A tool for optimal operation and design of batteries and its applications to self-consumption

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***Abstract*— This paper presents a tool for optimal operation and design of batteries and its applications to self-consumption. The recent improvements in capabilities and costs of battery storage technologies might enable new business opportunities. Battery storage is key for operating and managing hybrid off-grid, microgrid and self-consumption systems. The feasibility of integrating batteries in these systems has been shown in previous studies, but the profitability of these business opportunities needs to be demonstrated. The profitability of these opportunities depends on the technical restrictions of the batteries, the behavior of the demand, the grid restrictions, and the regulatory constraints.**

The analysis of the profitability requires an appropriate model. In its most generic formulation, the model considers electrical and thermal demand, photovoltaic and wind generation profiles, conventional generation and cogeneration, demand response capabilities, and heat pumps and resistors for conversion of electrical power into thermal power. The behavior of batteries is modelled with penalization costs for cycling and for levels of stored energy above or below the recommended margins, ensuring that they are dispatched in a conservative manner to prolong their lifespan. For systems connected to the grid, the maximum power and the limits on feeding excess energy are also considered.

The tool is applied to self-consumption considering a hotel building with a photovoltaic panel on its roof. Different business opportunities are studied such as storing the excess generation from renewable energy sources, reducing the power bill, or performing price arbitrage. The developed model compares combinations of batteries of different power ratings and capacities, along with different grid connection contracts to determine the cost for each. To do that, it considers the best allocation of the energy resources, both electrical and thermal, to minimize the total costs of the system. For comparing grid contracts, two variable costs are considered: one related to the maximum power rating, and the other to the energy consumption.

Keywords-Energy storage system; optimal sizing; microgrid; renewable energy sources; renewable energy integration

I. Introduction

The recent improvements in capabilities and costs of battery storage technologies [1], combined with the upcoming changes in the electric power system [2], [3] might enable new business opportunities. Battery storage is key for operating and managing hybrid off-grid, microgrid and self-consumption systems. The feasibility of integrating batteries in these systems has been studied in the literature [4]–[6], but the profitability of these business opportunities needs to be demonstrated. The profitability of these opportunities depends on the technical restrictions of the batteries, the behavior of the demand, the grid restrictions, and the regulatory constraints.

This paper presents a tool for optimal operation and design of batteries and its applications to self-consumption. A generic UC model that included ESS was modified to obtain the present tool. In its most generic formulation, the model considers electrical and thermal demand, photovoltaic and wind generation profiles, conventional generation and cogeneration, demand response capabilities, and heat pumps and resistors for conversion of electrical power into thermal power.

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II. MATHEMATICAL FORMULATION

In this section, the objective function of the model and the additions to the generic UC model are outlined.

A. Objective function

The objective function, shown in equation (1), minimizes the total costs of the system. These costs are those associated with generation, storage, and grid connection. In addition to that, feeding energy into the grid can reduce costs in cases where such strategies are allowed.

$$\min \sum_{g,ess,h} \left(c_{ren,h} + c_{ess,h} + c_h^{grid} - c_h^{feed} + c_{shed,h} \right) \quad (1)$$

The costs associated with renewable energy sources is calculated in equation (2), as a fixed cost for each installed group plus a lineal cost for the power generation.

$$c_{ren,h} = C_{ren}^{fix} + C_{ren}^{lin} \cdot p_{ren,h} \qquad \forall ren, h \quad (2)$$

The cost of operation of the batteries was originally modelled with a fixed cost for every hour the battery was online, plus a linear cost proportional to the energy throughput. New constraints have been added to the UC model in order to allow operating the ESS according to recommended practices. Equation (3) shows the calculation of the total costs associated to the batteries.

$$\begin{aligned} c_{ess,h} &= C_{ess}^{fix} \cdot \delta_{ess,h} + C_{ess}^{lin} \cdot (p_{ess,h}^{gen} + p_{ess,h}^{con}) + \\ &+ C_{ess,h}^{cycle} + C_{ess}^{SOCpen} \cdot (E_{ess,h}^{outofmargin}), \quad \forall ess, h \end{aligned} \quad (3)$$

1) Cycle limit

By penalizing the end of a charge or discharge, the battery will tend to maximize the charge and discharge cycles, rather than perform several consecutive small cycles which increases degradation [7]. Equation (4) shows how the penalization cost of the battery cycling is calculated, with binary variables that trigger when the battery stops charging and discharging, respectively.

$$C_{ess,h}^{cycle} = C_{cycle}^{pen} \cdot \left(\delta_{ess,h}^{charge\_end} + \delta_{ess,h}^{discharge\_end} \right) \quad (4)$$

2) Depth of Discharge

In addition to cycle limits, upper and lower limits of the state of charge (SOC) are established. The range of values of the SOC outside these limits can be used, but the system will acknowledge the extra degradation incurred [8]. Most optimization systems impose hard limits so the battery will never exit the "safe" zone, effectively reducing the available energy, because precise modelling of the variation of degradation and maximum power output of the battery with state-of-charge is complex and very computing-intensive [9]. Due to this, the aforementioned compromise was reached. The variable to which the penalization factor is applied is shown in equation (5).

$$E_{ess,h}^{outofmargin} = \begin{cases} E_{ess,h} - E_{ess}^{high} \text{ if } E_{ess,h} > E_{ess}^{high} \\ E_{ess}^{low} - E_{ess,h} \text{ if } E_{ess,h} < E_{ess}^{low} \end{cases} \quad (5)$$

In equation (6), the costs associated to the grid connection are calculated as the sum of the cost due to the maximum power contracted and the cost due to energy consumption. When net balance is active, the energy fed to the grid can be consumed back with a reduced cost. If feeding energy to the grid is allowed, it can have an associated energy tariff, as shown in equation (7).

$$\begin{aligned} c_{grid,h} &= C_{grid}^{fix} + C_{grid,h}^{lin} \cdot p_{grid,h} + \\ &+ C_{grid,h}^{lin,fed} \cdot p_{grid,h}^{fed}, \quad \forall h \end{aligned} \quad (6)$$

$$c_{feed,h} = C_{feed,h}^{lin} \cdot p_{feed,h}, \quad \forall h \quad (7)$$

If load shedding is allowed, equation (8) calculates the associated penalization costs.

$$c_{shed,h} = C_{shed} \cdot p_{dr,h}^{down} \quad (8)$$

B. Restrictions

1) Electrical demand balance

Electrical demand balance is described in equation (9). The power generation is the sum of the net electrical power of generator units, the power supplied by the grid, the power generation of renewable energy sources, and the power discharged by the storage. The total demand of the system is the sum of the demand profile, the power fed to the grid, and the power used to charge the storage. In addition, demand management can reduce or increase the demand profile temporally, either with zero net balance or load shedding.

$$\begin{aligned} & p_{grid,h} + \sum_{ren} p_{ren,h} + p_{ess,h}^{gen} - p_{ess,h}^{con} + \\ & + \sum_{dr} \left(p_{dr,h}^{down} - p_{dr,h}^{up} \right) = D_h^e + p_{feed,h} \quad \forall h \end{aligned} \quad (9)$$

2) Zero net balance of demand management

Equation (10) establishes the requirement for demand management to have zero net energy balance in an established time horizon $IC^{D,dr}$ (for example, from 9 to 18 each day).

$$\sum_{h \in IC^{D,dr}} \left(p_{dr,h}^{down} - p_{dr,h}^{up} \right) = 0 \quad (10)$$

For load shedding, this equation does not apply.

3) Limits of generation and consumption

The power generated (or consumed) by each element is limited. For renewable energy sources, equation (11) sets the limits if they are controllable, and equation (12) if they are not. In the latter, the power generated must be equal to the power available, or be zero.

$$P_{ren}^{\min} \le p_{ren,h} \le P_{ren}^{real} \cdot \delta_{ren,h}, \quad \forall ren, h \quad (11)$$

$$p_{ren,h} = P_{ren}^{real} \cdot \delta_{ren,h} \qquad \forall ren \notin \boldsymbol{IC}^{ren} \quad (12)$$

Equations (13) and (14) ensure that the storage and demand management stay within their rated limits.

$$\begin{aligned} &P_{ess}^{gen,\min} \leq p_{ess,h}^{gen} \leq P_{ess}^{gen,\max} \quad \forall ess,h \\ &P_{ess}^{con,\min} \leq p_{ess,h}^{con} \leq P_{ess}^{con,\max} \quad \forall ess,h \end{aligned} \tag{13}$$

$$\begin{aligned} &P_{dr}^{up,\min} \leq p_{dr,h}^{up} \leq P_{dr}^{up,\max} \quad \forall dr,h \\ &P_{dr}^{down,\min} \leq p_{dr,h}^{down} \leq P_{dr}^{down,\max} \quad \forall dr,h \end{aligned} \tag{14}$$

Equation (15) establish the power limits for the grid. A binary variable impedes simultaneous power extraction and injection, while allowing to restrict injection to the grid if it is not allowed.

$$\begin{aligned} &0 \leq p_{grid,h} \leq P_{grid}^{\max} \cdot \delta_{grid,h} \quad \forall h \\ &0 \leq p_{feed,h} \leq P_{feed}^{\max} \cdot (1-\delta_{grid,h}) \quad \forall h \end{aligned} \tag{15}$$

4) State of charge of storage

Equation (16) determines the state of charge of storage for each hour, according to the previous hour and the charges and discharges.

$$e_{ess,h} = e_{ess,h-1} - \frac{p_{ess,h}^{gen}}{\eta_{ess}^{gen}} + \eta_{ess}^{con} \cdot p_{ess,h}^{con} \quad \forall ess,h \tag{16}$$

Equation (17) forces the state of charge of the storage to be the same at the end of the simulation that at the beginning, so the optimization will not fully discharge the storage at the end of the simulation to reduce costs for the simulated time window, without accounting for the impact on the following hours.

$$e_{ess,hfinal} \geq e_{ess,h0} \quad \forall ess \tag{17}$$

Equation (18) establishes the upper and lower limits of the state of charge in storage.

$$E_{ess}^{\min} \leq e_{ess,h} \leq E_{ess}^{\max} \quad \forall ess,h \tag{18}$$

5) Net balance management

If net balance is allowed, the restriction in equation (19) is established,, which forces the total energy drawn from the grid at a reduced cost to be equal to the energy fed to the grid.

$$\sum_h (p_{grid,h}^{fed} - p_{feed,h}) = 0 \tag{19}$$

III. CASE STUDY

The hourly electrical demand profile of a hotel during a week, which can be seen in Figure 1, has been studied.

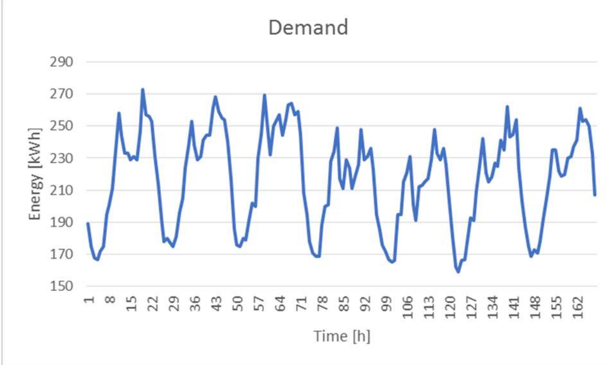

Figure 1. Demand profile

A series of scenarios have been simulated, with each having a different amount of solar power installed. TABLE I shows the considered installed solar power average power, and Figure 2 shows the generation profile for the low PV case.

TABLE I. AVERAGE SOLAR POWER

	Average power (kW)
Low PV	49
High PV	98

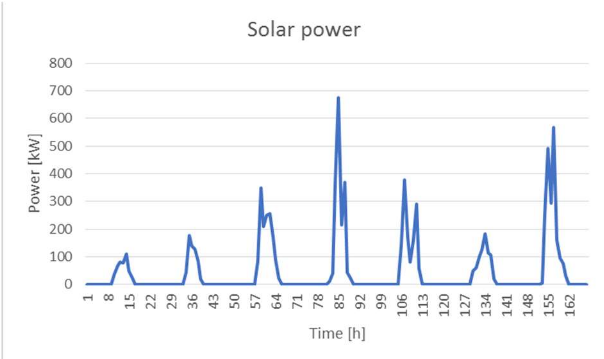

Figure 2. Solar power generation

For each scenario, the connection schemes to the grid with the maximum power and power term shown in TABLE II are considered. In addition, the cost of energy shown in Figure 3 is considered for all the schemes.

TABLE II. GRID CONFIGURATIONS

	Max Power (kW)	Power term (€/h)
grid1	200	0.27
grid2	300	0.40
grid3	400	0.54

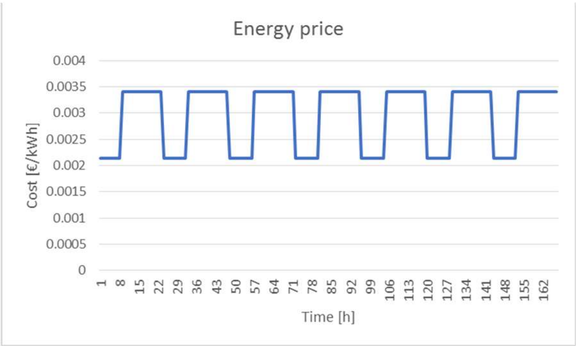

Figure 3. Energy from grid price

The characteristics of the ESS considered are in TABLE III. All ESS have a penalization of 0.01€ per cycle to avoid excessive cycling. In addition, ESS 3 and 4 have penalization costs for exiting their recommended SOC zone of 0.005€/kWh of throughput in these charge levels, but their energy capacity within the recommended range is equal to the total capacity of ESS 1 and 2, respectively. A penalization of 20€ per kWh of demand not supplied was chosen.

TABLE III. BATTERY TECHNICAL DATA

	Max Power (kW)	Max charge (kWh)	High charge (kWh)	Low charge (kWh)	Efficiency
eess1	100	420	420	0	0.94
eess2	200	840	840	0	0.94
eess3	100	500	460	40	0.94
eess4	200	1000	920	80	0.94
eess5	100	1500	1500	0	0.85

Firstly, a case with low penetration and the costs of the batteries set to zero has been simulated. TABLE IV shows the value of the objective function for each simulated scenario. The lowest grid installed power is not enough to meet the demand, so the costs with no ESS and with ESS 1 are very high due to the penalization caused by demand not supplied. ESS 3 also has penalization costs, albeit lower due to the extra capacity outside the recommended SOC. ESS 2 and 3 obtain the same values, as ESS 4 is operated without exiting the recommended SOC, while ESS 5 is slightly worse due to lower efficiency.

For grids 2 and 3, the results obtained are very similar. The ESS allow to store the solar energy that exceeds the demand. Since the solar generation is not controllable, it can either generate all the available power or zero. Due to this, when solar available power is above the demand, none of it can be used unless an ESS can absorb the difference.

TABLE IV. RESULTS WITH LOW PV AND NO ESS COSTS.

	Grid 1	Grid 2	Grid 3
No ESS	54927.69	164.29	186.79
ESS 1	4929.46	157.40	178.59
ESS 2	132.30	152.11	172.92
ESS 3	798.14	157.32	179.75
ESS 4	132.31	150.29	173.85
ESS 5	138.29	156.91	179.31

Secondly, a case with high PV penetration was simulated, with the results shown in TABLE V. The results are conceptually identical to those in the previous case. It must be noted that ESS 5 fails to avoid lost demand in this case, while it had no issues with low PV generation. Figure 4 shows the electrical balance, with the top part containing the demands and the bottom part the generation. The charge of the ESS coincides with the solar generation above the demand, and with the moments when the demand is lower than the grid power, in order to have enough energy to meet the peak demand.

TABLE V. RESULTS WITH HIGH PV AND NO ESS COSTS

	Grid 1	Grid 2	Grid 3
No ESS	59904.56	165.23	187.73
ESS 1	9192.16	156.84	179.36
ESS 2	129.37	151.21	172.69
ESS 3	6202.17	156.09	178.55
ESS 4	130.82	151.93	172.04
ESS 5	1048.13	156.65	179.93

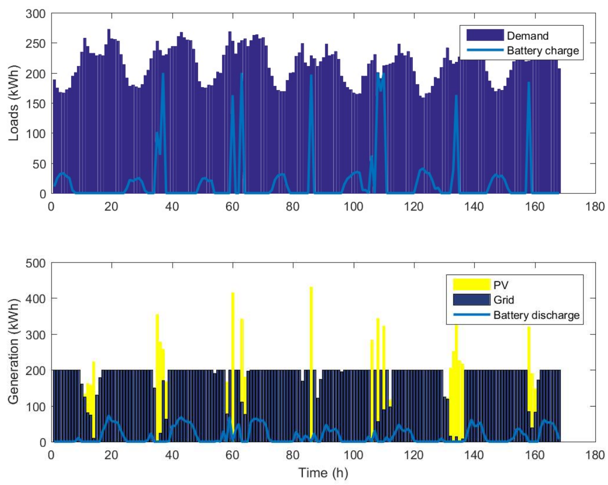

Figure 4. Electrical balance for ESS 2 with no costs, grid 1 and high PV.

Thirdly, a cost is associated to the throughput of each battery, and the simulations are repeated. With these, the results in TABLE VI and TABLE VII are obtained. With low penetration, the results are similar to that of the first case for grid 1, with slightly higher results due to the added costs. With grids 2 and 3, however, having no storage becomes the best option, as the costs of charging and discharging the ESS are higher than the savings they provide. The savings procured by ESS 2 with grid 1 relative to having no storage and grid 2 are 16.35€/week. Assuming a 10-year lifetime for ESS 2, it would save 8502€ in its lifetime, which is orders of magnitude below the cost of such a battery (around 250k€).

With high penetration, the ESS manage to reduce costs, but by a smaller margin than in the case with no ESS costs. Figure 5 and Figure 6 show the use of ESS 2 with grid 1 without and with ESS costs, respectively. It can be seen that both figures have similar contents, with the ESS being charged with excess solar power and discharged later to avoid demand loss.

TABLE VI. RESULTS WITH LOW PV AND ESS COSTS

	Grid 1	Grid 2	Grid 3
No ESS	54927.69	164.29	186.79
ESS 1	4698.58	164.29	186.79
ESS 2	147.94	164.29	186.79
ESS 3	813.91	164.29	186.79
ESS 4	147.95	164.29	186.79
ESS 5	153.31	164.29	186.79

TABLE VII. RESULTS WITH HIGH PV AND ESS COSTS

	Grid 1	Grid 2	Grid 3
No ESS	59904.56	165.23	187.73
ESS 1	9179.77	160.06	182.56
ESS 2	146.28	158.49	181.00
ESS 3	6173.48	160.04	182.54
ESS 4	146.28	158.50	181.00
ESS 5	1064.22	159.70	182.20

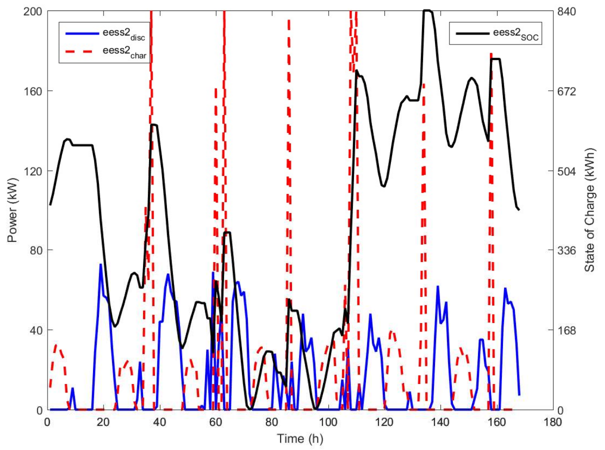

Figure 5. Use of ESS2 with grid 1, high PV and no ESS costs

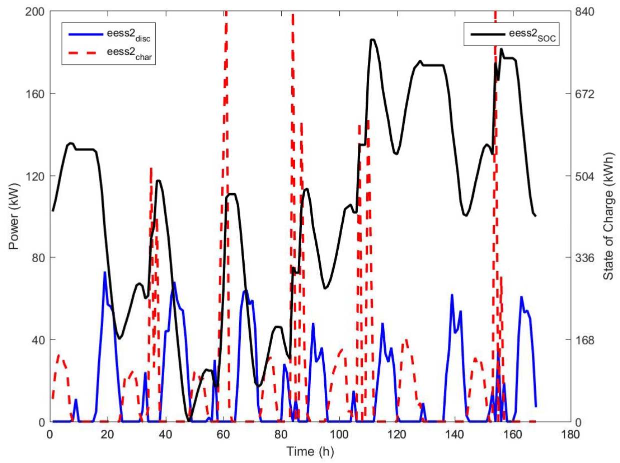

Figure 6. Use of ESS2 with grid 1, high PV and ESS costs

IV. CONCLUSIONS

In this paper, a new tool to optimize the size of batteries and maximum power from the grid has been presented. The tool employs a Unit Commitment model, modified to account for the costs of storage use and the impact of degradation, to simulate the optimal dispatch for each ESS and grid power combination. The economic terms included in the model allow to assess the impact of ESS in the analyzed systems with ease.

A case study has been performed, with the tool determining the best ESS-grid combination for a building with two levels of solar power generation. The results show that the tool can either provide the optimal dispatch without accounting for the costs of the ESS, or provide a preliminary economic study based on the cost of use of the ESS. In this case, the use of storage allows to reduce dependence on the grid, allowing to setup a maximum contracted power lower than the peak demand of the system, and to take full advantage of the solar generation. Despite that, the savings procured by installing storage in the studied building are too low to justify investment costs.

Finally, as shown in the case study, the presented tool can optimize the use of batteries and determine the combination of battery and grid connection with the lowest objective function value, with the possibility of including the investment costs of the battery in the objective function.

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