unit equivalent output impedance of the inverter.

C. Step 3: Battery Bank Design

In this step, the association of number batteries in series N_s and parallel N_p are estimated. In this sense, an important point to be analyzed is the voltage margin (δ) between the maximum battery bank voltage and minimum dc-link voltage of the BESS dc/ac stage. Since the inclusion of dc-dc stage is considered in the battery bank design, the margin guarantees a better performance of the dc-dc stage during the battery charging and discharging processes. Thus, this margin may be adopted (δ higher than one) to guarantee an acceptable dynamic performance of the dc/dc converter control. However, in this work, δ equal to 1 was used and the unstable cases are not considered in the power losses and cost evaluation.Thus, the number of batteries in series (N_s) and parallel (N_p) can be estimated, for a given V_{dc}, by the following equations, respectively:

$$N_s = \text{floor}\left(\frac{V_{dc}}{V_{batmin}\delta}\right). \quad (4)$$

$$N_p = \text{ceil}\left(\frac{N_{min}}{N_s}\right). \quad (5)$$

The total number of batteries (N_T) is calculated as $N_s.N_p$. As observed, depending on the V_{dc} value, different configurations of N_s and N_p can be obtained. The V_{dc} value ranged from V_{dcmin} to V_{dcmax} was applied to (4) and (5). Then, the configuration which presents the lowest N_T is selected. If the N_T repeats for more than one V_{dc} value, then the combination with the lowest V_{dc} is considered in order to have a lower power losses in the semiconductor devices.

III. BATTERY SELECTION CRITERIA

Once the optimal number of batteries was selected, some important characteristics of the battery bank are analyzed to select the best battery for the application. In this work, six criteria are considered: dc-link voltage of the BESS inverter, battery bank volume (Vl_b), battery bank power losses (PL_b), battery bank cost (c_b), battery lifetime (LF) and storage capacity index (In_{Cap}). Each criterion are described in the following paragraphs.

The dc-link voltage of the BESS is important for the battery selection process, since it directly affects the reliability of the power electronic components. Thus, when the V_{dc} increases, the switching power losses of the semiconductor devices also increases [17]. Consequently, the junction temperature of the semiconductor devices increases, which leads to thermal stress and reduces reliability of the semiconductor devices, as presented by [18], [19]. Therefore, the V_{dc} is an interesting variable to be analyzed since it directly impacts the power losses of the BESS dc/ac stage.

The battery bank volume is an important parameter for battery decision. For large battery bank volume, issues related to the physical construction and transportation can be limiting factors. For each battery, the Vl_b can be calculated by multiplying the N_T by the volume of a single battery (Vl_{bat}).Depending on the battery's format, further details in the volume calculation should be carried out, as this factor may affect their stacking.

The power losses dissipated in the battery bank due to the internal battery resistance affect the efficiency of the storage system. The total power losses of the storage system calculated in this work is presented by:

$$PL_b = \left(\frac{r_{bat}N_s}{N_p}\right)(C_nC_r)^2 \quad (6)$$

where r_{bat} is the internal resistance of a single battery. In addition, the association of the number of batteries in series and parallel is also taken into account.

Depending on the N_T selected, different energy capacities can be observed for each battery association. In addition, the capacity of energy storage directly affects the autonomy time of the system. Therefore, this criterion needs to be taken into account during battery selection. The energy capacity index is defined by the ratio between the energy stored by the battery bank (En_{Stored}) and the total energy produced by the system ($En_{Generated}$).

The cost of the battery bank may make the project unfeasible. In this work, the total price is calculated by the multiplication of N_T by the price of a single battery (c_{bat}) (obtained through the manufacturer's catalog).

In general applications, the battery lifetime (LF) is shorter than that of other components, such as capacitor and semiconductor power devices [20]. The replacement of the battery bank affects the cost and payback of the entire system. Two important issues related to the battery lifetime are presented:

- The association of batteries in series and parallel affects the lifetime of the battery due to the voltage and current levels to which the battery is subjected [21];
- The lifetime methodology depends on the battery technology. Thus, in this work the methodologies for lead-acid and Li-ion batteries proposed by [22] and [21] respectively, are used.

The aging model used in this work to compute the lifetime of a lead-acid battery is based on the Schiffer weighted Ah-throughput model, proposed in [22]. This is a consolidated model in the literature for lead-acid batteries, since it considers that the operating conditions are typically more severe than those used in standard tests of cycling and float lifetime. Therefore, phenomena such as corrosion, acid stratification, gassing, sulfation and sulfate crystal growth are taken into account [22]. In fact, those phenomena are modeled and used as weighted factor in the Schiffer model.

The lifetime model used for Li-on batteries was proposed by [21]. This model considers aging process due to two important factors: cycling and calendar mechanism. Cycling are related to the battery power cycling and calendar is related to the idle operation mode. Thus, the SOC mission profile is used in the cycle counting rainflow and idle counting algorithm to extract the main parameters of each charge/discharge cycle and idle operation cycle.

IV. MULTIPLE CRITERIA DECISION MAKING

Based on the criteria considered in the last section, it necessary to choose a method to select the best battery for the BESS application. Thus, the MCDM is adopted [23]. Some methods, such as TOPSIS, is common used in the selection process in the MCDM techniques. This method is able to select and order the input parameters based on the weights chosen by the user. In this work, the TOPSIS method, proposed by [24] is used, as shown in Figure 3.

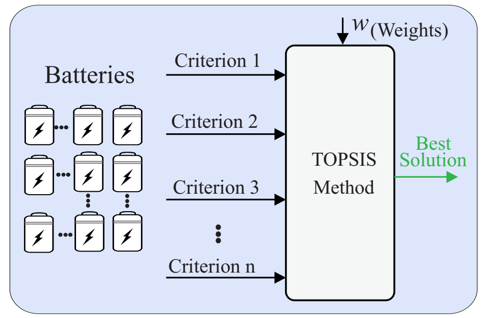

FIGURE 3. TOPSIS method used to select the best battery based on the selected criteria.

This method assumes that if each attribute takes a monotonically increasing or decreasing variation, then it is easy to define an ideal solution. Thus, the best solution is composed of all the best attribute values achievable, while the worst solution is composed of all the worst attribute values achievable. Therefore, TOPSIS finds a solution which has the shortest distance from the ideal solution in the Euclidean space.

A. Battery Weighted Criteria

As observed in Figure 3, it is necessary to define the weights of the battery criteria in the TOPSIS method. Thus, in this work, the AHP (Analytic Hierarchy Method) is used. This method is a powerful multicriteria decision-making tool that has been used in numerous applications in various fields of economics, politics and engineering [25]. With the AHP method, the user can give his opinion in the criterion importance level. Thus, the battery can be chosen based on the characteristic desired by the user. Basically, the AHP is composed by three steps, as presented below.

1) Relative importance of different criteria with respect to the goal: In this step, a pair-wise comparison matrix is created. Basically, this matrix confronts all the criteria based on the scale of relative importance x_{ij}, which is presented in Table 1. As observed, the importance level of a criterion in relation to the others ranges from 1 (equally important) to 9 (absolutely more important).

TABLE 1. Scale of Relative Importance of the Criteria

Numeric Scale x_{ij}	Conceptual Scale
1	Equal
3	Moderate
5	Strong
7	Very Strong
9	Absolute
2,4,6,8	Intermediate values

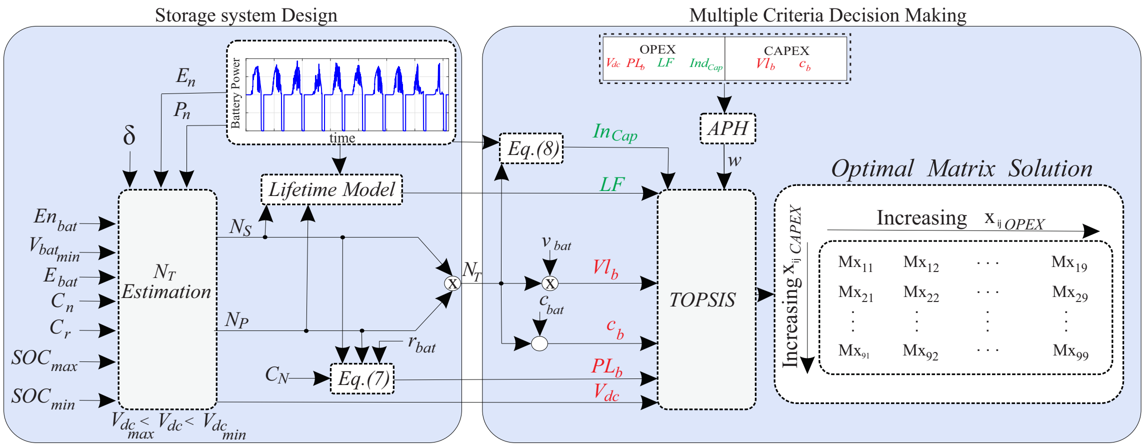

FIGURE 4. Proposed methodology used for the selection of the battery, based on the CAPEX and OPEX concepts.

Table 2 presents the pair-wise comparison matrix. As observed, each criterion a is confronted to each other, and the relative scale is used. The line criterion of the matrix is always compared to the row criterion. In addition, when the same criterion is compared, the value 1 is used, since they are equally important to the selection process.

TABLE 2. The Pair-Wise Comparison Matrix

	a_1	a_2	...	a_m
a_1	1	x_{12}	...	x_{1m}
a_2	$1/x_{12}$	1	...	x_{2m}
...	...	...	...	...
a_m	$1/x_{m1}$	$1/x_{m2}$	...	1

2) Pair-wise matrix normalization: In this step, the pair-wise matrix is normalized. Each element is normalized using the sum of the elements of the respective row.

3) Weight calculation: Finally, in this step, the weights for the criteria are estimated. Thus, the weight for each criterion is calculated based on the average of the elements in the line matrix.

Thus, the TOPSIS and AHP methods are the techniques from the MCDM which are used to select the battery. Before apply the AHP and TOPSIS methods, the criteria are separated into two groups based on the CAPEX and OPEX concepts. The idea is separate the criteria related to the operation of the BESS (V_{dc}, PL_b, Ind_{Cap} and LF) and the initial capital spend to the project (Vl_b and p_b). Thus, only the parameters of battery cost and volume are considered CAPEX while the other parameters are considered OPEX, as presented in Figure 5. In addition, it is important to note the color separation in Figure 5. The increasing of the red criteria refers to a negative parameter in the battery selection model. On the other hand, the increasing of the green criteria are a positive parameter for the battery selection model. As example, the battery with higher power losses is not a good criterion for the battery selection. However, the battery with a higher lifetime is interesting for the selection process.

FIGURE 5. Criteria separation into OPEX and CAPEX groups.

The division of these groups is performed to estimate the criteria weights. Thus, the user can give relative importance to the CAPEX or OPEX group. In order to have a more generic results, the AHP methods was performed varying all the possible combination to the relative importance. Thus, the x_{ij} can have two values: $x_{ij_{CAPEX}}$ and $x_{ij_{OPEX}}$. Each of them is varied from 1 to 9 and all the combinations are considered in the generic solution. Therefore, the best solution matrix based on the relative weights of OPEX and CAPEX are represented in Figure 6. Thus, the user can choose the best battery solution based on the relative importance of OPEX and CAPEX group.

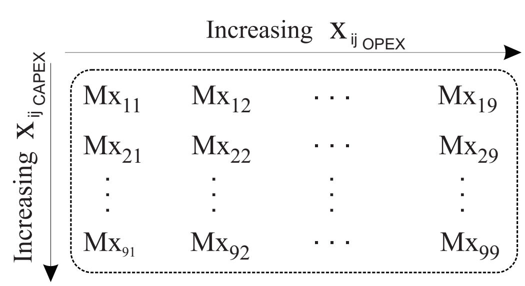

FIGURE 6. Optimum matrix of the battery solution.

Since the weights are estimated by the AHP method, the TOPSIS is used to order the best battery to the application. In order to have a better understand of the proposed battery selection methodology, Figure 4 is presented. As observed, the first step is to perform the battery bank sizing. Thus, the parameters from the project (energy and power requirements) and information from the battery manufacturer datasheet are taken into account. Thus, the six criteria are estimated according to the methodology presented in this chapter. Finally, the criteria are applied to the TOPSIS method. The AHP method is also used to vary the OPEX and CAPEX relative importance. Thus, the optimum matrix is generated.

V. CASE STUDY

The Federal University of Viçosa was considered the installation where the proposed methodology is applied. The University is connected to the medium voltage grid (13.8 KV) and it is classified as Group A, according to ANEEL [26]. The demand of electrical power consumed by the University over one year was measured and it is presented in Figure 7. As observed, during the peak time, from 5:00 to 8:00 pm, there are considerable power consumed, which increases the cost spent to the electrical energy consumption. The installation of a PV system connected to a BESS is possible solution to reduce the cost with the electrical energy. Thus, the energy produced by the PV modules during the day is stored and used to supply the loads during the peak time.

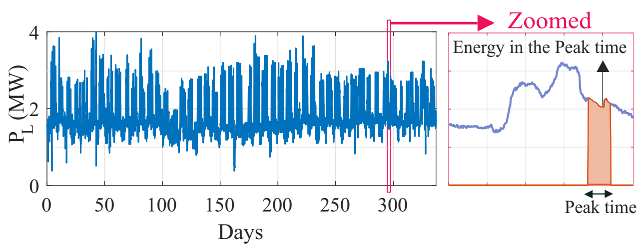

FIGURE 7. Load mission profile over one year with sample time equal to 5 min.

The energy consumed by the load during the peak hours for all the days over one year is calculated and the highest value is used to size the PV system. The value of 7.5 MWh was obtained as the maximum energy consumed by the load. Considering the peak time of three hours, the nominal active power for the PV inverter should be equal to 2.5 MW. Thus, a commercial solution is used in this work. Five PV inverters of 500 kW, manufactured by WEG, are adopted [27]. Thus, the PV system was sized based on mission profile of solar irradiance (G) and ambient temperature (T_a) of Goiânia (with a 1-minute sample time), in Goiás (Brazil).The mission profile of G and T_a are presented in Figure 8.a and 8.b. The maximum power generated by the PV system was set at 500 kW (which is the nominal power of the PV inverter. Thus, the mission profile of the BESS reference power can be identified based on the PV generation and the energy consumed by the load during the peak hour. The mission profiles of solar irradiance, ambient temperature and the BESS reference power are presented in Figure 8.c.

The reference mission profile for a typical week is presented in Figure 9. As observed, the BESS is charged with the energy generated by the PV system and supplies the load during the peak hours. In addition, the discharging process is not considered during the weekend, since the price of electrical energy is generally the same over the day.

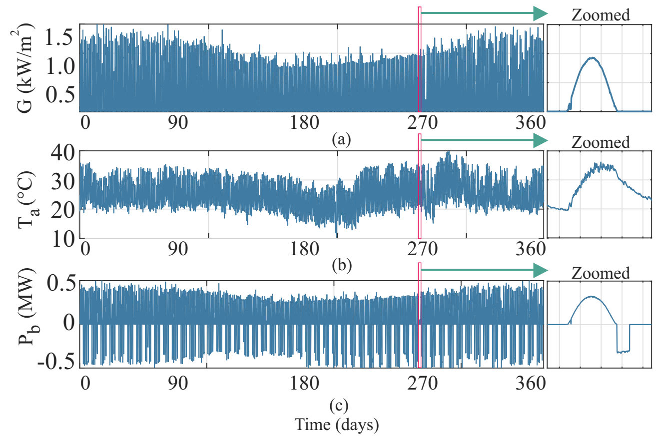

FIGURE 8. One year mission profile of the battery bank power (a) Solar irradiance, (b) ambient temperature and (c) battery bank power mission profile .

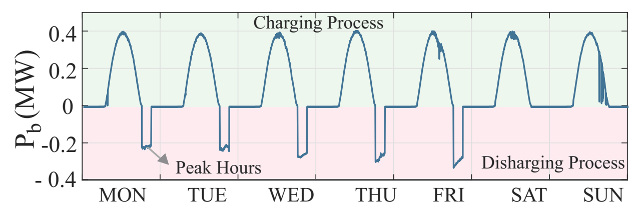

FIGURE 9. Representation of the BESS peak shaving operation over one week.

With regards to the batteries which can be used in the project, 27 batteries (called M =1, 2 ...27) are selected. In addition, 14 Li-ion batteries are considered, 7 manufactured by Power Brick [28] and 7 manufactured by Chargex [29].These batteries present nominal capacity from 30 Ah to 220 Ah. In addition, 14 Li-ion batteries manufactured by Power Brick [28] and Chargex [29] are considered. The batteries were numbered from 1 to 27, and their main parameters are summarized in Figure 10. The lead-acid batteries correspond to the model 1 to 13, the Li-ion batteries from Power Brick correspond to the models 14 to 20 and the batteries manufactured by Chargex correspond to the models 21 to 27. The SOC interval for all the batteries models was considered from 20% to 100%, and the battery temperature was considered constant and equal to 30°C.

VI. RESULTS

The first step is to determine the total number of batteries necessary, considering the energy and power requirements. Figure 11.a shows the number of batteries in series and parallel, and Figure 11.b shows the total number of batteries for each battery type. As observed, for all the three manufactures, the N_T decreases with the C_N increasing, since a higher level of energy stored is expected for batteries with higher nominal capacity (in Ah).

Including N_T, the six criteria considered in this work are estimated and shown in Figure 12. As observed, V_{dc} can

M	C_N (Ah)	E_{bat} (W)	Vl_{bat} (m^3)	r_{bat} ($m\Omega$)	c_{bat} (pu)	$V_{bat\,min}$ (V)
			Lead acid batteries - MOURA			
1	30	215	0.005	8.7	1.00	10.0
2	36	218	0.006	7.1	1.16	10.0
3	45	308	0.006	6.9	1.25	10.0
4	45	308	0.007	6.9	1.25	10.0
5	55	341	0.007	6.2	1.55	10.0
6	63	465	0.009	5.0	1.71	10.0
7	80	484	0.012	4.9	2.52	10.0
8	100	605	0.012	5.2	5.14	10.0
9	105	624	0.014	4.9	2.75	10.0
10	150	880	0.026	3.1	3.77	10.0
11	170	1029	0.022	3.3	8.85	10.0
12	175	1059	0.035	2.5	3.88	10.0
13	220	1207	0.035	2.5	4.52	10.0
			Li-on batteries - Power Brick			
14	20	260	0.002	5.0	5.74	10.5
15	30	380	0.002	3.3	8.07	10.5
16	40	510	0.005	2.5	10.27	10.5
17	45	580	0.005	2.2	12.00	10.5
18	70	900	0.007	1.4	14.82	10.5
19	100	1280	0.009	1.0	22.89	10.5
20	250	3200	0.027	0.4	48.60	10.5
			Li-on batteries - Chargex			
21	20	240	0.002	5.0	4.02	10.5
22	35	420	0.003	2.9	7.26	10.5
23	40	480	0.005	2.5	8.07	10.5
24	50	600	0.005	2.0	9.69	10.5
25	75	900	0.011	1.3	15.35	10.5
26	80	960	0.012	1.2	16.16	10.5
27	100	1280	0.014	1.0	20.21	10.5

FIGURE 10. Batteries and its main parameters.

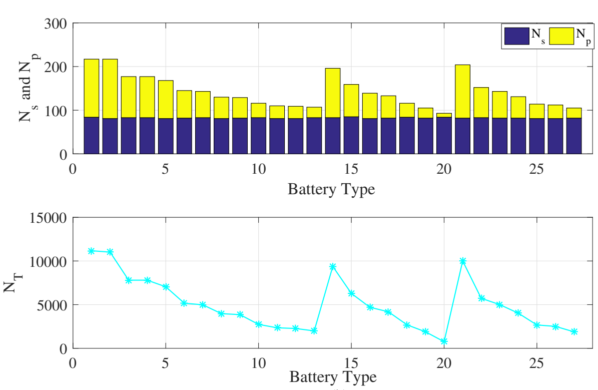

FIGURE 11. Battery design estimations: (a) number of batteries in series and in parallel and (b) total number of batteries.

present different values for each battery type. The lowest and highest V_{dc} values are 1126,0 V and 1170.8 V, respectively. This fact is explained based on the N_T estimation process, since the chosen dc-link voltage is related to the lowest number of batteries. In addition, the PL_b and vol_b values are higher for the lead acid batteries, when compared to the Li-on batteries. On the other hand, the LF is higher for the Li-on batteries. These results are explained based on the characteristics of the battery technologies.

As observed, the In_{Cap} can present different values for each battery type. The highest In_{Cap} value is obtained for the M19. This results can be explained based on the storage energy capacity of the battery bank, which is related to the total number of battery and the energy storage capacity of each the battery type. In addition, the price for the Li-ion batteries are higher than the lead-acid batteries. The price of the battery bank was normalized based on the lowest price value, which is from battery number 6.

Initially, the proposed methodology is applied only to the lead-acid battery. Thus, the optimum matrix solution is presented in Figure 13. As observed, if the relative importance is given to OPEX, the M7 is the optimal solution. On the other hand, if the relative importance is given to the CAPEX, the M6 is presented as the best solution. In addition, when the relative importance between the OPEX and CAPEX are closely, the M5 is considered the best solution. In terms of percentage as the best solution in the optimal matrix, the M7 appears 62.96%, M6 appears 19.75% and M5 appears 17.28%.

Similar analysis is performed for the Li-on batteries, and the optimal matrix solution is shown in Figure 14. If the relative importance is given to OPEX, the M19 is considered the best option. On the other hand, when more relative importance is given to the CAPEX, M20 is considered the best battery choice. In terms of percentage as the best solution in the optimal matrix, the M19 appears and M20 appear 62.96% and 37.04%, respectively.

Finally, the methodology proposed was applied to the 27 batteries and the matrix solution is presented in Figure 15. As observed, when the CAPEX relative index increases, the M6 is considered the best solution. On the other hand, when OPEX relative index increases, the M19 is considered the best solution. In addition, when the relative importance between the OPEX and CAPEX are closely, the M20 is considered the best solution. In addition, for all the combinations of $x_{ij_{CAPEX}}$ and $x_{ij_{OPEX}}$, the M6, M19 and M20 appears 18.75%, 30.86% and 43.20% of times the best solution, respectively.

VII. CONCLUSIONS

This paper proposes a methodology for the selection of the best battery solution based on the CAPEX and OPEX matrix. This proposed methodology was applied to the 27 batteries. The parameters of the dc-link voltage, battery bank voltage, power losses, price, lifetime and energy storage capacity were taken into account. These parameters were separated in OPEX and CAPEX groups, and the best solution based on the relative importance of those two groups were analyzed.

In addition, the lead-acid battery model manufactured by MOURA was selected when the CAPEX presented high

M	C_N (Ah)	E_{bat} (W)	Vl_{bat} (m^3)	r_{bat} ($m\Omega$)	c_{bat} (pu)	$V_{bat\,min}$ (V)
	Lead acid batteries - MOURA					
1	30	215	0.005	8.7	1.00	10.0
2	36	218	0.006	7.1	1.16	10.0
3	45	308	0.006	6.9	1.25	10.0
4	45	308	0.007	6.9	1.25	10.0
5	55	341	0.007	6.2	1.55	10.0
6	63	465	0.009	5.0	1.71	10.0
7	80	484	0.012	4.9	2.52	10.0
8	100	605	0.012	5.2	5.14	10.0
9	105	624	0.014	4.9	2.75	10.0
10	150	880	0.026	3.1	3.77	10.0
11	170	1029	0.022	3.3	8.85	10.0
12	175	1059	0.035	2.5	3.88	10.0
13	220	1207	0.035	2.5	4.52	10.0
	Li-on batteries - Power Brick					
14	20	260	0.002	5.0	5.74	10.5
15	30	380	0.002	3.3	8.07	10.5
16	40	510	0.005	2.5	10.27	10.5
17	45	580	0.005	2.2	12.00	10.5
18	70	900	0.007	1.4	14.82	10.5
19	100	1280	0.009	1.0	22.89	10.5
20	250	3200	0.027	0.4	48.60	10.5
	Li-on batteries - Chargex					
21	20	240	0.002	5.0	4.02	10.5
22	35	420	0.003	2.9	7.26	10.5
23	40	480	0.005	2.5	8.07	10.5
24	50	600	0.005	2.0	9.69	10.5
25	75	900	0.011	1.3	15.35	10.5
26	80	960	0.012	1.2	16.16	10.5
27	100	1280	0.014	1.0	20.21	10.5

FIGURE 12. Battery Models and the main parameters.

Increasing $X_{ij\ OPEX}$ →; Increasing $X_{ij\ CAPEX}$ ↓

	1	2	3	4	5	6	7	8	9
1	M7	M7	M7	M7	M7	M7	M7	M7	M7
2	M5	M7	M7	M7	M7	M7	M7	M7	M7
3	M6	M5	M7	M7	M7	M7	M7	M7	M7
4	M6	M5	M5	M7	M7	M7	M7	M7	M7
5	M6	M6	M5	M7	M7	M7	M7	M7	M7
6	M6	M6	M5	M5	M7	M7	M7	M7	M7
7	M6	M6	M6	M5	M5	M7	M7	M7	M7
8	M6	M6	M6	M5	M5	M5	M7	M7	M7
9	M6	M6	M6	M6	M5	M5	M7	M7	M7

FIGURE 13. Optimum matrix solution for the lead-acid battery models (form M1 to M13).

importance level compared to the OPEX. On the other hand, the Li-ion battery manufactured by Power Brick was selected as the best solution. In addition, the Li-on battery model was selected as the optimum solution in 70.07% of the possible combinations between $x_{ij\,CAPEX}$ and $x_{ij\,OPEX}$. Finally, the proposed battery selection method is a generic methodology which can compare batteries using different technologies and

Increasing $X_{ij\ OPEX}$ →; Increasing $X_{ij\ CAPEX}$ ↓

	1	2	3	4	5	6	7	8	9
1	M19	M19	M19	M19	M19	M19	M19	M19	M19
2	M20	M19	M19	M19	M19	M19	M19	M19	M19
3	M20	M20	M19	M19	M19	M19	M19	M19	M19
4	M20	M20	M20	M19	M19	M19	M19	M19	M19
5	M20	M20	M20	M19	M19	M19	M19	M19	M19
6	M20	M20	M20	M19	M19	M19	M19	M19	M19
7	M20	M20	M20	M20	M20	M19	M19	M19	M19
8	M20	M20	M20	M20	M20	M20	M19	M19	M19
9	M20	M20	M20	M20	M20	M20	M20	M19	M19

FIGURE 14. Optimum matrix solution for the Li-ion battery models (form 14 to 27).

Increasing $X_{ij\ OPEX}$ →; Increasing $X_{ij\ CAPEX}$ ↓

	1	2	3	4	5	6	7	8	9
1	M20	M20	M19	M19	M19	M19	M19	M19	M19
2	M6	M20	M20	M19	M19	M19	M19	M19	M19
3	M6	M20	M20	M20	M19	M19	M19	M19	M19
4	M6	M6	M20	M20	M20	M19	M19	M19	M19
5	M6	M6	M20	M20	M20	M20	M20	M19	M19
6	M6	M6	M6	M20	M20	M20	M20	M20	M19
7	M6	M6	M6	M20	M20	M20	M20	M20	M20
8	M6	M6	M6	M6	M20	M20	M20	M20	M20
9	M6	M6	M6	M6	M6	M20	M20	M20	M20

FIGURE 15. Optimum matrix solution for lead-acid and Li-ion batteries(form 1 to 27).

from different manufactures. The user can add or remove criterion in the battery selection process.

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PLAGIARISM POLICY

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