A techno-economic analysis of Li-ion battery energy storage systems in support of PV distributed generation

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Abstract: Energy storage systems (ESS) have recently been subject of a widespread interest among the energy market. This great relevance is due to the opportunity of ESS to overcome or, at least, mitigate the drawbacks caused by the intermittency and uncertainty of renewable energy sources (RES), that are posing relevant challenges to the operation and management of electrical power grids. In this context, ESS could also play a key role in increasing the host capacity of RES, the reliability of electricity distribution systems and the share of self-consumption of distributed energy resources (DER). Among the different ESS technologies, the lithium ion (Li-ion) is considered one of the most promising, thanks to its favorable characteristics in terms of energy conversion efficiency, energy and power density and lifetime. However, nowadays Li-ion batteries have high investment costs and their economic feasibility is still uncertain. The aim of this work is to assess the economic feasibility of the application of Li-ion batteries in support of distributed generation (DG), by evaluating the total cost of ownership (TCO) under different scenarios. The proposed method has been applied to a real-world application, performing a sensitivity analysis of the numerical results in order to evaluate the effects of the variability in the parameters.

Keywords: Energy storage system, batteries, lithium-ion, total cost of ownership, life cycle cost.

1. Introduction

In recent years, the attention of the energy market operators has been highly focused on energy storage systems (ESS). This increasing interest is due to the opportunity of ESS to overcome or, at least, mitigate the effects of the intermittency and non-programmability of renewable energy sources (RES), that are causing relevant problems to the power system operations and control. In this context, ESS could also play a key role in increasing the host capacity of renewable energy sources (RES), the reliability of electricity distribution systems and the share of self-consumption of distributed energy resources (DER), thus providing a relevant contribution in achieving the energy targets imposed to the European members by 2020 and 2050. Furthermore, the application of ESS in support of distributed generation (DG) from RES could allow the increase of revenues from those power plants which are characterized by missing or decreasing feed in tariffs, thanks to the increase of their self-consumption.

Among the different energy storage technologies, battery energy storage systems (BESS), that is those systems that store energy in the form of electrochemical energy, are widely used for the support of distributed generation and have been applied in many different installations (Office of Electricity Delivery & Energy Reliability, 2016), from small to medium size applications (from few kWh to several MWh). Many different BESS technologies are currently used or still under development; among these, the lithium ion (Li-ion) is considered one of the most promising, thanks to its favourable characteristics in terms of energy conversion efficiency, energy and power density and lifetime (Cho et al., 2015).

Even if in the recent years the price of the Li-ion batteries dropped significantly, the capital cost of the batteries and the uncertainty in costs for their operation and maintenance still represent a possible obstacle of BESS adoption rising.

Some economic models for the optimal design of BESS, with different setting, different assumption and different parameters modelling, have been recently presented by several authors (Bortolini et al., 2014; Bradbury et al., 2014; Fares and Webber, 2014; Zanoni and Marchi, 2014). Moreover, a life cycle cost (LCC) methods to evaluate the profitability of BESS, taking into account all the expenses that the ownership has to bear during the system lifetime (e.g. operation and maintenance costs, replacement costs, etc…) has been proposed by (Zakeri and Syri, 2015).

However, to the best of the authors knowledge, all these works proposed general models and the economic analyses of BESS investment did not encompass all the relevant aspects (such as charge and discharge efficiency of batteries or efficiency of the power conversion system, the self-discharge of the storage system, the influence of depth of discharge on the lifetime of the batteries).

The main aim of this work is to present an holistic economic model for the total cost of ownership of BESS. A case study with the real-world application of the model have been performed and related sensitivity analyses have been executed in order to evaluate the effects of the input parameters change.

2. Energy balance and BESS modelling

In the following, the methods and models adopted for the computation of the energy balance of a DG and BESS combined system are briefly described. The model considers the case where a generic DG system and the user’s loads are both connected to the grid at the same point of delivery. In this case, storage systems are typically used to increase the share of self-consumption of the DG system, by storing the excess of energy produced and, afterwards, release it when the power demand of the loads
is higher than the DG production. The method used to compute the energy flows from and to the BESS and its state of charge (SOC) is based on a discrete-time model, whose finite-state machine is depicted in Fig. 1.

![Finite-state machine used for the computation of the power flows of the BESS and of its state of charge (SOC).](image)

For each time period $t$ of duration $\tau$, the power flows (considered as constant during each period) and the SOC of the BESS at the end of the period are computed taking into account the following variables and parameters: the difference from the DG power output and the loads' demand, the nominal power of the BESS, the maximum available charge and discharge power of the BESS (considered as function of the SOC), the efficiency of the BESS power conversion system (PCS), the charge and discharge conversion efficiencies of the batteries and the self-discharge rate (SDR) of the system.

The main notations used throughout the document are given in the following table.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{max}}$</td>
<td>maximum BESS nominal power [kWp];</td>
</tr>
<tr>
<td>$E_r$</td>
<td>energy rate of the storage system [kWp/kWh];</td>
</tr>
<tr>
<td>$E_{TS,j}$</td>
<td>amount of energy produced by the DG system, measured after the DC/AC conversion stage, and stored into the BESS during the time period $t$ [kWh];</td>
</tr>
<tr>
<td>$P_{TS,j}$</td>
<td>charge power of the batteries, measured before the AC/DC conversion stage, during the time period $t$ [kW];</td>
</tr>
<tr>
<td>$E_{TS,j}$</td>
<td>amount of energy released by the BESS, measured after the DC/AC conversion stage, during the time period $t$ [kWh];</td>
</tr>
<tr>
<td>$P_{TS,j}$</td>
<td>discharge power of the batteries, measured after the DC/AC conversion stage, during the time period $t$ [kW];</td>
</tr>
<tr>
<td>$P_{DG,j}$</td>
<td>power produced by the DG system, measured after the DC/AC conversion stage, during the time period $t$ [kW];</td>
</tr>
<tr>
<td>$P_{L,i}$</td>
<td>power demand of the loads during the time period $t$ [kW];</td>
</tr>
<tr>
<td>$\eta_b$</td>
<td>nominal charge and discharge efficiency of the batteries;</td>
</tr>
<tr>
<td>$\eta_{PCS}$</td>
<td>nominal efficiency of the BESS power conversion system;</td>
</tr>
<tr>
<td>$SDR$</td>
<td>self-discharge rate of the ESS [%/hour];</td>
</tr>
<tr>
<td>$SOC_i$</td>
<td>state of charge of the storage system at the beginning of the time period $t$ [%];</td>
</tr>
<tr>
<td>$DOD$</td>
<td>Maximum allowed depth of discharge of the system [%];</td>
</tr>
<tr>
<td>$\tau$</td>
<td>duration of each time period [hours];</td>
</tr>
</tbody>
</table>

The nominal power of the storage system ($P_{\text{BESS}}$) can be evaluated taking into account the maximum power allowed by the whole battery pack (as function of the storage size, $S$) and the maximum nominal power of the storage system:

$$P_{\text{BESS}} = \min\{E_r \cdot S, P_{\text{max}}\}$$

(1)

Usually the maximum charge and discharge power of Lion batteries is strictly correlated to their nominal capacity by means of a typical parameter $E_r$, that represents the ratio between their nominal power and the storage capacity. However, in some cases, the required storage size for the specific application would lead to a nominal battery power that could exceed the nominal power of both the DG system and loads, thus implying unnecessary gains in the investment costs of the BESS power conversion system.

The charge power and the amount of energy stored into the BESS during the time period $t_i$ along with the value of its SOC, can be computed as follows:

$$E_{TS,i} = P_{TS,i} \cdot \tau$$

(2)

$$P_{TS,i} = \min\left\{ \frac{P_{TS,i} - P_{DG,i} \cdot \eta_{PCS} \cdot \tau}{\eta_s \cdot \eta_{PCS} \cdot \tau} \right\}$$

(3)

$$SOC_{i+1} = SOC_i + \frac{P_{TS,i} \cdot \eta_s \cdot \eta_{PCS} \cdot \tau}{S}$$

(4)

Similarly, the discharge power and the amount of energy released by the BESS during the time period $t_i$ and the value of its SOC at the end of the same period, can be computed using of the following equations:

$$E_{TS,i} = P_{TS,i} \cdot \tau$$

(5)

$$P_{TS,i} = \min\left\{ \frac{\min\{P_{TS,i} - P_{DG,i} \cdot \eta_{PCS} \cdot \tau\}}{\eta_s \cdot \eta_{PCS} \cdot \tau} \right\}$$

(6)

$$SOC_{i+1} = SOC_i - \frac{P_{TS,i} \cdot \tau}{\eta_s \cdot \eta_{PCS} \cdot \tau}$$

(7)

Finally, during idle times, the SOC can be computed taking into account the self-discharge effect over time:

$$SOC_{i+1} = \max\{0, SOC_i - SDR \cdot \tau\}$$

(8)

3. Total cost of ownership

In order to evaluate the economic feasibility of a storage system, the total costs for the installation, operation and maintenance over its entire lifetime should be considered. According to the international standard IEC 60300-3-3 (International Electrotechnical Commission (IEC), 2004), the lifecycle of a product should consist of the following
six cost-causing phases: (a) concept and definition, (b) design and development, (c) manufacturing, (d) installation, (e) operation and maintenance and (f) disposal. These different cost components can also be grouped into more aggregated categories: investment costs, I (concept definition, design, development, manufacturing and installation), ownership costs, O and M (operation and maintenance) and recycling or disposal costs. However, for the specific case study, disposal costs are not taken into account since they are not of users’ competence. Consequently, the TCO becomes:

\[
TCO = I + \frac{\sum Q_k + M}{(1 + \rho)^n} \tag{9}
\]

where the subscript \( k \) [year] represents the single unit period among the overall period of time, \( n \) [years] the lifetime of the device or system and \( \rho \) the annual discount rate.

### 3.1. Investment costs

The investment cost, \( I \), consists of three components (Sandia National Laboratories, 2003), as defined in eq. 10: the power conversion system (PCS) cost, function of the BESS nominal power \((P_{\text{BESS}})\), the cost related to the energy storage capacity \((S)\) and the balance of plant (BoP) cost, that includes all the costs related to auxiliary controllers, design, installation and grid connection (considered as function of \( P_{\text{BESS}})\).

\[
I = c_{\text{PCS}} \cdot P_{\text{BESS}} + c_s \cdot S + c_{\text{BoP}} \cdot P_{\text{BESS}} \tag{10}
\]

### 3.2. Ownership costs

The ownership costs are represented by all the costs and revenues that occur during the entire lifetime of the ESS. Storage systems allow to increase the share of self-consumption of the DG system by storing the excess of energy produced during a time period (typically a day), and then releasing it when the power from the DG is lower than loads’ power demand (the so called time-shift function). In grid-tied power plants without ESS, when the energy production is larger than the loads’ demand, the electricity is sold back to the grid at the corresponding feed-in tariff \((p_{\text{fE}})\). Consequently, the integration of a storage device in a DG system generates costs due to the loss of sales, since the energy stored into the device is not sold to the grid, and revenues due to lower energy consumptions (purchased at price \( p_{\text{mp}} \)) and, possibly, to feed-in tariff premiums \((p_{\text{pp}})\) for the increase of energy self-consumption. As a consequence, the operation costs \( O_k \) can be expressed as follows:

\[
O_k = \sum_{i=1}^{m} [P_{\text{fE}} \cdot E_{\text{fE},i} - (P_{\text{fE}} + P_{\text{pp}}) \cdot E_{\text{fE},i}] \tag{11}
\]

where \( m \) represents the number time periods \( t \) in each \( k \)-th period. Maintenance costs \((M_k)\) include the periodic planned maintenance costs \((M_{\text{p}})\) and the variable unscheduled maintenance costs \((M_{\text{v},k})\), such as repair or replacement of failed or damaged battery packs. The variable maintenance cost (described by eq. 12) is function of the probability of failure \( f_j \) which may be due to several issues and can be categorized into three different failure modes (McDowall, 2007):

- Infant mortalities, defined through a Weibull distribution, with parameters \( x \) and \( \beta \);
- Random faults, caused by other latent defects. These failures are more difficult to characterize and tend to be random in nature; thus, they can be described by a uniform distribution with parameter \( \delta \);
- Wear-out failures, related to the gradual deterioration due to the aging of the batteries’ cells. The distribution which best fits this phenomenon is the exponential distribution, with parameter \( \gamma \).

\[
M_{r,k} = f_{\text{PCS},k} \cdot c_{\text{PCS}} \cdot P_{\text{BESS}} + f_{\text{BESS},k} \cdot c_s \cdot S \tag{12}
\]

The global failure rate distribution for the storage device is given by the sum of the three distributions defined above, which gives the characteristic “bathtub curve”, typical for electronic components (McDowall, 2007).

### 4. Numerical study

#### 4.1 Input data and model parameters

The methods and models described in section 2 and 3 have been applied to a real-world application, represented by a small manufacturing firm in Brescia, Italy, with a PV power plant of 112 kWp and an annual energy consumption of about 120 MWh (nearly equal to the annual expected PV production, according to the typical design specification of PV power plants). Data of both the PV’ power output and loads’ power consumption have been recorded over a time period of one year with a time resolution of 10 minutes. An example of the time series of data, referred to July the 1st 2015, is depicted in Fig. 2.

![Fig. 2: Sample data of the PV production and loads’ consumption of the test case considered in the numerical study. Shown data represent the average power values (in alternating current) recorded during July the 1st 2015, with a time resolution of 10 minutes.

The numerical study has been performed by applying the energy and economic models over a time horizon of 10 years, corresponding to the expected useful file of Li-ion batteries (as reported by (Cho et al., 2015)), varying the overall storage capacity \( S \). The aging of the PV modules over the given time horizon has been taken into account by decreasing the PV power output by a rate of 1%/year. The complete list of parameters used for the simulation are reported in Table 2 and Table 3.
4.2 Results and discussion

The results of the overall energy balance for different storage sizes (S) are shown in Fig. 3, while an example of the system’s behavior with a storage capacity of 120 kWh and a BESS nominal power of 100 kWp is depicted in Fig. 5. As shown by the results of Fig. 3, the installation of a storage system would lead to a relevant increase of the share of self-consumption of the PV plant, up to twice the values achieved without storage.

For what concerns the economic analysis, it has been performed considering four different combinations (in the following referred as scenarios) of subsidies and feed-in tariffs, with reference to the Italian regulation system and energy market prices. A summary of the scenarios considered in the simulation is reported in Table 4.

Scenario 1 represents the case of a new PV power plant, without economic subsidies for the produced or self-consumed energy, while scenario 2 is representative of an existing PV plant which can benefit from the last Italian subsidy scheme (“V Conto Energia”). Scenarios 3 and 4 are based on Scenario 1 assuming, respectively, a 30% and 50% subsidy scheme for the total investment costs (I), as recently proposed by the German government (Scenario 3) and by the Italian Lombardy region (Scenario 4).

For each scenario, a sensitivity analysis has been carried out by assuming two different price reduction of the specific cost of the storage capacity (50% and 80%, respectively). This approach is based on the assumption that, in the near future, the market price of Li-ion batteries could show relevant price decline, similarly to what happened in the PV market, where the price of PV modules decreased by the 80% between 2008 and 2013. The TCO with current specific storage prices is shown in Fig. 4, while Fig. 6 and Fig. 7 show the TCO results assuming, respectively, a 50% and 80% price reduction.

Table 2: BESS and TCO model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{max}$</td>
<td>100 kWp</td>
<td>$\rho$</td>
<td>0.04</td>
</tr>
<tr>
<td>$Er$</td>
<td>1 kWp/kWh</td>
<td>n</td>
<td>10 years</td>
</tr>
<tr>
<td>$\eta_{BESS}$</td>
<td>0.96</td>
<td>$c_s$</td>
<td>600 €/kWh</td>
</tr>
<tr>
<td>$\eta_{PCS}$</td>
<td>0.94</td>
<td>$c_{PCS}$</td>
<td>250 €/kWh</td>
</tr>
<tr>
<td>SDR</td>
<td>5%/day</td>
<td>$c_{SP}$</td>
<td>80 €/kWh</td>
</tr>
<tr>
<td>DOD</td>
<td>90%</td>
<td>$M_t$</td>
<td>50 €/year</td>
</tr>
</tbody>
</table>

Table 3: Probability of failure parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.12</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>$\delta$</td>
<td>2·10⁻³</td>
<td>1·10⁻³</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>2·10⁻⁷</td>
<td>1·10⁻⁴</td>
<td></td>
</tr>
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</table>

Fig. 3: Overall energy balance of the system for increasing values of storage capacity S.

Fig. 4: Economic results for the different scenarios assuming the current specific cost of the storage capacity.

Fig. 5: Example of energy balance results between the 1st and 21st of June for a storage system of 120 kWh and 100 kWp.
feasibility could be achieved only by means of a 50% price reduction of the storage capacity specific cost.

schemes, ion technology cannot be considered economically feasible. In conclusion, we believe that, even if representing one of the most promising technology for the support of the penetration of RES, Li-ion batteries are still economically unprofitable, being their initial investment costs a relevant obstacle in the diffusion at industrial and users level.

Moreover, the expectation of even high price reductions of the specific storage capacity costs seems to be not sufficient to allow the economic profitability of storage systems. In fact, only in the case of a joint 80% price reduction and a 50% subsidy for the total investments, the economic analysis leads to positive (even though not that striking) results, with a minimum TCO value of -2.7 k€ after 10 years.

5. Conclusions

In this work we presented a techno-economic model for the assessment of a Li-ion battery energy storage system supporting distributed generation. The proposed model has been applied to a real-world application, performing a numerical sensitivity analysis in order to evaluate the effects of the variability in the parameters on the Total Cost of Ownership.

The results show that with the present parameters the Li-ion technology cannot be considered economically feasible, even with the support of the existing subsidy schemes observed in some regions (i.e. Germany or Lombardy Italian region). In addition, we noted that, even in the case of relevant price reductions (up to 80% less than the current prices), the installation of Li-ion storage systems still wouldn't be profitable, and that its economic feasibility could be achieved only by means of a combination of subsidies from local governments and of high price reductions.

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References


