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Lithium-ion Battery Modelling for the Energy Management Problem of Microgrids

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Abstract: This paper presents the mathematical modelling to represent lithium-ion (li-ion) batteries in the Energy Management (EM) problem of a Microgrid (MG). It is developed a detail mathematical modelling for the li-ion batteries considering the degradation cost associated with the operation, controllable and uncontrollable charging ramps, and others limits and operating characteristics given by the manufactures. Besides the li-ion battery degradation cost, we analyse different approaches comparing models without this cost, a quadratic and a piecewise degradation cost; furthermore, it is analysed a linear cost considering the life expectancy based on the number of cycles of the battery. To analyse the proposed and different modelling approaches we include the battery model in an EM problem of a MG along with wind, photovoltaic generation resources connected to the main grid, also including a back-up generator. This problem is modelled as a deterministic mixed-integer linear (or quadratic) problem, where the associated results to eleven cases are used in the analyses and comparisons to the li-ion battery modelling related to costs, constraints and the number of time steps within a 24-hour planning horizon.

1. Nomenclature

The notation used throughout the paper is presented below.

Index / Sets

e	index related to batteries ($e \in E$);
i	discretisation step index associated with the battery reserve;
n	index for the piecewise linearization quadratic equations costs to the battery ($n \in N$);
t	index for the time step ($t \in ND$).

Variables

cbI_{et}	cost from the piecewise linearization of battery e (€ h ⁻¹) in step t ;
$dcbd_{et}$	absolute discharge power output difference between $t-1$ and t time step of battery e (kW);
eb_{et}	energy of battery e (kWh) in step t ;
pbc_{et}	power charge of battery e (kW) in step t ;
pbd_{et}	power discharge of battery e (kW) in step t ;
pde_t	system deficit (kW) in step t ;
pex_t	excess generation (kW) in step t ;
pgb_t	power purchased from the grid (kW) in step t ;
pgs_t	power sold to the grid (kW) in step t ;

- rb_{et} reserve of battery e (kW) in step t ;
- ub_{et}^{aux1} binary variable that indicates whether battery e is on constant current charge ($ub_{et}^{aux1} = 1$) in step t ;
- ub_{et}^{aux2} binary variable that indicates whether battery e is on constant voltage charge ($ub_{et}^{aux2}=1$) in step t ;
- ub_{et} binary variable that indicates whether battery e is charging ($ub_{et} = 1$) in step t ;
- ug_t binary variable that indicates whether the MG is importing energy ($ug_t = 1$) in step t ;

Parameters

- AB_e battery e SOC target (%);
- BB_e battery e cost parameter ($\text{€ Cbat h}^{-1} (\text{kWh})^{-1}$);
- BP_t energy purchase price in step t ($\text{€} (\text{kWh})^{-1}$);
- CB_e battery e maximum charge (kW);
- $CB2_e$ charge constant of the linear equation to the battery e (kW);
- CD load deficit incremental cost ($\text{€} (\text{kWh})^{-1}$);
- CE system excess energy incremental cost ($\text{€} (\text{kWh})^{-1}$);
- CUB_{et} battery e cost (€ h^{-1}) in step t ;
- DB_e battery e maximum discharge (kW);
- D_t forecast load demand in step t (kW);
- EBF_e final energy of battery e (kWh);
- EBI_e initial energy of battery e (kWh);
- EB_e^{max} battery e maximum energy (kWh);
- EB_e^{min} battery e minimum energy (kWh);
- ED forecasted error associated with the load demand (%);
- EPV forecasted error associated with the photovoltaic generation (%);
- EPW forecasted error associated with the wind generation (%);
- FB_e battery e discharge incremental cost parameter ($\text{€} (\text{kWh})^{-1}$);
- GB_e battery e linear charge incremental cost parameter ($\text{€} (\text{kWh})^{-1}$);
- H horizon time (h);
- HB_e battery e quadratic charge cost parameter ($\text{€ kWh (kW)}^{-2} \text{ h}^{-1} \text{ Cbat}^{-1}$);
- IB_{en}, JB_{en} battery e linear SOC energy deviation cost parameters at the linearization n (€ h^{-1});
- ND number of time steps in the planning horizon;
- PBL_e power lost in one time step of battery e (kW);

PGB_t^{max}	grid maximum power import (kW) in step t ;
PGB_t^{min}	grid minimum power import (kW) in step t ;
PGS_t^{max}	grid maximum power export (kW) in step t ;
PGS_t^{min}	grid minimum power export (kW) in step t ;
PV_t	forecast photovoltaic power (kW) in step t ;
PW_t	forecast wind power (kW) in step t ;
RB	number of time steps to the reserve of the system;
SP_t	energy selling price in step t (€ (kWh) ⁻¹);
SPC_e	SOC set point where the battery charges ramp change from the constant current to constant voltage (%);
α_e	charge gradient of the linear equation to the battery e (kW (kWh) ⁻¹);
δ_e	incremental cost associated with the use cost on the pulse operation (€ (kWh) ⁻¹);
η_e^{bc}	charge efficiency of battery e (%);
η_e^{bd}	discharge efficiency of battery e (%).

2. Introduction

The integration of controllable load demands, energy storage systems, small renewable generators, electrical vehicles is a trend in modern the power systems. The inclusion of these Distribution Energy Resources (DERs) might reduce fossil fuel consumption, load peak shaving, as well as postpone investments in new transmission and distribution lines [1, 2]. In this new paradigm, it is important to highlight the Microgrid (MG) concept, which can be roughly defined as a group of DERs that might operate connected or in island operation with the main grid [3].

A methodological challenge that supports the operation issues of a MG is the Energy Management (EM) problem [4, 5]. In general, to solve this problem with a centralized control is necessary to minimise, over a planning horizon, an objective function subject to economic and technical constraints. The economic control is a dispatch problem, which is given by the on/off status and the respective output active power of each controllable DER. This dispatch is used as reference for the voltage and frequency control in MG real-time operation. Because it is necessary to minimise an objective function subject to constraints, the centralized EM could be performed based on the solution of an optimisation problem.

The Energy Storage Systems (ESSs) are important for the MG, especially due to the intermittent characteristics of the renewable generation and load demand, the requirement reserve of the system and the island operation of the MG, for instance [6]. Consequently, the presence of ESSs in a MG might also increase significantly the quality and reliability of energy supply. The most common ESSs are batteries,

super capacitors, flywheels, compressed air and superconducting magnetic energy storage. Even for the same type of ESS, several characteristics in the modelling could be different, depending on the size and technology employed, as presented, for example, in [7] for the chemical batteries. Regarding the batteries, the most ascending technology nowadays are the lithium-ion (li-ion) batteries, used in electric cars, mobile phones and notebooks [8-10].

In the literature, there are different modelling approaches of the li-ion batteries that are represented in the optimisation EM problems. For instance: modelled as a generic storage system; as [11, 12] when is used an incremental cost at the discharge and/or charge based on the expectancy of the number of cycles for charge and discharge; modelled considering the annual maintenance and acquisition cost for planning studies [13]; or as [14, 15] presenting a specific function for the degradation cost. Regarding the operational constraints for [11, 12, 13, 14, 15], in general, they are associated with the limits of charge, discharge, initial energy, final energy and energy balance considering the efficiency and previous energy states. These modelling deals with important aspects of the battery dispatch management since the charges and discharges (with a high efficiency) will influence the SOH and also are linked to the SOC of the batteries. Others physical characteristics usually not considered for this battery technology are the moderate discharge, which is better for a battery than pulse discharge depending on the li-ion technology, and the constant current and voltages stages characteristics for the charge [8-10, 16]. Batteries do not have always accessible power control, having a self-charging management, and the system reserve requirement is also an important issue to the batteries in a microgrid.

Paper most important contributions to the lithium-ion batteries modelling to the MG EM are summarize: comparing the different approaches to the cost in the objective function; including new constraints to prevent pulse discharging and to the charging characteristics; including new constraints when it is not possible to control the charging; comparing the different number of time steps within a 24-hour horizon. The MG EM problem to investigate the new contributions is obtained by solving a deterministic mixed-integer linear (or quadratic) problem [17], where the 24-hour planning horizon is discretised in time steps of one, ten and 30 minutes for a microgrid with batteries, wind and photovoltaic generators supplying a load demand, considering a back-up generator.

This paper is organized as follows: in the next section, the modelling of the li-ion battery is presented; then, in Section 4, a complete EM modelling for a generic MG, along with the complete optimisation model related to the EM problem, is described; in Section 5, it is presented the MG and the computational experiments; finally, Section 6 provides the conclusions of this paper.

3. Lithium-Ion Batteries Modelling

The li-ion batteries can be classified as [18]. Each of these Lithium-ion batteries have particularities for a specific use, although, in this paper we are proposing a modelling in a generic way.

3.1. Cost function

In [14] is proposed a cost by an approximate positive semi-definite quadratic function for the li-ion battery use (due to the degradation of the State of Heal - SOH) in which is taking into account the deviation of the State of Charge (SOC) from a set point and the energy charge and discharge in one time step. The degradation costs were developed to a li-ion battery acquisition of 400 € (kWh)⁻¹, although the parameters are proportional if the acquisition price were different. The equation is presented in (1).

$$CUB_{et} = BB_e \cdot (eb_{et} / EB_e^{\max} - AB_e)^2 + FB_e \cdot pbd_{et} + GB_e \cdot pbc_{et} + HB_e / EB_e^{\max} \cdot pbc_{et}^2 \quad (1)$$

The graphic for the first part of the degradation cost is given in Fig. 1a. It is possible to notice the quadratic function costs and two possible approximations with three and five linear equations to define the same behaviour. The same approach is used to the degradation cost due to the charge, as presented at Fig. 1b. The costs linked to the discharge degradation are considered zero as long as it meets the upper limit.

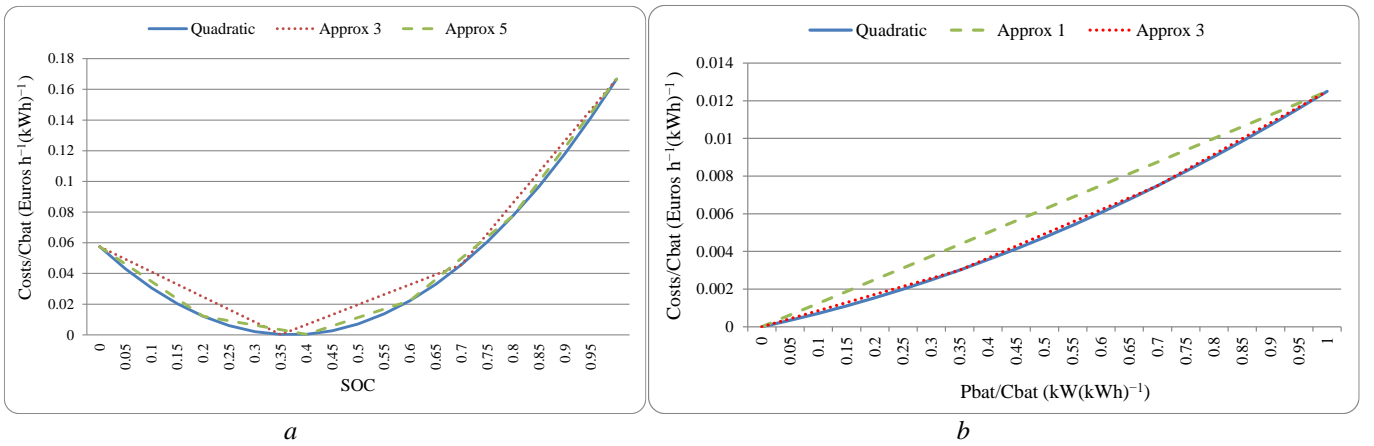


Fig. 1. Li-ion battery degradation cost functions
a Degradation cost due to the deviation of the SOC
b Degradation cost due to the deviation of the charge

Fig. 1a and Fig. 1b are normalized and have the same behaviour presented in [14].

Mathematically, it is possible to use a piecewise linearization without binary variables to (1) because the function associated is convex. The linearization process of the deviation from the SOC with n linear equations in (1) is given by:

$$\min f = cbl_{et} \quad (2)$$

$$\text{s.t.: } cb1_{et} \geq IB_{en} \cdot eb_{et} / EB_e^{\max} + JB_{en} \quad (3)$$

Notice in (3) that the parameters IB_{en} and JB_{en} could be estimated in several ways. We choose the simplest way with two points of SOC and two costs from (1). The same approach is used to the charging cost using pbc_{et} .

Others function cost approaches found in literature are due to the number of cycles. For example, if is considered that a battery could perform 1,500 cycles, having the maximum energy and the acquisition price, this cost is considered constant and approximated by an incremental cost that depends on the discharge and/or charge.

3.2. Constraints

The following item is to present the actual literature constraints and the new constraints to the li-ion batteries as the characteristics described in Section 2.

Fig. 2 presents an approximation of a li-ion battery charge characteristics in constant current and constant voltage after the *SPC*, depending on the SOC [19].

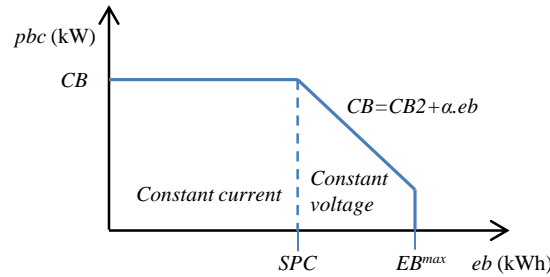


Fig. 2. Schematic lithium-ion charge characteristics

The curves presented in Fig. 2 are not exactly constant and linear in the real li-ion battery, although it is possible to obtain the data from the manufactory or tests to adapt the equations. The important factor is the change on the maximum charge power after a certain state of charge.

The efficiency is very high for the charge and discharge, and the self-discharge is very low for this battery technology. The temperature influence is negligible in this paper due to the constant temperature assumption.

The energy balance, charge, discharge and others characteristics are modelling as the following constraints:

$$eb_{e,t+1} - eb_{et} + \left(pbd_{et} / \eta_e^{bd} - \eta_e^{bc} \cdot pbc_{et} \right) \cdot H / ND = -PBL_e \cdot H / ND, \quad t \in \{2, \dots, ND-1\} \quad (4)$$

$$eb_{e2} + \left(pbd_{e1} / \eta_e^{bd} - \eta_e^{bc} \cdot pbc_{e1} \right) \cdot H / ND = -PBL_e \cdot H / ND + EBI_e, \quad (5)$$

$$eb_{eND} - \left(pbd_{eND} / \eta_e^{bd} - \eta_e^{bc} \cdot pbc_{eND} \right) \cdot H / ND = PBL_e \cdot H / ND + EBF_e, \quad (6)$$

$$-eb_{et} + \sum_{i=1}^{RB} \left[rb_{e,t-1+i} / \eta_e^{bd} \right] \cdot H / ND \leq -EB_e^{\min}, \quad eb_{et} \leq EB_e^{\max}, \quad (7)$$

$$0 \leq pbc_{et} \leq CB_e, \quad 0 \leq pbc_{et} \leq CB2_e + eb_{et} \cdot \alpha_e, \quad (8)$$

$$0 \leq pbd_{et} \leq DB_e, \quad 0 \leq rb_{et} \leq 2 \cdot DB_e, \quad (9)$$

$$pbc_{et} - ub_{et} \cdot CB_e \leq 0, \quad (10)$$

$$ub_{et} \cdot DB_e + pbd_{et} \leq DB_e, \quad (11)$$

$$ub_{et} \in \{0,1\} \quad (12)$$

The constraint (4) is the energy balance of the battery throughout each time step, where the energy for the next step depends on the energy in the current time step, the charge or discharge power, the efficiency and the loss of energy at each time step. Note that the power is converting to energy including the time with H/ND . The initial and final energy for the li-ion battery e are defined by the constraints (5) and (6), respectively. The constraints of minimum and maximum battery energy are given by (7). In (7) the reserve constraint requires a minimum energy each time step with the variable rb_{et} , considering RB time steps ahead. The ramp constraints for the battery charge are given by (8) with the constant current and constant voltage equations, while (9) are constraints related to discharge and reserve requirements. The reserve could discharge twice the power of the normal discharge. We set this higher than the nominal discharge because the reserve is not frequently used. When the energy reserve is used up to DB_e , is just for a couple minutes and there is a not considerable damaging consequence for the battery. Constraints (10), (11) and (12) are used to prevent the battery charge and discharge in the same time step t (situation which could occur when there is excess intermittent generation).

The new equations for the constraints above are in (7) with the minimum energy, in (8) with the charge constant voltage limits and in (9) with the reserve limits. Other equations besides (10)-(12) to prevent the charge and discharge in the same step t could be used, although we prefer this approach which is reliable.

New constraints, if is not possible control the charge power (e.g., when the power control is not accessible and it is performed by a switch on/off), are devolved with the following equations:

$$-pbc_{et} + ub_{et}^{aux2} \cdot CB_e + ub_{et} \cdot 10000 \leq 10000, \quad (13)$$

$$-pb_{et} + \alpha_e \cdot eb_{et} + ub_{et} \cdot 10000 + ub_{et}^{aux1} \cdot CB2_e \leq 10000, \quad (14)$$

$$-ub_{et}^{aux1} \cdot SPC_e \cdot EB_e^{\max} + eb_{et} \leq SPC_e \cdot EB_e^{\max}, \quad (15)$$

$$-ub_{et}^{aux2} \cdot SPC_e \cdot EB_e^{\max} - eb_{et} \leq -SPC_e \cdot EB_e^{\max}, \quad (16)$$

$$ub_{et}^{aux1} + ub_{et}^{aux2} = 1, ub_{et}^{aux1} \in \{0,1\}, ub_{et}^{aux2} \in \{0,1\} \quad (17)$$

Equations (13) and (14) are set in the minimum and maximum charge in the same level, while (15), (16) and (17) are the logical auxiliaries binaries variables to verify if the SOC is in the current or voltage constant charge (considering that the battery will be in the constant voltage charge in $SPC_e=70\%$ of the SOC). Number 10000 is just to guarantee a big number, although other bigger value than the maximum charge could be used.

As described before, the moderate discharge is better for a battery than pulse and aggregated loads. Then, it is proposed in this paper to use an incremental cost (18) and some constraints to decrease this, as follows:

$$\delta_e \cdot dpbd_{et}, \quad (18)$$

$$pbd_{et} - pbd_{e,t-1} - dpbd_{bt} \leq 0, \quad (19)$$

$$-pbd_{et} + pbd_{e,t-1} - dpbd_{et} \leq 0, \quad (20)$$

Constraints (19) and (20) compute the increase and decrease of power, respectively, during two consecutive time steps. To prevent pulse, the use cost should be set on δ_e . Computational tests show that even with a small incremental cost (e.g. 1×10^{-4}) the pulse discharge is prevented.

4. Optimisation Model

The EM optimisation problem of a MG is similar to the classical unit commitment problem [20], although is strictly related to the physical characteristics and the regulatory framework in which a MG is inserted. In this paper, the MG can buy or sell energy in a day-ahead horizon from the main grid. Additionally, the model considers a MG with load demand, li-ion batteries, and photovoltaic and wind generators. The back-up generator is not included at the connected operation and is not presented in the optimisation model. The modelling of wind and photovoltaic generators does not consider the cost due to the acquisition, as well as the operational cost. Thus, wind and photovoltaic generators are included in the energy balance constraints as negative load demands, whose values as supplied by a forecast model. Furthermore, it is assumed that there is a (good) forecast for the intermittent generation and load demand. Accordingly, the optimisation problem related to this paper is given by:

$$\min f = \sum_{t=1}^{ND} \left\{ \sum_{e=1}^E [CUB_{et} + \delta_e \cdot dpbd_{et}] + [BP_t \cdot pgb_t - SP_t \cdot pgs_t + CD \cdot pde_t + CE \cdot pex_t] \right\} \cdot H / ND \quad (21)$$

$$\text{s.t.:} \quad \sum_{e=1}^E (pbd_{et} - pbc_{et}) + pgb_t - pgs_t + pde_t - pex_t = D_t - PV_t - PW_t, \quad (22)$$

$$-\sum_{e=1}^E rb_{et} - pde_t \leq -D_t + PV_t + PW_t - ED \cdot D_t - EPV \cdot PV_t - EPW \cdot PW_t, \quad (23)$$

$$PGB_t^{\min} \leq pgb_t \leq PGB_t^{\max}, \quad PGS_t^{\min} \leq pgs_t \leq PGS_t^{\max}, \quad (24)$$

$$pgb_t - ug_t \cdot PGB_t^{\max} \leq 0, \quad ug_t \cdot PGS_t^{\max} + pgs_t \leq PGS_t^{\max}, \quad ug_t \in \{0,1\} \quad (25)$$

Battery constraints (4)-(12), (18)-(20).

The objective function (21) is composed by the batteries costs, grid costs and profits associated with grid energy transactions and the artificial variables for deficit and excessive power generation. The customer electricity cost is given by the difference between the revenue associated with exported energy and the cost of imported energy by the MG. Depending on the regulatory framework, it is necessary to replace prices by tariffs in (21). The deficit and the excess generation, in each step t , are modelled as [5].

Equation (22) is the energy balance constraints and (23) is the MG reserve requirements. Notice in (23) that the batteries reserves have to supply the load demand plus the forecasted errors, because it is the only controllable DER online for ND time steps to the backup generator start the operation. If the batteries reserve is not enough to supply the reserve requirements, the deficit will be different than zero. In this case, it is possible to check the cost impact and, depend on the probability to lose the main grid at that time, discount this cost from the final result. The li-ion battery has the possibility to supply instantly more power than the capacity which is stipulate in this modelling, although when this happen, the battery life will decrease more than the normal operation [18]. A rule was applied on (7): if the time step is bigger than the time to the reserve, the reserve rb_e will be multiplied by the time relation. The main difference of these equations to the actual literature is (23).

Equation (24) represent the limits of energy transactions with the grid, where is considered a limit amount of minimum and maximum power to each time step, while (25) prevent the import and export energy with the grid in the same step t .

The formulation considers a connected operation with the main grid, if the values of $PGB(S)_t^{\min(\max)}$ are set to zero and the costs and constraints associated with the back-up generation are included, the optimisation problem then represents an island operation of the MG.

5. Computational Experiments

To present the numerical experiments, we use a MG with batteries, and wind and photovoltaic generators supplying a load demand, considering a back-up generator. The MG is presented in Fig. 3.

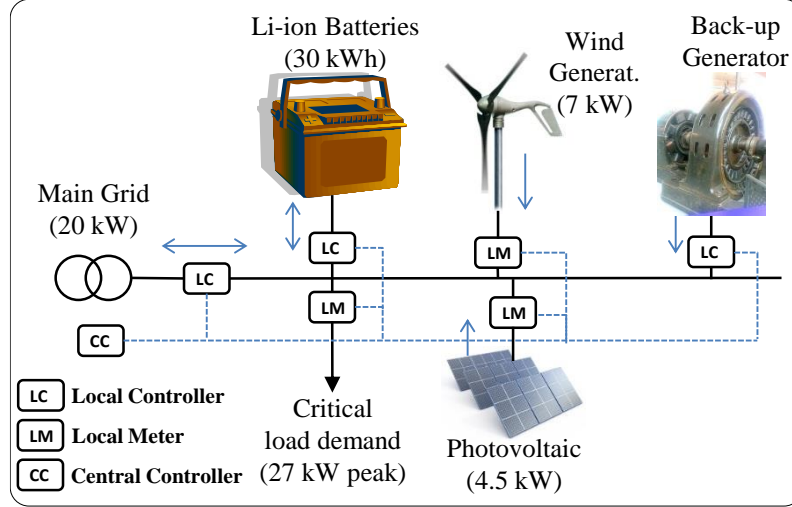


Fig. 3. MG schematic configuration

The MG central controller (energy manager) is responsible for the EM, sending control signals to the DERs through the local controllers and receiving information through the local controller and the local meters. The telecommunication infrastructure is considered reliable and represented by the dotted line in Fig. 3.

5.1. Input data

The planning horizon H is 24 hours, discretised in 1-minute time steps (therefore, $ND = 1440$). Due to intermittent generation in the EM, it might be necessary discretize the planning horizon in steps of few minutes [21]. The cases consider 1 minute step time, except when indicated, although with a generic modelling with a possibility to face others discretizations.

The acquisition price of the li-ion battery is consider 400 € (kWh)^{-1} . Others important data related to the li-ion battery are presented in Table 1.

Table 1 Lithium-ion battery parameters

AB	BB	CB	DB	EB^{max}	EB^{min}	EBI	EBF	PBL	FB	GB	HB	SPC	δ	η_{bc}	η_{bd}
0.37	0.42	18	30	30	3	11.1	11.1	0	0	6×10^{-3}	6.5×10^{-3}	6×10^{-3}	1×10^{-4}	0.93	0.96

Fig. 4a shows the forecast values of load demand and the renewable generation. Besides, the forecast energy prices (sell/purchase), is detailed in Fig. 4b.

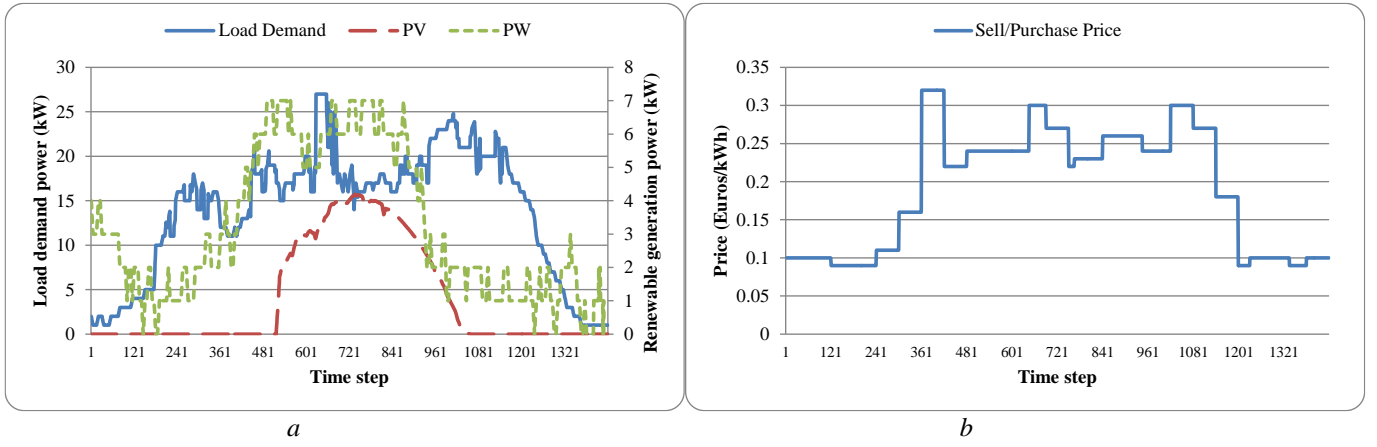


Fig. 4. Input data

a Load demand and renewable generation power

b Energy price input data

The maximum power grid interchange is 20 kW in all time steps, and the minimum is null. The deficit incremental cost (CD) is 10 € (kWh)⁻¹, and the excess generation incremental cost (CE) is 0.01 € (kWh)⁻¹. The forecast errors of the intermittent generation are 10% for the wind and solar and 5% for the demand. The time to reserve to the generator start-up (RB) is 10 minutes.

5.2. Computational Results and Analyses

The computational model is implemented in MATLAB 2011b, and the tests were executed on an Intel quadcore i7 2.80 GHz CPU. The solver Gurobi 6.0.0 is used to solve the optimisation modelling with the standard input parameters.

The results are categorized into eleven cases:

- (i) base, which is related with the data presented previously with a quadratic cost (1) and the incremental cost (18), with all the constraints presented at section 3.2, except (13-17);
- (ii) without the battery costs, right side of (8) and (18-20);
- (iii) without the battery costs, therefore with the constraints as base case;
- (iv) incremental cost of 1500 cycles at the discharge, with the constraints as base case;
- (v) incremental cost of 3000 cycles at the discharge, with the constraints as base case;
- (vi) cost based on the piecewise linearization from (1), with 5 linear equations to the energy deviation costs and 2 linear equations to the battery charge costs;
- (vii) cost based on the piecewise linearization from (1), with 20 linear equations to the energy deviation costs and 8 linear equations to the battery charge costs;

- (viii) cost based on the piecewise linearization from (1), with 50 linear equations to the energy deviation costs and 20 linear equations to the battery charge costs;
- (ix) same as base case, although with 144 time steps discretization;
- (x) same as base case, although with 48 time steps discretization;
- (xi) same as case (ix), although the charge control will be just with a switch, without controlling the power of the charge, including (13-17) at the modelling.

After several tests, these eleven cases were carefully selected to obtain the results for this paper. The case (i) considers the real degradation costs and the new proposed constraints due to physical characteristics of the lithium-ion batteries. Case (ii) is the general modelling to batteries, without costs or the physical characteristics, while case (iii) just does not consider the costs, although is more realistic considering the physical peculiarities for the lithium-ion battery as constraints. Cases (iv) and (v) consider an incremental cost instead of the real degradation cost, proportional the number of cycles given by manufactures. Cases (vi), (vii) and (viii) are to show the case base with a piecewise linearization for nonlinear costs with different approximations. Cases (ix) and (x) are to investigate the effects of different numbers of time steps discretization within a 24-hour planning horizon. Lastly, case (xi) presents the results when it is not possible to control the power to the battery charge.

Results for the EM case (i) are presented in the Fig. 5.

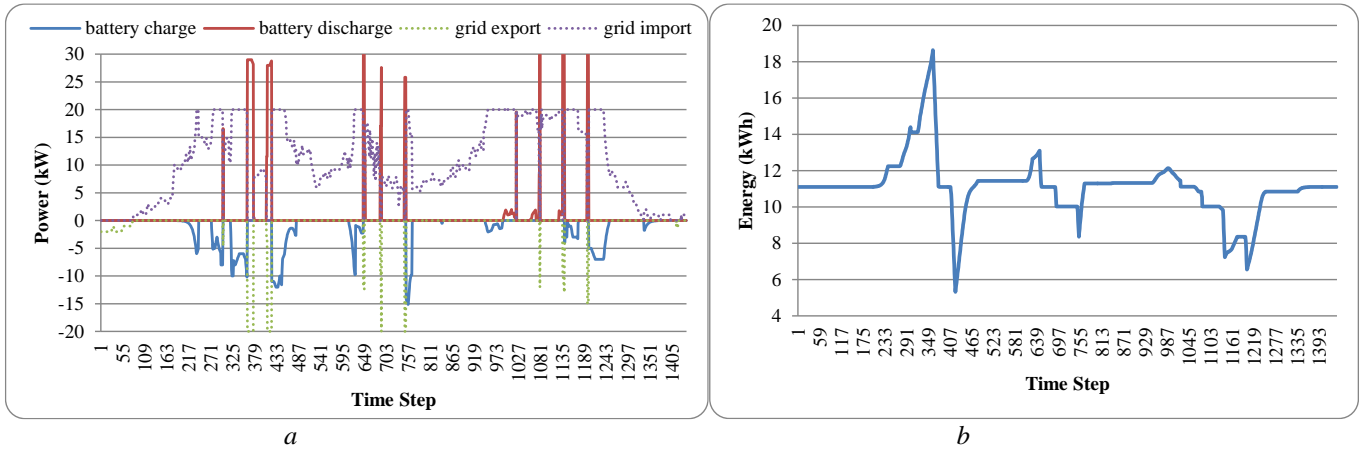


Fig. 5. Case (i) MG EM and li-ion battery energy
a MG EM
b Li-ion battery energy

Continuous line for the MG EM in Fig. 5 until Fig. 8 presents the battery charge and discharge, with the positives values for discharge power and negatives for charge, while the dotted line are the grid power export and import, with negatives values to export and positive values to import.

Fig. 5a presents the MG EM to the case (i), which is the base case, with the power of the li-ion battery and the grid. The battery discharge occurs mostly when the price to import energy is high, as presented in Fig. 4b, or when the maximum power imported from the grid is not enough to supply the liquid load demand (demand minus the renewable generation), which happens three times between the times steps 990 and 1140. The charge occurs near the discharge, when the price is low, preventing the energy been distant from the set point energy, as presented on Fig. 5a and 5b. Lower the charge rate, better to the li-ion battery life expectancy, been less costly and having a better solution to the optimisation problem.

The EM cost without the li-ion battery is 60.99 €, considering the deficit incremental cost when the maximum possible import power from the grid is not enough to supply the liquid load demand. The objective function result from the EM to case (i) is 48.77 €, as presented at Table 2, which represent 20.03 % less. The degradation cost from the li-ion battery is 1.07 € as presented besides at Table 2.

The results for the EM to cases (ii) and (iii) are presented in the Fig. 6.

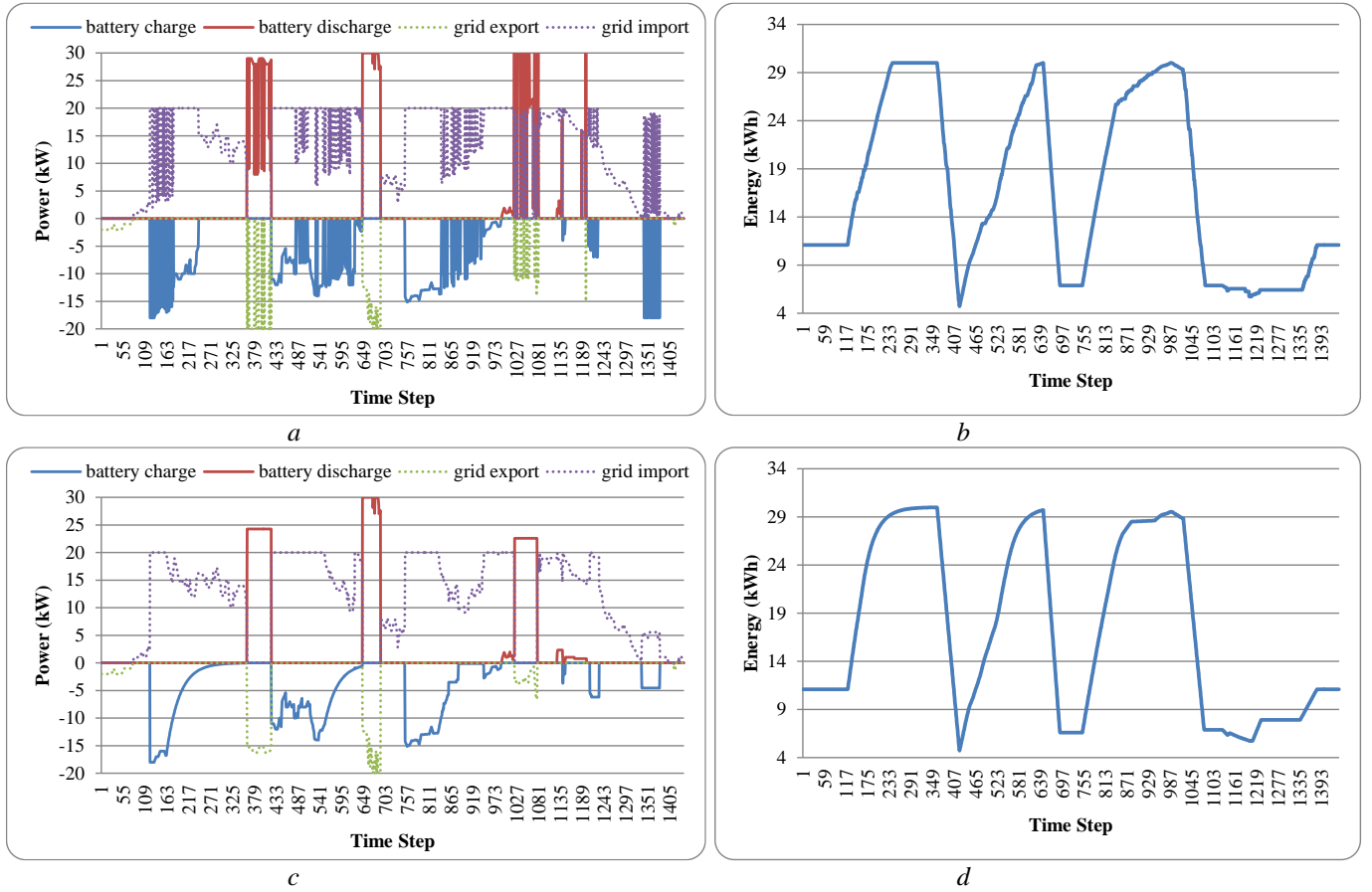


Fig. 6. Case (ii) and (iii) MG EM and li-ion battery energy

a MG EM case (ii)

b case (ii) li-ion battery energy

c MG EM case (iii) li-ion battery energy

d case (iii) li-ion battery energy

In case (ii), because there are no constraints related to maximum charge ramp after certain energy, to pulsing discharge and any degradation cost, the EM solution is very different from the case (i), as shown in Fig. 6a. The result shows the great use of the battery, with 3 full cycles as presented at Fig. 6b, just respecting the maximum and minimum charge (without the characteristic from Fig. 2), discharge and energy, as well the reserve requirements. The EM related to the case (iii) differs from the case (ii) due to the inclusion of the constraints to the model, as shown in Fig. 6c. The discharge and charge characteristics are evidentially different, with the same number of cycles as show at Fig. 6d. The objective function for the cases (ii) and (iii) are 43.35 € and 43.40 €, respectively. These values are not real, as the degradation cost presented at Table 2 of 39.45 € and 41.91 € are not considered. To be more realistic these values should be added to the objective function.

The results for the EM to cases (iv) and (v) are presented at the Fig. 7.

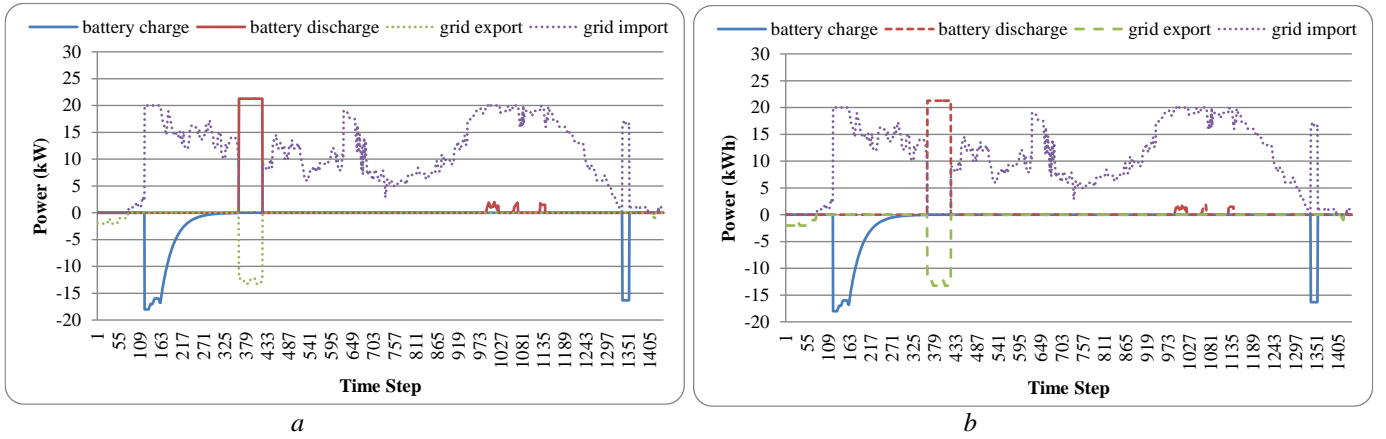


Fig. 7. Case (iv) and (v) MG EM

a MG EM case (iv)

b MG EM case (v)

Due to the high incremental cost due to the li-ion battery use, the EM to case (iv) mostly do not use the battery, just when the power import from the grid to supply the load is not enough, as shown at Fig. 7a. The case (v) has half of the incremental cost; then, the economic use also charge the battery when the grid price is low (from time step 121 until 360) and discharge when the price is high (from time step 361 until 420). This use reduces the EM from 50.27 € to 48.31 €; moreover, this price difference does not consider the real degradation cost. If the degradation cost was considered, the EM to case (iv) is better to the microgrid costs than the EM to case (v).

The EM cases (vi), (vii) and (viii) use the piecewise linearization to approximate the degradation costs and are similar to case (i), with a slight difference in dispatch and the objective function values, as presented in Table 2. These differences could be greater depending on the battery usage (e.g. maximum of

6 € to the energy degradation cost as presented at Fig. 1 to $H = 24$ with 5 linear equations). The difference in the computational time is also something to take into account. The accuracy of the linear approximation depends on the number of break points. More break points better the accuracy of the linear approximation, therefore adding an abundance of break points induces to a significant increase in the computational burden [22].

Fig. 8 presents the EM associated with cases (ix) and (x) considering number of time steps $ND = 144$ and $ND = 48$.

Comparing cases (ix) and (x) with case (i), it is possible to visualize the same behaviour of the EM, although with less precision. In the case (ix) the number of time steps is the same as the amount of time necessary to the reserve requirement. As consequence of the reserve requirement, case (ix) has a better analysis than case (x), which lacks precision at this point. The dispatch peaks and the intermittent characteristics also are not at the same level with a greater discretization, which could result as power trade limit problems with the main grid.

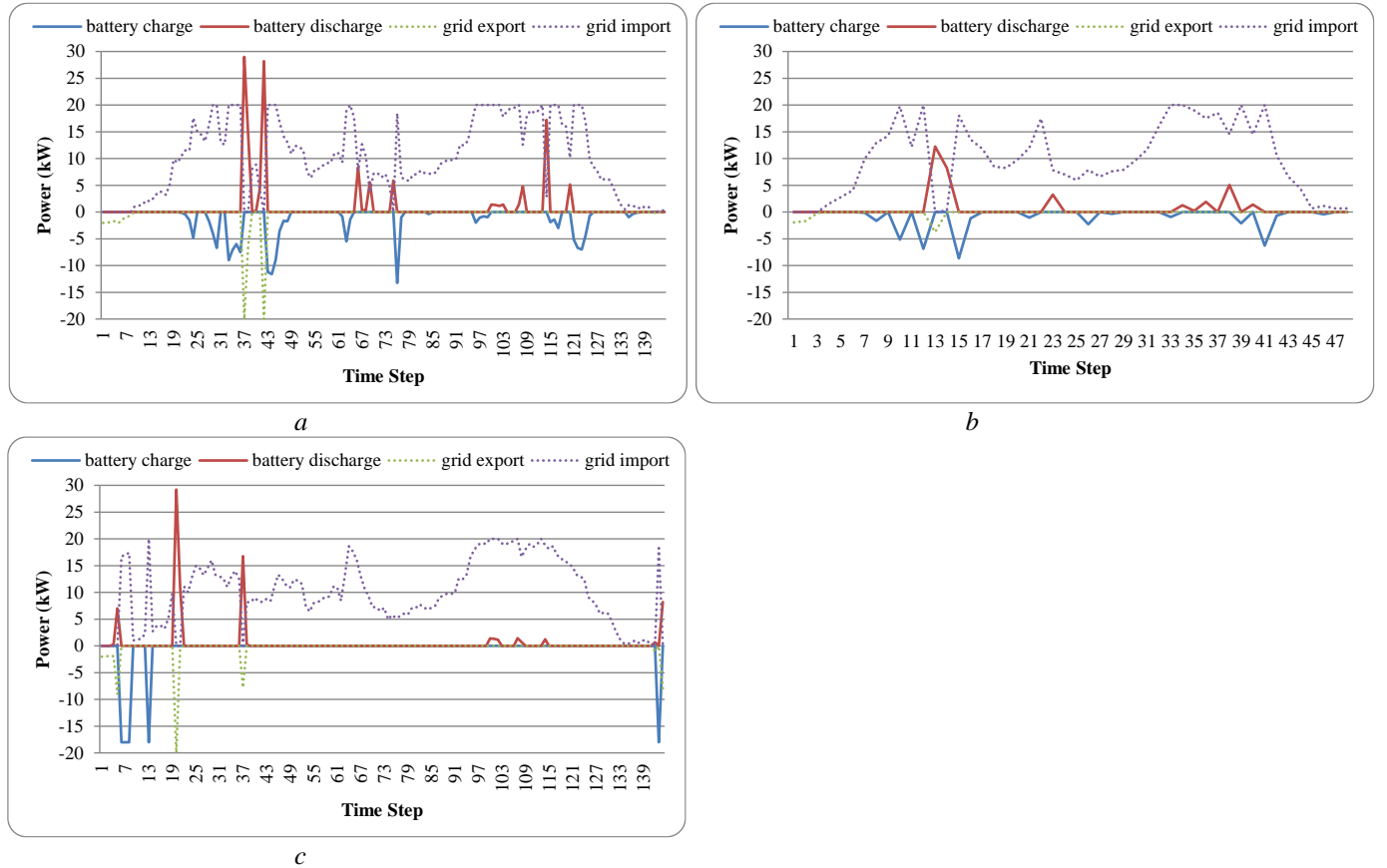


Fig. 8. Case (ix), (x) and (xi) MG EM

- a MG EM case (ix)
- b MG EM case (x)
- c MG EM case (xi)

Case (xi) is used to present the EM results when the charge power is not possible to control, as shown in Fig. 8c. The EM with 1440 time steps is not possible to be achieved within 60 s due to increase of the binary variables and the new constraints; then, it is used a discretization of 144 time steps. The charge occurred 5 times, in the time steps 6-8, 13, and 143 with the stipulated power CB , respecting (13)-(17).

Table 2 summarizes the cases, the problem size and the results from the MG EM problem.

Table 2 Cases and results

Case	Battery costs	New constr.	Time steps	Variables ^e (c) cont. (b) binary	Constr. ^e	Objective function (€)	Degrad. cost (€)	Comput. time (s)
(i)	Quadratic	yes	1440	12858 (c) 2,880 (b)	18,466	48.77	1.07 ^f	6.43
(ii)	without	no	1440	9,932 (c) 2,880 (b)	11,277	43.35	39.45	0.46
(iii)	without	yes	1440	12,819 (c) 2,880 (b)	18,427	43.40	41.91	1.01
(iv)	1500 cycles	yes	1440	12,819 (c) 2,880 (b)	18,427	50.27	0.10	0.63
(v)	3000 cycles	yes	1440	12,819 (c) 2,880 (b)	18,427	48.31	19.56	0.73
(vi)	piecewise linearization ^a	yes	1440	15729 (c) 2,880 (b)	28,393	49.51	1.28 ^f	1.28
(vii)	piecewise linearization ^b	yes	1440	15733 (c) 2,880 (b)	55,145	48.89	1.12 ^f	3.14
(viii)	piecewise linearization ^c	yes	1440	15735 (c) 2,880 (b)	108,805	48.78	1.06 ^f	5.47
(ix)	Quadratic	yes	144	1282 (c) 288 (b)	1,840	48.84	1.07 ^f	0.08
(x)	Quadratic	yes	48	426 (c) 96 (b)	613	49.19	0.99 ^f	0.02
(xi)	Quadratic	yes ^d	144	1133 (c) 576 (b)	2,396	52.43	2.91 ^f	1.61

^a with 5 linear equations to the energy and 2 linear equations to the battery charge

^b with 20 linear equations to the energy and 8 linear equations to the battery charge

^c with 50 linear equations to the energy and 20 linear equations to the battery charge

^d with the charge control just with a switch, without controlling the power of the charge

^e constraints and variables after the pre-solve from the solver

^f these costs are considered in the objective function.

Regarding the computational performance the case (i), with the quadratic cost and the new constraints, has the biggest computational time to solve the problem, as presented in Table 2. Case (viii) even with a detailed approximation of the objective function with the biggest number of constraints has a better performance than case (i). The case (xi) where is not possible to control the power of charge has not reached convergence by the minimum tolerance for 1440 time steps, then, it was performed with 144 time steps, mostly due to the modelling approach to equalize the lower and upper limit of power charge. In this sense, it has a lower performance if compared to case (ix) which is the same, although with the possibility to control the power to charge.

6. Conclusion

The proposed equations and approaches to modelling the peculiarities for the lithium-ion batteries were successfully implemented and tested. The main conclusions associated with the different li-ion battery costs modelling approaches can be summarized as follows: it is necessary to include real degradation cost, as presented in case (i), or with good approximation, as it was performed with the piecewise linearization in cases (vi), (vii) and (viii); the use of the li-ion battery without considering any costs or using an incremental cost based on the number of cycles gives a low quality EM solution, with high degradation costs as presented in cases (ii), (iii) and (v), or without the use as case (iv). In addition, the main conclusion regarding charge and discharge characteristics are: controlling the power and the period of the charge is better than just controlling when the charge occurs, as the comparison between cases (ix) and (xi); it is necessary to model the behaviour of the charge if the battery could be charged more than a specific SOC; the inclusion of the constraints to lessen the pulse discharging, even using a small incremental cost near the algorithm convergence tolerance, without a clear equation of the degradation, gives a better performance to the solution. Both last previous conclusions could be made comparing cases (ii) and (iii), even without a proper use of the degradation cost, with and without the constraints. Finally, another conclusion is that the greater number of time steps in the planning horizon better is the solution, as presented comparing cases (i), (xi) and (xii). In this sense, the number of time steps should be the one which could take into account the important dynamics of the DERs, such as the reserve of 10 min. The presented modelling could also be used to the planning and sizing problems of microgrids. This contribution gives a few preliminary insights and might point toward others issues to the li-ion battery modelling as the efficiency, charge and discharge nonlinearities, as well as the temperature influence where it is not negligible (e.g. electric vehicles).

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