Assessing the Economics of Customer-Sited Multi-Use Energy Storage

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Abstract—This paper presents an approach to assess the economics of customer-sited energy storage systems (ESSs) which are owned and operated by a customer. The ESSs can participate in frequency regulation and spinning reserve markets, and are used to help the customer consume available renewable energy and reduce electricity bill. A rolling-horizon approach is developed to optimize the service schedule, and the resulting costs and revenues are used to assess economics of the ESSs. The economic assessment approach is illustrated with case studies, from which we obtain some new observations on profitability of the customer-sited multi-use ESSs.

I. INTRODUCTION

Energy storage systems (ESSs) are a promising ingredient for reliable integration of renewable energies into future power grids. ESSs are however costly at the present stage, and recent studies showed that they are unlikely to generate a net profit if ESSs are used to provide a single service. This motivates the use of ESSs for multiple service provision [1].

When ESSs are scheduled for multiple services concurrently, potential conflicts occur due to the limited power and energy capacities available. An ideal scheduling approach needs to address the conflicts in an optimal way, such that the net profit is maximized subject to operational and service constraints. So far, only a few studies have been conducted, partially addressing the encountered challenges. Among them, [2] presents a coarse framework to investigate the net profit, but leaves the nontrivial modeling of the optimization objective and constraints to readers for specific applications. Reference [3] develops a mixed-integer linear programming model focusing on maximizing the revenue without considering the costs of ESSs. More recently, [4] presents a concrete optimization formulation in a rolling-horizon framework. However, the formulation does not appropriately capture the operating costs of ESSs which are dependent on their varying charge and discharge rates [5].

This work considers customer-sited ESSs which provide multiple services. The ESSs are used to participate in regulation and spinning reserve markets, and help the customer consume available renewable energy and reduce time-of-use (TOU) electricity bill. We develop a comprehensive scheduling model which captures the dynamics of ESSs and associated aging costs, the supported services and associated revenues, and all major service and operational constraints. By optimizing the schedule using a rolling-horizon approach, we are able to assess profitability of the ESSs. Different from aforementioned literature [2], [3], [4], we include the support of self-consumption of renewable energy and embed a more realistic aging model for the ESSs. When the storage is made of Li-ion batteries, the aging model characterizes the battery aging cost in terms of its instant charge/discharge rate and the duration, which was experimentally established in [5].

II. MODELING THE ESSS AND THEIR SERVICES

We use $\mathcal{N}$ to denote the set of ESSs. The time is discretized into slots, each with a duration of $T_s$. The charge and discharge of ESSs are scheduled periodically to support self-consumption of renewable energy, frequency regulation, spinning reserve, and TOU electric bill reduction. The mathematical models of the ESSs and the four supported services are developed in this section.

A. Modeling the ESSs

We assume that a customer owes and operates multiple ESSs, each of which follows a generic model used in [6]. Let the charge and discharge rates of ESS $i$ be scheduled as $p_{i,t}^c$ and $p_{i,t}^d$ for time slot $t$, respectively. And let $v_{i,t}$ indicate the working mode of the ESS $i$, which is 1 (or 0) if it is not discharged (or charged). These variables satisfy

$$0 \leq p_{i,t}^c \leq v_{i,t}^c p_{i,t}^{c\max}, \quad 0 \leq p_{i,t}^d \leq (1 - v_{i,t}) p_{i,t}^{d\max},$$

(1)

where $p_{i,t}^{c\max}$ and $p_{i,t}^{d\max}$ are the corresponding upper bounds. The two constraints ensure that charge and discharge comply with the rate limits and do not happen in the same time slot. After charge/discharge, the state of charge (SOC) of the ESS $i$, denoted by $s_{i,t}$, renews into

$$s_{i,t} = s_{i,t-1} + T_s (v_{i,t}^c p_{i,t}^c - p_{i,t}^d / \eta_{i,d}) / E_{i}^{cap},$$

(2)

where $\eta_{i,d}$, $\eta_{i,c} \in (0, 1)$ are the energy conversion coefficients, and $E_{i}^{cap}$ is the energy capacity of ESS $i$. The SOC must be maintained within certain limits in order to protect the ESSs, and this will be discussed later in Section II-F.

Both charge and discharge incur an aging cost, which is the money loss of the initial investment. Let the cost be estimated as $C_i^c(p_{i,t}^c)$ and $C_i^d(p_{i,t}^d)$ for charging and discharging ESS $i$ at the rates of $p_{i,t}^c$ and $p_{i,t}^d$ for one hour, respectively. The cost of operating ESS $i$ in time slot $t$ is then given by

$$C_i(p_{i,t}^c, p_{i,t}^d) = T_s C_i^c(p_{i,t}^c) + T_s C_i^d(p_{i,t}^d).$$

If the ESSs use Li-ion batteries, the cost can be approximated by a piece-wise linear function which is further obtained by solving the following linear program [5], [6]:

$$C_i(p_{i,t}^c, p_{i,t}^d) \approx \frac{\alpha_i T_s}{0.8E_{i}^{cap}} \min_{\zeta_{i,t}} \zeta_{i,t}^E S S,$$

s.t., $\gamma_{i,c} [1000 \times a_k^{ESS} (p_{i,t}^c)^2 + n_k^{ESS} p_{i,t}^c] + \frac{1 - \gamma_{i,c}}{\eta_{i,d}^k} \times [1000 \times a_k^{ESS} (p_{i,t}^d)^2 + n_k^{ESS} p_{i,t}^d] \leq \zeta_{i,t}, \forall k \in \mathcal{K}_{ESS}$,

(3)

where $\alpha_i$ is the unit capital cost ($$/Wh) to purchase ESS $i$; $\zeta_{i,t}$ is an auxiliary variable; $\gamma_{i,c}$ is the fraction of a single
cyclic aging cost incurred by fully charging the battery from empty; \( n_i \triangleq E_i^{\text{cap}}/0.0081 \), which is the number of battery modules that form the ESS \( i \), each with a capacity of 0.0081 kW; and \( \{ a_k, b_k \}_{k \in \mathcal{K}_{\text{ESS}}} \) are the coefficients associated with the linear segments as indicated by a certain set \( \mathcal{K}_{\text{ESS}} \).

B. Service for self-consumption of renewable energy

The customer has installed renewable energy generators. The aggregate generation power for time slot \( t \) is denoted as \( p_i^{c,t} \). For time slot \( t \), let the customer be scheduled to consume the renewable energy at a rate of \( p_i^{c,e,t} \), and the surplus renewable energy be charged to ESS \( i \) at a rate of \( p_i^{c,e,s,t} \), and the remaining renewable energy be exported to the market at a rate of \( p_i^{c,e,m,t} \). These power variables satisfy

\[
0 \leq p_i^{c,e,s,t} \leq d_t, \quad 0 \leq p_i^{c,e,t} \leq p_i^{c,max}, \quad 0 \leq p_i^{c,e,s,t} \leq p_i^{c,max},
\]

\[
p_i^{c,e,t} + p_i^{c,e,s,t} + \sum_{i \in N} p_i^{c,e,t} \leq p_i^{c,e,m,t}, \tag{4}
\]

where \( d_t \) is the load demand of the customer, and \( p_i^{c,max} \) is the maximum power that can be injected to the grid. The last inequality admits curtailment of surplus renewable generation, if any.

Given the electricity purchase price \( c_i^p \) and sale price \( c_i^v \), we can compute the revenue of consuming renewable energy with the help of ESSs as

\[
R_{\text{ac}}(p_i^{c,e,t}, p_i^{c,e,s,t}, \{ p_i^{c,e,t} \}_{i \in N}) = T_s c_i^p (\sum_{i \in N} p_i^{c,e,t}) + T_s c_i^v p_i^{c,e,s,t},
\]

of which the first part owes to the avoided purchase of energy from the market, and the second part owes to the surplus renewable energy exported to the market.

C. Service for frequency regulation

Frequency regulation aims at stabilizing the grid frequency at a desired value. Let \( u_{i,t}^{\text{fr,up}} \) be an indicator which is 1 for ramp up regulation and 0 otherwise. The minimum power to participate in the regulation market is required to be \( p_i^{c,min} \). The ESSs may participate in the market or not, as indicated by \( v_i^{d} \), equal to 1 and 0, respectively. Let ESS \( i \) charge at a rate of \( p_i^{c,e,t} \) if \( u_{i,t}^{\text{fr,up}} = 0 \) and discharge at a rate of \( p_i^{c,d,t} \) if \( u_{i,t}^{\text{fr,up}} = 1 \).

The power variables satisfy

\[
0 \leq p_i^{c,d,t} \leq d_t, \quad 0 \leq p_i^{c,e,t} \leq d_t, \quad 0 \leq p_i^{c,d,t} \leq d_t,
\]

\[
0 \leq p_i^{c,d,t} \leq c_i^v d_t \quad \forall i \in N,
\]

\[
0 \leq p_i^{c,e,t} \leq c_i^p d_t \quad \forall i \in N,
\]

\[
p_i^{c,d,t} = \sum_{i \in N} (1 - u_{i,t}^{\text{fr,up}}) p_i^{c,e,t} + u_{i,t}^{\text{fr,up}} p_i^{c,d,t} \geq v_i^{d} p_i^{c,min}, \tag{5}
\]

where the first two inequalities ensure that charge and discharge for the regulation service do not happen concurrently.

Consider the payment scheme implemented by PJM in USA

[7], [8]. The regulation service is paid by the committed power capacity (denoted by \( p_i^{c,t} \)) and the regulation performance (dictated by the performance score \( p_i^{c,t} \) and the regulation mileage ratio \( p_i^{c,t} \)). The performance score \( (p_i^{c,t}) \) is computed based on the regulation performance in the past period; and the mileage ratio \( (p_i^{c,t}) \) is the mileage of the fast regulation signal divided by the mileage of the slow (or conventional) regulation signal, both in the past service period. The Regulation Market Capacity Clearing Price (RMCCP) is denoted by \( c_i^{\text{RMCCP}} \), and the Regulation Market Performance Clearing Price (RMPCP) is denoted by \( c_i^{\text{RMPCP}} \). Both prices are updated at a period of \( T_s \).

The revenue of the regulation service is then computed as

\[
R_{\text{fr}}(p_i^{c,t}, p_i^{c,d,t}, v_i^{d}) = c_i^{\text{RMCCP}} \sum_{i \in N} (p_i^{c,d,t} - p_i^{c,t}),
\]

where the first term owes to the service provided, and the second term accounts for the revenue obtained from the energy charged/discharged to/from the ESSs.

D. Service as spinning reserve

Consider a spinning reserve market which periodically publishes a reserve availability price, denoted by \( c_i^{r} \). The minimum participation power is required to be \( p_i^{r,min} \) and the minimum commission time is \( T_{r,min} \). The ESSs may be scheduled to support this service, which is dictated by a binary variable \( v_i^{r} \), 1 for participation and 0 otherwise. Let \( p_i^{r,d,t} \) be the power reserved by ESS \( i \), which is the commissioned maximum discharge rate under contingencies. The reserved power satisfies

\[
0 \leq p_i^{r,d,t} \leq c_i^{r} T_s \sum_{i \in N} p_i^{r,d,t} \tag{6}
\]

The minimum support time will be enforced via constraint \([10]\) ahead. The revenue for this service is calculated by

\[
R_{\text{sr}}(v_i^{d}) = c_i^{r} T_s \sum_{i \in N} p_i^{r,d,t} \tag{10}
\]

E. Service for TOU electricity bill reduction and preparation for future services

With TOU electricity pricing information, the ESSs may be used to reduce the electricity bill by charging and discharging the storage appropriately. At the meantime, the ESSs may be charged/discharged to prepare for future services. Let the aggregate charge and discharge rates of ESS \( i \) for such purposes be scheduled as \( p_i^{c,c,t} \) and \( p_i^{c,d,f,t} \) for time slot \( t \), respectively. The revenue obtained from the charged and discharged energy is computed as

\[
R_{\text{sr}}(p_i^{c,c,t}, p_i^{c,d,f,t}) = T_s c_i^{p} \sum_{i \in N} (p_i^{c,d,f,t} - p_i^{c,c,t}),
\]

which owes to the avoided or desired purchase of energy from the market. The charge and discharge rates satisfy

\[
0 \leq p_i^{c,d,f,t} \leq p_i^{c,max}, \quad 0 \leq p_i^{c,c,t} \leq p_i^{c,max}, \tag{7}
\]

F. Feasibility constraints to support the multiple services

To support the four services above, we must have

\[
p_i^{c,e,t} + p_i^{c,e,s,t} + p_i^{c,c,t} = v_i^{c} c_i^{p} T_s p_i^{c,max}, \tag{8}
\]

\[
p_i^{c,d,t} + p_i^{c,d,f,t} = v_i^{d} c_i^{p} T_s p_i^{c,max}, \tag{9}
\]

\[
s_{i,min} + p_i^{r,d,f,t} \leq s_{i,\text{cap}} E_i \leq s_{i,t} \leq s_{i,\text{max}}, \tag{10}
\]

for each \( i \in N \). Constraints \([8]\) and \([9]\) are related to the aggregate charge rate and discharge rate for multiple services, respectively. Constraint \([10]\) imposes SOC limits.
to protect the ESSs from being over charged or discharged, in which \( s_{i, \min}, s_{i, \max} \in (0, 1) \) are the required limits and \( p_{i,t}^{\text{sr},d} \) is the energy committed as spinning reserve. The three constraints link up the four services provided by the ESSs, through which the conflicts in between will be resolved via optimization.

The right hand side of the inequality in [9] contains a term \( v_{i,t}^{c}p_{i,t}^{\text{sr},d} \), which is bilinear in the two decision variables. It is desirable to reformulate this term into a linear equivalent form. Introduce an auxiliary variable \( z_{i,t} \). Then, \( z_{i,t} \) is equal to \( v_{i,t}^{c}p_{i,t}^{\text{sr},d} \) if it satisfies the following constraints:

\[
0 \leq z_{i,t} \leq p_{i,t}^{\text{max}}v_{i,t}^{c},
\]

\[
p_{i,t}^{\text{sr},d} + p_{i,t}^{\text{max}}(v_{i,t}^{c} - 1) \leq z_{i,t} \leq p_{i,t}^{\text{sr},d},
\]

(11)

The equivalence is easy to verify with the McCormick linearization method [9]. Therefore, we can replace \( v_{i,t}^{c}p_{i,t}^{\text{sr},d} \) with \( z_{i,t} \) subjected to the above constraints, which makes constraint [9] completely linear in the variables.

III. THE STORAGE MANAGEMENT OPTIMIZATION PROBLEM AND ITS SOLUTION

The storage management optimization problem is defined to maximize the total net profit (namely, minimize the total net loss) over a rolling horizon subject to service requirements and operational constraints. Given a decision time point \( t \), the time slots within a look-ahead horizon for a size of \( H \) are denoted by the set \( \mathcal{H}_t \). The optimization will be performed using the forecast data over the horizon.

The total net profit (TNP) over the horizon sums up the revenues earned from the four services minus the operating cost incurred to the ESSs. With the storage aging cost \( C_\text{age} \) computed from the linear program [3], the TNP can be shown to have the following specific form:

\[
\text{TNP}(t) = \sum_{\tau \in \mathcal{H}_t} \left( \sum_{i \in \mathcal{N}} \left( R_{\text{p}}(p_{i,\tau}^{\text{p}}, p_{i,\tau}^{\text{re}}) + R_{\text{d}}(p_{i,\tau}^{\text{d}}, p_{i,\tau}^{\text{fc}}) \right) - \sum_{i \in \mathcal{N}} C_\text{age}(p_{i,\tau}^{\text{p}}, p_{i,\tau}^{\text{d}}) \right) + \min_{\mathcal{N}} \text{ESS}
\]

\[
= T_s \left( \sum_{\tau \in \mathcal{H}_t} \left( c_{\text{p}}p_{\tau}^{\text{p},\text{re}} + c_{\text{d}}p_{\tau}^{\text{d},\text{fc}} + p_{\tau}^{\text{p},\text{re}}p_{\tau}^{\text{d},\text{fc}} + 2p_{\tau}^{\text{p},\text{re}} + c_{\text{ESS}}p_{\tau}^{\text{d},\text{max}} - \min_{\mathcal{N}} \text{ESS} \right) \right)
\]

which is subject to the constraints in [3]. We have used the revenue and cost expressions introduced in the previous subsections and also the equalities in constraints [8] and [9] to deduce the TPN.

Since the decision variables \( \{p_{i,\tau}^{\text{br},\text{d}} \}, \{p_{i,\tau}^{\text{fc}} \} \) do not appear in TNP\((t)\), we can eliminate these redundant variables and simplify constraints [8] and [9] to the following:

\[
p_{i,\tau}^{\text{p},\text{re}} + p_{i,\tau}^{\text{d},\text{fc}} \leq v_{i,t}^{c}p_{i,t}^{\text{max}},
\]

\[
p_{i,\tau}^{\text{br},\text{d}} \leq p_{i,t}^{\text{max}} - (1 - v_{i,t}^{c})p_{i,t}^{\text{max}} - p_{i,t}^{\text{sr},d} + z_{i,t},
\]

(12)

(13)

for each \( i \in \mathcal{N} \). Here the variable \( z_{i,t} \) is an equivalent of \( v_{i,t}^{c}p_{i,t}^{\text{sr},d} \), satisfying constraint [11]. By minimizing TNP\((t)\) with the new constraints, the solution of \( \{p_{i,\tau}^{\text{br},\text{d}} \}, \{p_{i,\tau}^{\text{fc}} \} \) can then be recovered from [8] and [9].

### TABLE I: PARAMETERS OF THE ESSs. THE POWER IS IN UNIT OF kW AND THE ENERGY IS IN UNIT OF kWh.

| Type | \( E_{i}^{\text{cap}} \) | \( s_{i, \min} \) | \( s_{i, \max} \) | \( P_{i}^{\text{d}, \text{max}} \) | \( V_{i}^{\text{c}} \) | \( V_{i}^{\text{d}} \) |
|------|-----------------|---------------|---------------|-----------------|-------|-------|
| 1    | 480             | 0.2           | 0.9           | 102             | 74    | 0.82  | 0.88  |
| 2    | 720             | 0.2           | 0.9           | 148             | 113   | 0.85  | 0.90  |

Consequently, the ESS management problem is defined as

\( \text{P0:} \min - \text{TNP}(t) \)

subject to, \( (11) - (7), (10) - (13) \), \( \forall i \in \mathcal{N}, \tau \in \mathcal{H}_t \)

where the subscript \( \tau \) instead of \( t \) is used in all constraints, and constraint [5] refers only to the inequalities. In \( \text{P0} \), the power variables are \( p_{i,\tau}^{\text{p},\text{re}}, p_{i,\tau}^{\text{d},\text{fc}} \) and \( p_{i,t}^{\text{br},\text{d}}, p_{i,t}^{\text{fc}} \) for charge and \( p_{i,t}^{\text{br},\text{d}}, p_{i,t}^{\text{fc}} \) for discharge of each ESS \( i \in \mathcal{N} \) in each time slot \( \tau \in \mathcal{H}_t \), and \( p_{i,\tau}^{\text{p},\text{re}}, p_{i,\tau}^{\text{d},\text{fc}} \) for the customer to self-consume and sell available renewable energy in each time slot \( \tau \in \mathcal{H}_t \).

The auxiliary variables are binary variables \( \{v_{i,\tau}^{c} \}, \{v_{i,\tau}^{d} \} \) for all \( \tau \in \mathcal{H}_t \), and real variables \( \{v_{i,\tau}^{\text{ESS}} \}, \{z_{i,\tau} \} \) for all \( \tau \in \mathcal{H}_t \).

The objective and constraints of \( \text{P0} \) are linear in the variables, except constraint [5] which is quadratic in the decision variables \( \{v_{i,\tau}^{c}, p_{i,\tau}^{\text{d}} \} \) for each \( i \in \mathcal{N} \) and \( \tau \in \mathcal{H}_t \). Therefore, the problem is a mixed-integer quadratic program (MIQP) and can be solved by standard MIQP solvers. Once an optimal solution is obtained, only the part for the first time slot \( t \) will be implemented to dispatch the ESSs. The schedule for the future time slot \( (t+1) \) will be determined in a similar way by shifting the time horizon forward by one slot and then solving the new optimization problem.

IV. CASE STUDY

This section assesses the economics of multi-use ESSs based on the scheduling approach developed above.

A. Simulation setup and input data

The demand is scaled historical hourly electricity demand of a college in California for a summer week [10]. The solar-PV generation, which has a peak equal to 60% of the peak demand, is scaled historical generation power for a summer week in Brussels [11]. The customer deploys two ESSs with specifications given in Table I. Their charge and discharge aging costs are estimated by (3), in which the model parameters are set the same as those in [6].

The hourly regulation signal and associated market clearing price are from the real operational records of PJM [12]. So are the hourly spinning reserve prices. The price of purchasing electricity from the market is obtained from PG & E [6], which consists of peak, mid-peak and off-peak prices for different periods of a day. The price of selling electricity to the market is 60% of the purchase price. The purchase and sale powers are unrestricted in our study.

B. Profitability of the multi-use ESSs

When the input data within the horizon is perfectly known, the total net profit obtained is shown in Fig. 1a. The profit decreases with the storage purchase price, and vanishes once the purchase price is higher than 300 $/kWh. On the
The above profit contains the contribution of solar energy which is assumed free here. To get rid of this contribution and obtain the value solely for the use of ESSs, we subtract the above profit with the one obtained without having any ESSs. This yields the reduced profits shown in Fig. 1(b).

When the storage purchase price is fixed to 100 $/kWh, the charge/discharge schedules for $H$ equal to 2 and 4 are shown in Fig. 2. The associated revenues and storage operating costs are given in Table II. As can be seen, the higher profit for the case with $H = 4$ owes to appropriate use of the ESSs for regulation and reserve services and for reducing the electricity bill. The results in Table II also indicate that, in the absence of free solar energy, using ESSs to support only one or two of the services may not cover the associated cost and hence would be unable to yield a positive profit.

### C. Impact of forecast errors

It is of interest to see how forecast errors affect the economic results. Let the load demand, the renewable generation power, the regulation market clearing price and the spinning reserve availability price be forecasted with zero-mean and uniformly distributed errors. The maximum errors are proportional to the magnitudes are small relative to the reference profits. This indicates that the economic assessment approach is somehow robust to forecast errors.

### V. Conclusions

This paper developed a rolling-horizon optimization approach to schedule customer-sited ESSs for multi-service provision. The operating cost and yielded revenues were used to assess the economics of the ESSs. The effectiveness of the proposed approach was illustrated with case studies. Future research will investigate the impact of storage energy and power capacities on the economics of multi-use ESSs.

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