Energy storage management with energy curtailing incentives in a telecommunications context

Isaias F. Silva, Cédric Bentz, Mustapha Bouhtou, Matthieu Chardy, Safia Kedad-Sidhoum

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Isaias F. Silva
Orange Labs, Cedric-Cnam
isaias.faria@orange.com

C. Bentz
Cedric-Cnam
cedric.bentz@cnam.fr

M. Bouhtou
Orange Labs
mustapha.bouhtou@orange.com

M. Chardy
Orange Labs
matthieu.chardy@orange.com

S. Kedad-Sidhoum
Cedric-Cnam
safia.kedad_sidhoum@cnam.fr

1 Introduction

The electrical energy market has been subject to intensive research specially with the emergence of smart-grids providing more complex energy grids with multiple power sources, storage systems and local eco-friendly energy production [3, 7].

The use of batteries as backup in case of power outages is frequent in telecommunications companies that provide critical services to keep their network equipment always active [6]. In this context, for each equipment in the network there exists at least one battery for backup use and security rules on the battery usage must be considered. Firstly, it has to be immediately recharged to its full capacity B_{max} after each use. Furthermore, to increase the batteries' lifespan, they must be recharged with a constant boost power P_B.

However, those batteries could also be used for other purposes, such as participating in the energy market when they are not being used for backup. Since the energy price is not constant on time, batteries can be used in the periods when the energy costs more, also called *peak-time* periods, and recharged when the energy costs less as a strategy to reduce the electricity bill [4, 5, 10, 8]. However, there exists a limited amount U_{max} of energy that can be bought at each time period due to the grid capacity. With this bound and the battery capacity, trivial strategies such as buying all the energy demand over the planning horizon at the cheapest period are not possible. Such an energy market is known as *Retail Market*.

A second way is to use the batteries to participate to the *Curtailing Market*, introduced for the first time by Lee et a l. [9]. In this context, a company can be called to reduce its energy consumption by receiving a reward. Considering a typical energy production and distribution system usually composed by generators, transmission and distribution operators and clients, the transmission operator (TO) is the agent responsible for the energy transmission and for the grid stability. When the consumption demand in a system is larger than the energy production, the TO has either to use its electrical energy reserves (e.g. call nuclear plants to produce more) or to call the customers that have a huge energy demand to cut down their consumption for a period (performing a *curtailing*) giving them a reward [1, 9]. Usually, the reward depends on the amount of energy that is cut down during a curtailing and rules to participate in this market are priorly contractualized [2].

2 Problem Definition

The problem treated in our study can be formally described as follows. Let us consider a customer with an electrical energy demand W_t in each period t over a planning horizon of T discrete time periods. The unitary cost C_t used to compute the electricity bill at each period t given.

Each curtailing has a minimal (resp. maximal) duration D_{min} (resp. D_{max}) that must be respected. In addition, during a curtailing, a minimum amount of power must be cut down at each period of time. In other words, for each period t of a curtailing, there exists a maximal amount of energy U_t that can be bought from the supplier. The way such an amount is computed is imposed by the TO depending on the country. Our study is based on the french context where this amount is defined as $W - P_C$, $\overline{W}$ being the mean demand forecast over the curtailing. P_C is a contractualized power that must be cut down.

Furthermore, a minimum amount of energy B_{min} must remain in the battery and the battery must be fully charged at the beginning and at the end of the time horizon for network safety purposes.

Managing batteries while respecting both usage and market rules is a key aspect to keep the network safe at optimal cost. Our paper addresses this aspect in a single battery setting. To the best of our knowledge, this is the first study where batteries are used for backup as well as to participate in the curtailing market.

	Rules	Stock management setting
Battery usage requirements	• Maximal capacity B_{max}	• Inventory with a limited capacity
	• Safety energy level B_{min}	• Safety stock
	• Immediate recharge	• If the inventory is not being used, it must be replenished
	• Constant recharge rate P_B	• The inventory is replenished at constant rate
Curtailing Market requirements	• Minimal curtailing duration D_{min}	• Minimum number of consecutive periods for each stock usage
	• Maximal curtailing duration D_{max}	• The stock can not be used more than a maximum number of periods
	• Minimal amount of energy that must be cut down during a curtailing P_C	• A minimum number of items must be supplied from the inventory at any period of time when the stock is used
Spot Market requirements	• Maximal amount of energy that can be bought U_{max}	• A production capacity on each period is imposed

Table 1: Relation between the specific rules of the considered problem and the stock management setting

In this context, the battery can be viewed as a power stock and its management treated as a particular production planning problem with specific rules on the i nventory. The battery is ready for use and no setup or installation costs are considered, and a new curtailing can start only if the battery is fully charged. Schneider et al. [11] studied a single-period electrical energy storage system from an inventory model point of view and proposed a general translation of technical requirements for energy storage systems into requirements for inventory models. In a similar vein, Table 1 presents the relation between the specific rules of the considered problem and the stock management setting.

3 Contributions

First part of our study aims at modeling the problem providing the battery usage rules at optimal cost as a mixed integer program. However, due to the size of the real instances, the model becomes hard to solve. In this context, based at the structure of the problem, a polynomial time algorithm is also proposed providing over the planning horizon the battery usage rules at optimal cost.

The derived idea is the enumeration of a subset of all possible curtailings that can be performed, and the reduction to a longest path problem in a directed acyclic graph (DAG), created from the enumerated subset of curtailings.

Formally, a curtailing c can be represented by its start and end times denoted (f_c, l_c) and by the amount of energy X_c that is cut down over its duration, also called *Depth of Discharge*. A curtailing can be then defined by the triple (f_c, l_c, X_c). Since curtailing duration is bounded by D_{min} and D_{max}, all possible pairs (f_c, l_c) can be enumerated in $O(T^2)$ time. Originally, X is a continuous variable and can not be extensively enumerated. However, we have proved that there exists an optimal solution of the problem for which the value of X_c in each curtailing of the solution is either a multiple of P_B or a multiple of U_t. Consequently, for any pair (f_c, l_c) there exists at most T values of X_c that needs to be enumerated.

Since a curtailing is defined by $c = (f_c, l_c, X_c)$, we are able to compute its potential gain g_c due to the sequences at the battery use and recharge. Firstly, the sequence of recharge of the battery is imposed by the immediate recharge rule. Secondly, since we know X_c for each curtailing c, and the cost of purchasing energy at each time period, we can easily determine how much energy should be consumed from the battery during each period of the curtailing, in order to minimize the cost.

Finally, a graph $G = (V, A)$ can be created where each enumerated curtailing is represented by a vertex in V. Two dummy vertices s and t are also added in V. The set of arcs A is defined as follows:

- for any $v_1, v_2 \in V - \{s,t\}, v_1 \neq v_2$, an arc from v_1 to v_2 of weight g_{v_1} is added if v_2 can be performed after v_1 with respect to the start/end times and the last charging period.
- for all $v_i \in V, v_i \neq s$, an arc from s to v_i of weight 0 is added.
- for all $v_i \in V, v_i \neq s, v_i \neq t$, an arc from v_i to t of weight g_{v_i} is added.

By construction, the graph G is a DAG and the longest path from s to t can be computed in polynomial time [12]. Let $p*$ be a longest path from s to t, the set of vertices in $p*$ gives us directly the set of curtailings to be performed at optimal cost $c*$, which is the value of $p*$.

The proposed algorithm works for any variant of the problem such that the computation of U_t is not influenced by other curtailings. However, in some cases, the computation of U_t could be influenced by the Depth of Discharge of the curtailing previously performed. In this context, our algorithm can not be applied.

The complexity of the algorithm is $O(V + A)$, where $|V|$ is bounded by T^3 and $|A|$ by T^6.

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