Battery Energy Storage System (BESS) Optimization Model

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1 Problem Description

In this report, we present a mathematical model to generate an optimal schedule for a Battery Energy Storage System (BESS) participating in a simplified wholesale electricity market that offers three products: Energy, Regulation Up, and Regulation Down. Schedules for these products must be submitted by 10:00 AM each day for operations covering the following 24-hour period (midnight to midnight), with only one set of schedules allowed per day. The system aims to optimize the BESS's scheduling and product bids to maximize profit by considering energy and regulation market prices from a dataset containing hourly price data over the past year, all while adhering to operational constraints.

To achieve this optimization, we need to take into account a variety of factors, including the rules of the market, the operational capabilities of the BESS, and the pricing structures for energy and regulation services. The following assumptions detail these critical components, providing the foundation for the model development and the design of the scheduling system.

1.1 Assumptions

1.1.1 Market Rules and Participation

- The BESS can bid for all three products (Energy, Regulation Up, and Regulation Down) in any given hour.
- All submitted bids will be accepted by the market operator, provided there is sufficient State of Charge (SoC) in the BESS to deliver the energy.
- The market will deploy 10% of the accepted bid amount for regulation services.

1.1.2 BESS Specifications

- The BESS has a Nameplate power capacity of 100 MW and an energy capacity of 200 MWh, making it a two-hour duration asset.
- The system has a charge efficiency of 90% and a discharge efficiency of 90%.
- The asset is limited to performing a maximum of one full cycle per day (200 MWh charge and 200 MWh discharge).

1.1.3 Scheduling Horizon and Resolution

- Schedules must be generated daily for a 24-hour horizon (midnight to midnight) at an hourly resolution aligning with a Day-Ahead Market strategy.

1.1.4 Price

- Prices for energy and regulation services reflect market conditions over the past year.
- The generated optimal schedules are under the assumption of "perfect foresight", where the prices for energy and regulation services are known in advance for the entire 24-hour period.

With these assumptions in place, we can now move forward to define the structure of the model that will optimize the scheduling of the Battery Energy Storage System (BESS).

2 Model

Before delving into the model formulation, it is important to define the key parameters and decision variables that will be used in the optimization process:

2.1 Model Parameters

The parameters used in the optimization model are summarized in Table 1. These parameters define the storage system's physical and operational characteristics, as well as market prices for energy and regulation services.

Symbol	Storage Parameter	Value
M	Set of months	$M \subseteq \{1, 2, \ldots, 12\}$
D_m	Set of days in month m	$\{1, 2, \ldots, (29), 30, (31)\}$
T_d	Set of hours in day d	$\{1, 2, \ldots, 24\}$
L_d^R	Set of missing hours for charging energy prices in day d	
L_d^D	Set of missing hours for discharging energy prices in day d	
$L_d^{REG,R}$	Set of missing hours for regulation down prices in day d	
$L_d^{REG,D}$	Set of missing hours for regulation down prices in day d	
τ	Time period length	1 hour
$\bar{q}_D$	Maximum energy that can be discharged in a single hour of each day	Maximum charge power level(100)$\cdot\tau = 100$ MWh
$\bar{q}_R$	Maximum energy that can be charged in a single hour of each day	Maximum charge power level(100)$\cdot\tau = 100$ MWh
$\bar{S}$	Maximum energy storage capacity in a single hour of each day	200 MWh
S_t	Initial charge state at beginning of day 1	$50\%(\bar{S} = 200)$ MWh= 100 MWh
S'_0	Initial charge state at beginning of day $d > 1$	$= S_{24}$ in day $d-1$ (MWh)
γ_R	Charging efficiency	0.9
γ_D	Discharging efficiency	0.9
$\gamma^{REG,R}$	Fraction of regulation down that is actually deployed	0.1
$\gamma^{REG,D}$	Fraction of regulation up that is actually deployed	0.1
$p_{t,d,m}$	Price of energy at hour t of day d and month m (\$/MWh)	
$p_{t,d,m}^{\text{REG},R}$	Price of regulation down deployed at hour t of day d and month m (\$/MWh)	$= p_{t,d,m}^{\text{REG},D}$
$p_{t,d,m}^{\text{REG},D}$	Price of regulation up deployed at hour t of day d and month m (\$/MWh)	$= p_{t,d,m}^{\text{REG},R}$
$p_{t,d,m}^{\text{C},R}$	Price of capacity reserved for regulation down at at hour t of day d and month m (\$/MW)	$= p_{t,d,m}^{\text{REG},R}$
$p_{t,d,m}^{\text{C},D}$	Price of capacity reserved for regulation up at hour t of day d and month m (\$/MW)	$= p_{t,d,m}^{\text{REG},D}$

Table 1: Battery Storage Optimization Model Parameters

2.2 Decision Variables

The decision variables represent the storage system's actions and states. Table 2 lists these variables along with their ranges.For any month $m \in M$ and day $d \in D_m$, we have the following decision variables:

Symbol	Storage Decision Variables	Range
q_t^D	Energy discharge at hour t of the day (MWh)	$\mathbb{R}^+$
q_t^R	Energy charge at hour t of the day (MWh)	$\mathbb{R}^+$
$q_t^{\text{REG},R}$	Regulation down deployed at hour t of the day (MWh)	$\mathbb{R}^+$
$q_t^{\text{REG},D}$	Regulation up deployed at hour t of the day (MWh)	$\mathbb{R}^+$
$q_t^{\text{C},R}$	Capacity reserved for regulation down at hour t of the day (MW)	$\mathbb{R}^+$
$q_t^{\text{C},D}$	Capacity reserved for regulation up at hour t of the day (MW)	$\mathbb{R}^+$
S_t	Charge state at hour t of the day (MWh)	$\mathbb{R}^+$

Table 2: Decision Variables

With the parameters and decision variables defined, we can now proceed to the formulation of the optimization model.

2.3 Model formulation

Given that market participation follows a Day-Ahead Market strategy, we solve the following optimization problem for each $d \in D_m$ of month $m \in M$. The total profit is then obtained by summing the daily objective function values across all user given days and months. Specifically, the total profit is expressed as:

$$E_{total} = \sum_{m \in M} \sum_{d \in D_m} E_{d,m},$$

where $E_{d,m}$ represents the optimal profit earned for each day d of month $m \in M$ from the following optimization model.

2.3.1 Objective function

$$\text{(OF)} \quad E_{d,m} = \max \sum_{t \in T_d} \Big(p_{t,d,m} q_t^D - p_{t,d,m} q_t^R + p_{t,d,m}^{\text{REG},D} q_t^{\text{REG},D} - p_{t,d,m}^{\text{REG},R} q_t^{\text{REG},R} + p_{t,d,m}^{\text{C},D} q_t^{\text{C},D} + p_{t,d,m}^{\text{C},R} q_t^{\text{C},R} \Big).$$

2.3.2 Constraints

The optimization is subject to the following constraints:

1. Regulation Up/Down and Reserved Capacity Equalities:

$$\begin{aligned} &\text{(C1)} \quad q_t^{\text{REG},D} = \tau \cdot \gamma^{REG,D} q_t^{\text{C},D}, \quad \forall t \in T_d \\ &\text{(C2)} \quad q_t^{\text{REG},R} = \tau \cdot \gamma^{REG,D} q_t^{\text{C},R}, \quad \forall t \in T_d \end{aligned}$$

2. Daily State of Charge Dynamics:

$$\text{(C3)} \quad S_t = S_{t-1} + \gamma_R q_t^R - \gamma_D q_t^D + \gamma_R q_t^{\text{REG},R} - \gamma_D q_t^{\text{REG},D}, \qquad \forall t \in T_d, \text{ if } d = 1$$

$$S_t = \begin{cases} S_0' + \gamma_R q_1^R - \gamma_D q_1^D + \gamma_R q_1^{\text{REG},R} - \gamma_D q_1^{\text{REG},D}, & \forall d > 1, \text{if } t = 1, \text{(C4)} \\ S_{t-1} + \gamma_R q_t^R - \gamma_D q_t^D + \gamma_R q_t^{\text{REG},R} - \gamma_D q_t^{\text{REG},D}, & \forall t \in T_d \setminus \{1\}, \text{ if } d > 1, \text{(C5)} \end{cases}$$

3. Daily Energy Storage Limits:

$$\text{(C6)} \quad 0 \leq S_t \leq \bar{S}, \quad \forall t \in T_d$$

4. Daily Energy Charging and Discharging Limits:

$$\begin{aligned} &\text{(C7)} \quad 0 \leq q_t^R + q_t^{\text{REG},R} \leq \bar{q}_R, \quad \forall t \in T_d \\ &\text{(C8)} \quad 0 \leq q_t^D + q_t^{\text{REG},D} \leq \bar{q}_D, \quad \forall t \in T_d \end{aligned}$$

5. Daily Asset Cycle Limit Constraints:

$$\begin{aligned} &\text{(C9)} \quad \sum_{t \in T_d} q_t^R + q_t^{\text{REG},R} \leq \bar{S}, \\ &\text{(C10)} \quad \sum_{t \in T_d} q_t^D + q_t^{\text{REG},D} \leq \bar{S} \end{aligned}$$

6. Missing hours Constraints:

$$\begin{aligned} &\text{(C11)} \quad q_t^R = 0 \quad \forall t \in L_d^R \\ &\text{(C12)} \quad q_t^D = 0 \forall t \in L_d^D \text{(C13)} \qquad q_t^{\text{REG},R} = 0 \quad \forall t \in L_d^R \\ &\text{(C14)} \quad q_t^{\text{REG},D} = 0 \forall t \in L_d^{REG,D} \text{(C15)} \qquad q_t^{\text{C},R} = 0 \quad \forall t \in L_d^{REG,R} \\ &\text{(C16)} \quad q_t^{\text{C},D} = 0 \forall t \in L_d^{REG,D} \end{aligned}$$

7. Variable Domains:

$$\text{(C17)} \quad q_t^D, q_t^R, q_t^{\text{REG},R}, q_t^{\text{C},R}, q_t^{\text{REG},D}, q_t^{\text{C},D}, S_t \in \mathbb{R}^+, \quad \forall t \in T_d$$

The objective function (OF) maximizes the economic returns from energy storage operations for each day. The first term represents the revenue generated from discharging energy, the second term accounts for the costs associated with charging energy, the third term captures the revenue from regulation up deployment, the fourth term represents the cost associated with regulation down deployment, and the last two terms correspond to the revenues from the capacity reserved for regulation up and down. Constraint (C1) ensures that the actual deployed regulation up is a fraction of the regulation up capacity reserved ensuring consistency between commitment and usage. Constraint (C2) ensures that the actual deployed regulation down is a fraction of the regulation down capacity reserved ensuring consistency between commitment and usage. Constraints (C3) describes the evolution of the battery's state of charge during the first day under the charging, discharging, regulation up and regulation down affects accounting for efficiencies. Constraint (C4) describes the evolution of the battery's state of charge during each day rather than the first day at the first hour, under the charging, discharging, and regulation affects accounting for efficiencies. The initial state of each day rather than the first day at the first hour is equal to the state of charge of the asset at the ending hour (hour 24th) off the previous day. Constraints (C5) describes the evolution of the battery's state of charge during each day rather than the first day at the each hour rather than the first hour, under the charging, discharging, and regulation affects accounting for efficiencies. Constraint (C6) ensures that the daily state of charge must always stay within the physical limits of the battery asset. Constraints (C7-C8) guarantee that the energy (regular and regulation) used for charging or discharging must not exceed the maximum allowed quantity during the day. Constraints (C9-C10) assure that the cumulative energy charged or discharged during the day must not exceed the daily energy limits determined. It assures that battery can undergo a full charge to its maximum capacity or a complete discharge to zero capacity only once within a 24-hour period at each day. Constraint (C11-16) guarantees that if there is any missing hourly data in the price information, no bidding occurs. This means no charging, discharging, regulation up/down capacity reservation, or deployment decisions are made in that hour. Constraint (C17) show that all decision variables are $\mathbb{R}^+$ numbers, ensuring feasibility in the optimization process.