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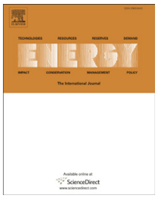

Maximum income resulting from energy arbitrage by battery systems subject to cycle aging and price uncertainty from a dynamic programming perspective☆

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ABSTRACT

This paper describes an approach to compute the maximum value of energy storage systems (ESS) in grid applications under uncertain energy prices. The value obtained is based on an optimal operation (consisting of charge/discharge sequences) of the ESS. In other words, it is the maximum value that may be obtained when the ESS charge/discharge sequence is adapted to the expected operational conditions.

To obtain that optimal value, this paper describes a dynamic program approach, with the particularity that the switching decisions are optimized considering an uncertain price evolution and a dynamic calculation of the aging cost. A practical implementation of this approach is proposed, in which the problem is conveniently sliced into matrices corresponding to single decisions. It is shown that such an arrangement, combined with shift and re-indexing operators, provides a fast solution to the optimization problem consisting of a huge number of decision evaluations. The algorithm is then applied to a number of European electricity markets, with a particular focus on arbitrage. The particularities of the algorithm solutions are analyzed, and it is shown that not considering the imperfect foresight and the aging impacts leads to considerable errors in valuing an ESS.

1. Introduction

1.1. Motivation

In developing a perspective on the viability of energy storage systems (ESS) in grid applications, it is necessary to calculate a figure of their cost. In this line, Lazard has recently introduced the concept of levelized cost of storage (LCoS) in an attempt to assimilate ESS to other generation technologies that have been conventionally valued by means of the well-known levelized cost of energy (LCoE). At the time of writing this paper, Lazard has published its second report on LCoS, where it articulates a cost framework with similar implications to those of the LCoE [1]. The interpretation of the LCoS is as simple as for LCoE: it is the cost of generating one kWh. However, it is particularly stressed in Lazard's report that the LCoS is not as straightforwardly calculated as the LCoE, because it depends on one or several “revenue streams,” such as frequency regulation, demand response, arbitrage, etc.

Different operating (charge/discharge) policies responding to those revenue streams lead to notably different economic values [1,2]. The charge/discharge pattern affects the operating expenses included in the ESS value by affecting (i) the cost associated to the purchase of energy from the grid, instead of the cost of purchasing primary energy or fuel [3], (ii) the opportunity cost incurred by not selling generated energy in case that the ESS is associated to a distributed generator [4], and (iii) the replacement costs because of the different aging caused to the ESS through is activation. It also affects the revenues, because differently from generation technologies, in grid-connected ESS positive and negative cash-flow terms cannot generally occur at the same time.

Lazard's calculations rely on the classical components of the LCoE: CAPEX, OPEX, and incomes. But apparently Lazard's report does not include the cost of aging derived from different charge/discharge patterns into its calculations; though that cost would directly modify the CAPEX over the calculation period by means of the replacement cost. This omission is in striking conflict with the

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fact that the ESS life cycle can be appreciably altered by the way in which it operates. In energy arbitrage in spot markets, the ESS must follow an uncertain electricity price evolution [5]. In supporting distributed generation, the ESS additionally follows the stochastic evolution of generation and load [6]. Ultimately it is the grid application—the revenue stream—that defines the ESS idle times and cycling pattern, hence ultimately altering the value of the CAPEX. However, the aging issue is notably left out of many comparative economic analysis [7–10].

1.2. Literature review

Aging of a battery ESS (BESS) can be defined as the modification of its properties—essentially the available energy and power, and the mechanical integrity of cells—with time and use. Two types of aging mechanisms are usually differentiated: during use (on cycling) and on storage (idle). Cycling generally damages the reversibility of materials, whereas storage aging, due to the interactions between active materials and the electrolyte, depends mostly on time and temperature. Storing aging determines the "calendar life" of the cell. Both mechanisms are usually considered as additive, but they can also interact between them [11]. Particularly the cycle-life of batteries, of chief interest in the generation of revenue streams, is affected by the depth of discharge (DoD) and the state of charge (SoC), as well as the operating temperature and the BESS chemistry. For instance, the anodes of Li-ion batteries undergo mechanical strain during cycling at high C-rate and high SoC. This is due to the insertion and de-insertion of the lithium ions, which produces cracks and fissures, and splits the graphite particles, making them less oriented compared to the original platelets. Eventually, it is the nature and orientation of the graphite particles that influences the reversibility of the anode [12]. Also it has been found that overcharging in long-term cycling induces a cumulative damage on $LiCoO_2$ cathodes in rechargeable lithium batteries, producing severe strain, high defect densities, and occasional fracture of particles [13]. Cation disorder, microcracks of the $LiCoO_2$, particles in the cathode, and the increase in thickness of the passive film on the anode due to the reduction of the electrolyte have been linked to the capacity fade of the battery during cycling as well [14]. When the DoD is increased during cycling, also positive active mass degradation quickens [15] and provokes a non-linear loss of lithium mass [16]. On the whole, cycle aging as a function of the battery operating characteristics is a complex mechanism.

Notably, these electrochemical mechanisms are of difficult implementation in an algorithm devoted to finding the BESS value in grid applications. Necessarily these degradation mechanisms must be translated into mathematical models for efficient integration into an optimization program. Those models must calculate the inflicted damage as a function of the exogenous variables that drive the ESS in its interaction with the electrical system. The alternatives in the literature differ amply in their complexity. In some cases, the figure of degradation is directly approximated as a percentage of the annual use of ESS, regardless of the cycle information [17]. On the opposite side, proposals such as [18] are comprehensive, though remarkably too complex to be applied in economic optimization programs. Other models are simpler, such as [19] for lead-acid batteries, which estimates the capacity degradation of the ESS following a current throughput profile. Wang and colleague's model is still much simpler, opting for a multiparametric exponential formulations that can be regressed against laboratory data [16]. However, it must be stressed that these models still appear to be too focused on the BESS maximum capacity reduction. In applied cost analysis it is actually an "approximate" figure of cost that is needed to evaluate the optimality of a decision. In this respect, Xu et al. proposed a formulation also based on stress factors as in Ref. [19]. But alternatively in their model, the degradation of a Li-ion battery is a function of the DoD and the average state of charge following a load profile [20]. In some sense, the approach is altogether similar to that in Ref. [19], but it concentrates on the exogenous aspects of the BESS operation, producing a simpler model that can be calibrated from degradation test data, as provided by the BESS manufacturer. Moreover, their model decomposes the degradation into a sum of stress factors (again as in Ref. [19]), which allows separate analysis of calendar and cycling degradation.

The above considerations about aging would allow incorporating the variable replacement cost into the computation of a BESS value. Indeed, some models in the line of Xu and colleagues' only require cycle information (number of cycles, DoD, and/or SoC) to produce an estimate of the BESS damage [20]. They are remarkably simpler to implement. For instance, the model in Ref. [20] has been used in Ref. [21] to calculate the economic value of exchanging energy using a Li-ion battery, by means of Matlab/Simulink simulations. But in the field of optimization—regarding the valuation of the BESS based on an optimal operation under electricity prices—only recently some authors have incorporated the cost of aging; revealing a more involved problem. A relevant and complete example was provided in Ref. [22]. In a regulation market framework, the authors considered that the cost of cycling at different depths of discharge (DoD) can be prorated and included into a constrained optimization program. The process needs to be simplified, nevertheless, because each time that the optimization program works out a prospective non-optimal solution, the aging value has to be re-assessed by means of new iterations. So the authors resorted to an equivalent cycling count to reduce the computational burden. A similar example, in which BESS was employed to avoid imbalance costs, can be found in Ref. [23]. In Refs. [24,25], again the cost derived from aging was calculated ex-post, as a function of daily operation. That is, ex-post calculation of aging seems a requisite of constrained optimization programs.

Incorporating aging into an optimization program is further complicated if the stochasticity of the state variables is considered. Most of the times, unique historical time series have been employed (instances are [4,26–28]), or single realizations of time-of-use tariffs [29]. However, this procedure entails that there is a perfect knowledge about the evolution of electricity price; which is a particularly inaccurate assumption in spot electricity markets. In other cases where the uncertainty in parameters and price are explicitly incorporated in the optimization procedure, the aging is not considered in turn [30]. Some exceptions are [25], employing Monte Carlo samples to recurrently run an optimization routine with ex-post aging calculation [31,32]; using a constrained optimization program where energy demand is randomly obtained and aging is computed through BESS total energy throughput [33]; proposing a dynamic program that incorporates calendar aging in a multiobjective function, where the uncertainty in loads is accounted for by using two representative days; and [34] where a stochastic dynamic program is, solved iteratively to account for uncertainty.

1.3. Aim and contributions

Our approach to incorporating stochasticity and aging into the valuation problem is different to the approaches based on constrained optimization problems. This paper proposes using a stochastic dynamic program approach to calculate the value of grid-connected ESS, operating under uncertain electricity prices.

Approached in this way, the problem can be sequentially solved as a set of subproblems. It does not require specialized optimization libraries, because it is entirely based on matrix operations. The decision of charging/discharging is made at each time step by observing (i) the expected payoff from switching and (ii) the aging