

Stacked Revenue and Technical Benefits of a Grid-connected Energy Storage System

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Abstract—This paper proposes a comprehensive evaluation of stacked revenue generated from grid-connected energy storage systems (ESSs). The stacked revenue from an ESS cannot be calculated by merely aggregating the benefits from various applications (e.g., energy arbitrage, frequency regulation, and outage mitigation) as the ESS may not be available for all types of applications during the same time intervals. This is because a quantity committed to one market may not be committed to another. In this paper, different types of applications for grid-connected ESSs are identified, and a model incorporating component reliability, power system operation constraints, and storage system operation constraints is developed to evaluate the composite revenue generated from these applications. In this model, the types of applications of ESSs are prioritized according to their intended contributions and system operating conditions. Sequential Monte Carlo simulation is used for evaluating the reliability improvement and a quadratically constrained linear programming model is built for estimating the maximum revenue from arbitrage and regulation markets. The proposed method is demonstrated on the IEEE reliability test system (IEEE-RTS) using historical PJM price data.

Index Terms—Arbitrage, cost-benefit, energy storage system, regulation, reliability.

I. INTRODUCTION

DEPLOYMENT of energy storage systems (ESSs) is gaining significant momentum due to economic incentives, power system regulation requirements, and integration of renewable energy sources. The ESSs have several applications in power systems including peak load shaving, power outage mitigation, and frequency regulation. Despite steadily decreasing costs, the capital cost of an ESS is still considerable, and a few applications of ESSs are directly related to economic incentives. Hence, a cost-benefit analysis is necessary to evaluate the profit and justify the investment. This paper investigates the economics of the system when several applications of the ESS are stacked together to generate a cumulative revenue. Benefits from reliability improvement, energy arbitrage, and regulation are considered in estimating the stacked revenue from ESSs.

An energy storage device can be considered as a device that mediates between energy generation and energy consumption [1]. The power balance constraint imposes the condition that generation must always equal consumption (including losses). This is not always feasible, especially after the integration

of renewable energy sources. Hence, the deployment of an ESS provides a reserve of electric power which can be used judiciously when the need arises. Utilities and research organizations have performed comprehensive research on the applications of ESSs in power systems [1], [2]. A number of studies have been dedicated to identifying individual use cases and generating revenues from ESSs [3], [4]. A co-operation scheme for wind power and battery storage to bid into electricity market in providing frequency regulation, in terms of monetary income, has been described in [5]. Also, estimation of maximum potential revenue of grid connected ESSs based on the arbitrage and regulation markets has been presented in [6]–[8]. However, in these studies, the benefits of outage mitigation are not considered. A quantitative method to determine the size of ESSs to meet specified reliability targets was proposed by one of the authors in [9] and [10]. The method presented in [9] and [10] was extended in [11] to quantify the size of the required energy storage to firm up wind power and improve system reliability to a specific target. Although the prior work presented in [9]–[11] shows the benefits of an energy storage system from the point view of improving system reliability and firming up wind generation, the cost-benefit from improving reliability and other merits is not presented.

Different types of ESSs are being used nowadays. Large storage facilities, including pumped hydro storage (PHS) and compressed air energy storage (CAES) have been developed for decades. Battery energy storage systems (BESSs) are also available for grid-scale applications. Sodium-sulfur batteries, vanadium-redox flow batteries, lithium-ion batteries, and lead-acid batteries have been used in grid level applications. For instance, a 200 MW, 800 MWh vanadium-redox flow battery storage project is under construction in Dalian, China which will become the world's largest battery storage facility when completed (expected commissioning on December 31, 2020) [12]. Also, according to the Energy Storage Database of the Department of Energy [12], lithium-ion batteries are widely used and applied in a significant majority of grid-scale battery storage projects. The work presented in this paper considers the potential benefits for different types of applications from fast-acting ESSs, such as batteries, flywheels, etc; determination of the type of storage to be used is beyond the scope of this work.

The stacked revenue from an ESS cannot be calculated by simply aggregating the benefits from individual applications because a quantity committed to one market may not be committed to another during the same time interval. Hence, they have to be prioritized based on several factors such as customer satisfaction and economic viability. In this paper, improving

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The work reported in this paper was supported in part by Consumers Energy Corporation, Jackson, MI, USA.

system reliability is prioritized along with generating revenues from energy arbitrage and frequency regulation. Also, the cost-benefit analysis for each individual application of ESSs is studied and stacked with other applications for estimating the possible maximum revenue. In this study, service continuity is considered with the highest priority. This means that in the event of an outage, the ESS should discharge in an attempt to minimize the downtime at the load, even though participating in the energy or regulation market may bring higher profit.

Sequential Monte Carlo simulation (MCS) is used to track the state of charge (SOC) of the ESS and the outage events in the system while evaluating the reliability indices and interruption cost. Also, the same sequence of failures is used for the tested cases to provide a common base for the comparisons. The variable behavior of load and the forced outages of generators are also captured by the sequential simulation. For estimating the revenue from electricity market, a quadratically constrained linear programming optimization problem is developed. In this model, the control strategy for the ESS not only considers the energy storage capacity and charging/discharging power limits, but also includes the market mechanism constraints and application priority.

The remainder of this paper is organized as follows. Section II discusses the different applications and technical benefits of an ESS. Section III explains the mathematical models that are developed to calculate the revenue generated from each use case. Section IV describes the ESS operation strategy and managing concerns. Section V presents case studies on evaluating the contribution of ESSs. Section VI provides concluding remarks.

II. APPLICATIONS OF ENERGY STORAGE SYSTEM

ESSs can provide several services, such as bulk energy services (electric energy time-shift and electric supply capacity), ancillary services (regulation, voltage support, etc.), transmission and distribution (T&D) infrastructure services (T&D upgrade deferral, transmission congestion relief, etc.) and customer energy management services (power quality, demand charge management, etc.) [1], [2], [13]. This section focuses on describing outage mitigation, energy arbitrage, frequency regulation, and other technical benefits of ESSs.

A. Mitigation of Outages

Numerous factors may affect system reliability, such as failures of generating units, system faults and equipment failures. All these factors may lead to loss of load. In such situations, an ESS can effectively support customer loads when partial or complete loss of power from the source utility takes place. Sometimes, due to the capacity constraint, it might not be possible for the ESS to completely mitigate the outage. However, for such an event, it can shorten the interruption duration or reduce the number of interrupted customers.

The ESS can be installed at the transmission level, distribution level, or close to a customer site. If the ESS is owned by a utility with a large capacity, it can be treated as a dispatchable resource (subject to its energy limit) in improving the reliability in the interconnected area. It can also serve the

customer needs at an outage event, especially in some critical locations such as hospitals and correctional facilities, which can significantly benefit from using an ESS. This support may require the ESS and customer loads to island during the outage and re-synchronize with the utility when power is restored.

B. Energy Arbitrage

An energy storage system can be utilized to store energy during off-peak hours and then discharge at peak demand period for peak shaving or load following. This helps to reduce the generation cost and postpone the need for peaking units. It is also profitable for the ESS owners as they can take advantage of the energy price difference. The Locational Marginal Price (LMP) is usually used for wholesale electricity price, which indicates the value of energy at a particular location at any given point of time. To gain maximum benefit from this application, the ESS should be charged with less expensive energy at off-peak hours and discharged during the peak hours when LMPs are high. Therefore, locations with large variability in LMPs can be considered as ideal locations.

C. Frequency Regulation

Frequency regulation is another service for which energy storage is well suited. Frequency regulation helps to maintain the grid frequency within specified limits and to comply with the Real Power Balancing Control Performance (BAL001) and Disturbance Control Performance (BAL002) Standards of the North American Electric Reliability Council [14].

The frequency of any system may deviate from the specified value if there is an unforeseen imbalance between the generation and the load. Several generator actions are needed at this moment to restore the frequency back to the normal operating range. These include primary, secondary, and tertiary frequency control and may range from a few seconds to several minutes. A fast-acting ESS can help in such a situation, which helps to restore the frequency very quickly. Many ESS technologies respond significantly faster than conventional fossil fuel generators such as coal units and combustion turbines [15]. This property of the storage devices has been utilized by several utilities.

D. Other Technical Benefits

ESSs can also be used in a variety of other technical applications (not directly related to monetary benefits) that are crucial to the power grid operation and equipment lifetime. These applications can be classified according to the customers that are being served, e.g., residential, commercial, or industrial customers. Some of these applications are described in this section.

1) *Voltage Flicker Mitigation*: In power distribution systems, voltage flicker is often a problem that needs to be addressed. It is harmful for all types of customers. Voltage flicker may damage electrical devices ranging from the most common appliances used in a household to large equipment used in the industry. It may also lead to spoilage from semi-finished products in an industry. However, if an ESS is

installed in the system, it helps to stabilize the voltage by ramping up or down within a very short period of time, thus protecting the customer equipment.

2) *Power Factor Improvement*: The requirements of power factor improvement can be seen mostly among industrial customers who use a significant amount of reactive power for their daily operation. In most of the cases, they are charged with a penalty from the utility serving them if the power factor drops below a pre-specified limit. Those customers will be greatly benefited if they already have an ESS installed at their facilities.

3) *Upgrade Deferral*: An ESS can also be used for the deferral of transmission/distribution system upgrades. It can help in delaying investments that would otherwise be necessary to maintain the transmission and distribution capacity in accordance with the load demand. For example, purchase of a new transformer with a high capacity may be avoided by using an ESS instead.

4) *Voltage-regulator Lifetime Extension*: The deployment of distributed generators, such as photo-voltaic (PV) and wind power at the distribution system level, may decrease the lifetime of voltage regulators due to the increase in voltage fluctuations (e.g., the number of tap-changes increases). If ESSs are used at the distribution system level, (e.g., at a feeder) to reduce voltage fluctuations, the number of tap-changes of the regulator can be reduced, thus extending its lifetime.

5) *Emission Reduction*: Climate change and global warming are matters of concern nowadays and they are mostly related to emissions from fossil-fueled power plants. Thermal power plants across the world are among the largest consumers of fossil fuels. Since the peak power generated from renewable energy sources may not coincide with the system peak, integration of ESSs with these sources will reduce the peak time and level and therefore significantly reduce emissions from fossil-fueled power plants [16]. In other words, ESSs can store clean energy at off-peak hours (e.g., when wind power generation is high at night while load demand is low) and then discharge it at peak hours [17].

III. MATHEMATICAL MODELING

In this section, the mathematical models for evaluating revenue from mitigating outages, participating in energy arbitrage, and regulation market are presented.

A. Value from Mitigating Outages

When a contingency occurs, such as failure of a generator or a transmission line tripping, the load demand may not be satisfied. In the sequential MCS, random component failures are simulated. For each hour, the system state is defined by the component states and capacities. The sufficiency of power supply to each load is the combined effect of operation and generation and transmission adequacy. Then, a feasible dispatch is sought by solving an optimization problem, subject to the equality and inequality constraints of the power system operation limits and the availability of system components [18].

Customer damage functions (CDFs) are usually applied to display customer interruption costs, which can be determined for a given customer type and aggregated to produce section customer damage function for the various classes of customers [19]. The value of CDF depends on the type of customer served (e.g., the interruption cost for an industrial user is higher than a residential or an agricultural user). Composite customer damage function (CCDF) at each load point can be calculated by aggregating the weighted individual sector CDF at that load point. The CCDF can be converted into another index, i.e., the interrupted energy assessment rate (IEAR) in \$/kWh to evaluate the monetary loss as a function of the energy not supplied. The equations below show how to evaluate the system reliability indices and interruption cost.

$$\text{Minimize } Cost^{\text{int}} = \left(\sum_{i=1}^{N_b} C_i \times IEAR_i \right) \quad (1)$$

subject to

$$\begin{aligned} P(V, \delta) - P_D + C &= 0 \\ Q(V, \delta) - Q_D + C_Q &= 0 \\ P_G^{\min} &\leq P_G \leq P_G^{\max} \\ Q_G^{\min} &\leq Q_G \leq Q_G^{\max} \\ V^{\min} &\leq V \leq V^{\max} \\ |F(V, \delta)| &\leq F^{\max} \\ -\pi &\leq \delta \leq \pi \end{aligned} \quad (2)$$

where C_i is the load curtailment at bus i , $IEAR_i$ is the Interrupted Energy Assessment Rate at bus i , C is the vector of load curtailments ($N_b \times 1$), C_Q is the vector of reactive load curtailments ($N_b \times 1$), V is the vector of bus voltage magnitudes ($N_b \times 1$), δ is the vector of bus voltage angles ($N_b \times 1$), P_D and Q_D are the vectors of real and reactive power loads ($N_b \times 1$), P_G and Q_G are the vectors of real and reactive power outputs of the generators ($N_g \times 1$), $P_G^{\min}$, $P_G^{\max}$, $Q_G^{\min}$ and $Q_G^{\max}$ are the vectors of real and reactive power limits of the generators ($N_g \times 1$), $V^{\max}$ and $V^{\min}$ are the vectors of maximum and minimum allowed voltage magnitudes ($N_b \times 1$), $F(V, \delta)$ is the vector of power flows in the lines ($N_\ell \times 1$), and $F^{\max}$ is the vector of power rating limits of the transmission lines ($N_\ell \times 1$). In the foregoing description, N_b is the number of buses, N_ℓ is the number of transmission lines, and N_g is the number of generators.

The above model implies that for any encountered scenario (generation and transmission availability and load state) power will be routed through the network in such a manner so as to minimize the system interruption cost.

1) *Loss of load probability (LOLP)*: The LOLP is a widely used reliability index and it can be estimated as follows,

$$LOLP = E[\hat{\theta}] \quad (3)$$

where

$$\hat{\theta} = \frac{1}{T} \sum_{i=1}^{N_c} T_i^{\text{down}} \quad (4)$$

and T_i^{down} is the duration of an interruption encountered during the sequential MCS. N_c is the total number of simulated cycles and T is the total period of simulation.

2) *Expected demand not supplied (EDNS)*: The EDNS is the sum of the products of probabilities of failure states and the corresponding load curtailments, which can be estimated as follows.

$$EDNS = E[\hat{d}] \quad (5)$$

where

$$\hat{d} = \frac{1}{T} \sum_{i=1}^{N_c} (T_i^{\text{down}} \sum_{j=1}^{N_b} C_j) \quad (6)$$

3) *Interruption Cost*: The interruption cost in this paper is defined as the annual interrupted energy cost and can be calculated as follows.

$$\text{Interruption Cost} = E[\hat{\phi}] \quad (7)$$

where

$$\hat{\phi} = \frac{1}{T} \sum_{i=1}^{N_c} (T_i^{\text{down}} \sum_{j=1}^{N_b} C_j \times \text{IEAR}_j) \quad (8)$$

4) *Value From Outage Mitigation*: The value of reliability provided by the ESS is calculated by comparing the interruption cost with and without an ESS. The ESS is operated with the objective of maximizing the revenue from the arbitrage and regulation market at normal operating states where the SOC varies with time. The integration of an ESS can be modeled by a multistate model to capture the varying behavior. For each state, if the SOC value and its corresponding probability is provided, then the value from this use case can be expressed as follows:

$$\text{Value}_{\text{rel}} = E[\hat{\phi}_{\text{base}}] - \sum_{n=1}^{N_{\text{soc}}} E[\hat{\phi}_n] p_n^{\text{soc}} \quad (9)$$

where N_{soc} is the total number of SOC states and p_n^{soc} is the corresponding probability. $E[\hat{\phi}_n]$ is the interruption cost when the initial SOC of an outage event is at the n th state and $E[\hat{\phi}_{\text{base}}]$ is the interruption cost for the base case without an ESS.

B. Revenue from Arbitrage Market

In this section, a model for calculating the revenue from energy arbitrage is defined. If the ESS is operated for a period of time T_m , the total revenue from the arbitrage market can be calculated as:

$$\text{Income}_{\text{arb}} = \sum_{t=1}^{T_m} R_t^{\text{mp}} (P_t^{\text{arbd}} - P_t^{\text{arbc}}) \tau \quad (10)$$

where R_t^{mp} is the locational marginal price (\$/MWh) of the system at time t ; τ is the market dispatch time interval (assumed to be one hour in this work), and P_t^{arbc} and P_t^{arbd} are the quantities of power used charging and discharging respectively at time t , (i.e., these represent the power purchased and sold in the arbitrage market).

C. Revenue from Regulation Market

Independent System Operators (ISOs) and utilities purchase frequency regulation service from ESSs to compensate area control error (ACE) and to maintain frequency stability. According to the Federal Energy Regulatory Commission (FERC) order 755, market operators are required to apply pay-for-performance mechanism which should reflect the speed and accuracy of the device. ESSs are able to respond rapidly while following the regulation signal and therefore are motivated to participate in the regulation market. In PJM market, two different regulation signals are applied, i.e., RegA and RegD. RegA is mostly designed for traditional regulating resources, which is a low-pass filtered ACE signal [20]. On the other hand, RegD is generally used for faster responding resources like energy storage, which is a high pass filtered ACE signal.

Different ISOs implement pay-for-performance using different models. In this paper, the estimation method is developed based on a method used by PJM Interconnection. PJM implements frequency regulation by using a payment method that consists of two parts; a capability payment based on regulation market capability clearing price (RMCCP) and a performance payment using regulation market performance clearing price (RMPCP). These two parts are added up to obtain the total revenue from regulation market. Both the capacity and performance payments employ an actual performance score. Also, the performance credit includes a mileage ratio. The calculations are shown in the following equations [20]. The capability credit for a particular hour can be calculated as follows.

$$\text{Capability Credit} = P_t^{\text{reg}} \times S_t \times R_t^{\text{rmccp}} \quad (11)$$

where P_t^{reg} is the hourly-integrated regulation capacity (MW), S_t is the actual performance score, and R_t^{rmccp} is the RMCCP at time t . Similarly, the performance credit is calculated as follows.

$$\text{Performance Credit} = P_t^{\text{reg}} \times S_t \times \beta_t \times R_t^{\text{rmpcp}} \quad (12)$$

where β_t is the mileage ratio for that hour and R_t^{rmpcp} is the RMPCP at time t . Here mileage represents the absolute sum of the movement of the regulation signal in a given period and is the proxy metric for the amount of work performed. In this case, the mileage ratio is the ratio between the requested mileages of RegD signal and the referenced traditional regulation signal (RegA), which is defined as follows.

$$\text{Mileage Ratio} = \frac{\text{Mileage RegD}}{\text{Mileage RegA}} \quad (13)$$

The total income from the regulation market is the total of capability credit and performance credit and is expressed as follows.

$$\text{Income}_{\text{reg}} = \sum_{t=1}^{T_m} [S_t (R_t^{\text{rmccp}} + \beta_t R_t^{\text{rmpcp}}) P_t^{\text{reg}}] \quad (14)$$

IV. ENERGY STORAGE SYSTEM OPERATION STRATEGY

In this section, the optimization model to estimate the maximum stacked revenue from improving system reliability and participating in energy and regulation markets is presented.

A. Objective

The objective of this problem is to estimate the maximum benefit from an ESS in the grid which is equal to the summation of value from outage mitigation ($\text{Value}_{\text{rel}}$), income from the arbitrage and regulation markets ($\text{Income}_{\text{arb}}$ and $\text{Income}_{\text{reg}}$) as stated in (15).

$$\text{Benefit} = \text{Value}_{\text{rel}} + \text{Income}_{\text{arb}} + \text{Income}_{\text{reg}} \quad (15)$$

In this paper, the reliability is given a higher priority than monetary benefits, which implies that in the event of an outage, the ESS should discharge to minimize the downtime of service to the load, no matter which use case brings more monetary benefits. During the periods when there is no outage event, the storage system is operated to maximize the revenue from the arbitrage or the regulation market. The value from outage mitigation can be evaluated by calculating the reduction in the interruption cost, which is presented in section III.

To estimate the income from the arbitrage and regulation, a quadratically constrained linear programming model is developed. In this optimization model, the variables are $P_t^{\text{arb}d}$, $P_t^{\text{arb}c}$ and P_t^{reg} , where $P_t^{\text{arb}d}$, $P_t^{\text{arb}c}$ are the quantities sold and purchased in the arbitrage market at time t ; P_t^{reg} is the committed regulation capacity at time t , which can be utilized for regulation up or down based on the regulation signal. The objective is to maximize the income from the energy and regulation markets as follows.

$$\begin{aligned} \text{Maximize} \quad & \sum_{t=1}^{T_m} \left[R_t^{\text{imp}} (P_t^{\text{arb}d} - P_t^{\text{arb}c}) \tau \right. \\ & \left. + S_t (R_t^{\text{rmccp}} + \beta_t R_t^{\text{rmcp}}) P_t^{\text{reg}} \right] \end{aligned} \quad (16)$$

B. Constraints

The operation of an ESS can be modeled by its energy storage capacity, charging and discharging power limits, charging and discharging efficiencies. The state of charge of an ESS reflects the ratio of the current capacity to the rated capacity, which depends on the SOC of the previous period and the current charging/discharging operation. The state of charge at time t is represented as follows.

$$\text{SOC}_t = \text{SOC}_{t-1} + \frac{\Delta E_t}{E^{\text{rated}}} \quad (17)$$

where E^{rated} is the rated energy capacity, and ΔE_t is calculated as below.

$$\Delta E_t = E_t^{\text{arb}c} - E_t^{\text{arb}d} + E_t^{\text{reg}c} - E_t^{\text{reg}d} \quad (18)$$

where $E_t^{\text{arb}c}$ and $E_t^{\text{arb}d}$ are the charged and discharged energy in the arbitrage market; $E_t^{\text{reg}c}$ and $E_t^{\text{reg}d}$ are the charged and discharged energy in the regulation market, respectively. They are calculated as follows.

$$\begin{aligned} E_t^{\text{arb}c} &= P_t^{\text{arb}c} \tau \gamma_c \\ E_t^{\text{arb}d} &= P_t^{\text{arb}d} \tau / \gamma_d \\ E_t^{\text{reg}c} &= \begin{cases} -P_t^{\text{reg}} \eta_t^{\text{reg}} \tau \gamma_c, & \text{if } \eta_t^{\text{reg}} < 0 \\ 0, & \text{otherwise} \end{cases} \\ E_t^{\text{reg}d} &= \begin{cases} P_t^{\text{reg}} \eta_t^{\text{reg}} \tau / \gamma_d, & \text{if } \eta_t^{\text{reg}} > 0 \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (19)$$

where η_t^{reg} is the RegD signal at time t , γ_c and γ_d are the charging and discharging efficiencies. The positive/negative sign of the RegD signal implies that the power system needs regulation up/down service and the ESS is required to discharge/charge accordingly.

The operation is subject to the following constraints.

$$\text{SOC}^{\min} \leq \text{SOC}_t \leq \text{SOC}^{\max} \quad \forall t \in T_m \quad (20)$$

$$0 \leq P_t^{\text{arb}d}, P_t^{\text{arb}c}, P_t^{\text{reg}} \leq P^{\max} \quad \forall t \in T_m \quad (21)$$

$$(P_t^{\text{arb}d} + P_t^{\text{arb}c}) \times P_t^{\text{reg}} = 0 \quad \forall t \in T_m \quad (22)$$

$$P_t^{\text{arb}d} \times P_t^{\text{arb}c} = 0 \quad \forall t \in T_m \quad (23)$$

$$P_t^{\text{arb}d}, P_t^{\text{arb}c}, P_t^{\text{reg}} = 0 \quad \forall t \in T^{\text{down}} \quad (24)$$

$$\text{SOC}_t = \text{SOC}_t^{\text{down}} \quad \forall t \in T^{\text{down}} \quad (25)$$

$$\sum_{t=1}^{T_m} (E_t^{\text{arb}d} + E_t^{\text{reg}d}) \leq \eta_{\text{cyc}} (\text{SOC}^{\max} - \text{SOC}^{\min}) \quad (26)$$

where T^{down} is the set of all intervals when the system has an outage event and the system is in a down state. $\text{SOC}_t^{\text{down}}$ is the state of charge at the time when the system is in the down state. T^{down} and $\text{SOC}_t^{\text{down}}$ are obtained from the sequential MCS. SOC is constrained with lower and upper bounds by $\text{SOC}^{\min}$ and $\text{SOC}^{\max}$ as shown in (20). Charging and discharging power limits are represented by (21). The quadratic constraint in (22) indicates that during each period, the ESS is assumed to participate in one market at most. Besides, it is assumed that the ESS cannot sell and buy energy in the arbitrage market simultaneously as stated in (23). Equation (24) shows that when an outage event occurs, the ESS should discharge to mitigate the outage and (25) implies the SOC should be equal to the SOC value at the down states.

The life of ESSs is a vital concern for the operators and utilities, which is determined by its calendar life and cycle life. Calendar life of an ESS captures its aging and degradation over time and is affected by several factors such as temperature and humidity. This implies that the battery degrades even though it is stored and unused. On the other hand, cycle life depends on cycle aging, which not only includes the number of cycles, but may also depend on the depth of discharge and the mean SOC of cycles. For example, deep cycles can reduce the life span of lithium-ion batteries significantly, but the cycle life of vanadium redox flow battery is not dependent on the depth of discharge [1]. To extend the lifetime of the ESS, (26) is included to limit the number of discharge cycles (η_{cyc}) [21].

V. CASE STUDIES AND RESULTS

In this study, the IEEE Reliability Test System (IEEE-RTS), which has been extensively used for power system reliability studies, is utilized for estimating the profit from mitigating outages by an ESS. This system consists of 24 buses, 33 transmission lines, 5 transformers, and 32 generating units. The system data, including generation capacities, transmission limits, load profile and reliability parameters, are provided in [22] and the single line diagram of this test system is shown in Fig. 1. Also, the IEAR values for this test system is presented in table I [23].

PJM historical data is utilized for evaluating the revenue from participating in energy and regulation markets [24]–[26].

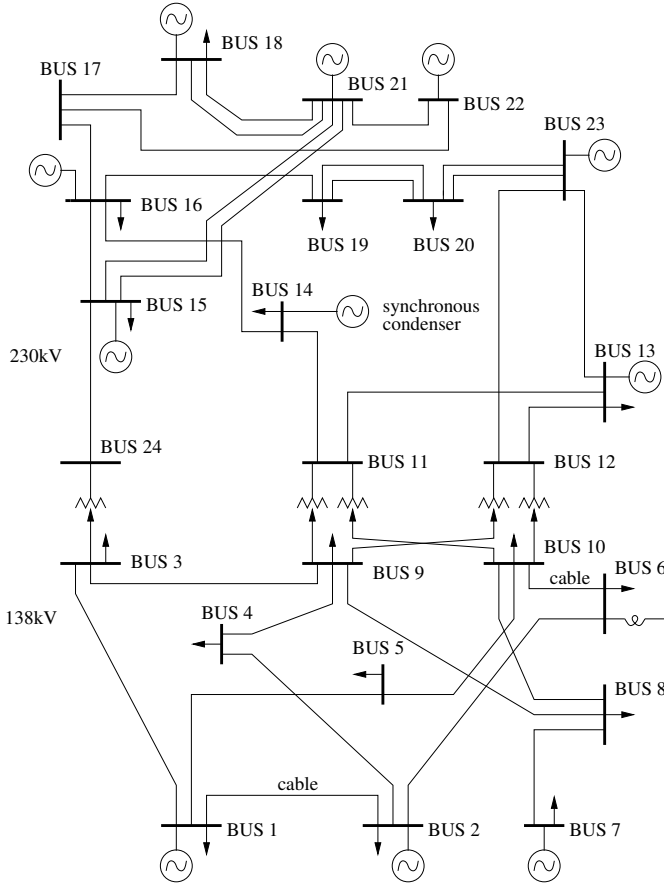


Fig. 1. Single line diagram for IEEE RTS

TABLE I
IEEE RTS-24 IEAR VALUES

Bus No.	IEAR (\$/kWh)	Bus No.	IEAR (\$/kWh)	Bus No.	IEAR (\$/kWh)
1	6.20	9	2.30	17	–
2	4.89	10	4.14	18	3.75
3	5.30	11	–	19	2.29
4	5.62	12	–	20	3.64
5	6.11	13	5.39	21	–
6	5.50	14	3.41	22	–
7	5.41	15	3.01	23	–
8	5.40	16	3.54	24	–

The historical data, including the LMP, RMPCP, RMCCP, mileage ratio, and RegD signal are available on the PJM website. Data from June, 2016 to May, 2017 are used in this study. In the PJM regulation market, the regulation up and down signals are considered as one signal. The RegD regulation signal is normalized so that the values lie between -1 and 1 , where the negative and positive signs represent for regulation down and up, respectively. All data used here are converted to hourly data.

A. ESS Size and Location

While determining the location and size of an ESS, several aspects need to be considered. First, the land availability needs

to be given importance. The utility or the investor needs to make sure that there is enough space for an ESS. An alternative is to use a mobile trailer which provides a flexible solution for smaller ESSs. Other concerns, such as noise regulations, customer types and existing system performance should also be taken into consideration. Locations which require system upgrades, have larger LMP fluctuations or inferior reliability may be better candidate locations than others. In this study, the candidate locations are evaluated based on the amount of reliability improvement it can bring to the system, i.e., the extent to which an ESS at a candidate location can improve the system EDNS and reduce the interruption cost. The power and energy capacity of the ESS are set as 20 MW and 20 MWh, and it is assumed that this chosen size is not sufficiently large to impact the market price.

The SOC is constrained between 15% and 95% to avoid very low or very high values. The charging and discharging efficiencies are both 85%. Redox flow batteries are considered for the demonstration, since they are suitable for grid-scale applications and have large cycle life [27], [28]. The ESS parameters are shown in table II.

TABLE II
ESS PARAMETERS

Parameter	Value
Power Capacity	20 MW
Energy Capacity	20 MWh
SOC^{min}	15%
SOC^{max}	95%
γ_c	85%
γ_d	85%

B. Solution Procedure

The results are obtained by following the three steps as shown in figure 2.

1) *Step I*: Estimate the distribution of the SOC and develop the multi-state model for the reliability analysis. The annual hourly SOC can be obtained by solving the optimization problem with the objective function (16) and subject to constraints (20)–(23) and (26).

2) *Step II*: Calculate the reliability indices and value from outage mitigation by solving the model represented by (1)–(9). Also, track the time interval when system is in down state (T^{down}) and the SOC at that time (SOC^{down}) for the next step, since the same sequence of failures is used to provide a common base for the comparisons.

3) *Step III*: Solve the optimization problem given in (16)–(26). The revenue from arbitrage and regulation market with market mechanism constraints and application priority is obtained.

The optimization problems in step I and III are solved by the General Algebraic Modeling System (GAMS).

C. Results

1) *Histogram of Annual SOC*: In this section, the histogram of hourly SOC for a year is presented. The histogram is

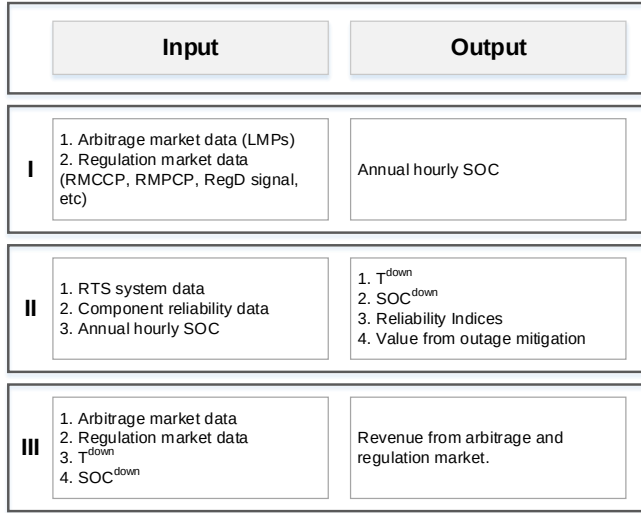


Fig. 2. Proposed solution procedure

shown in figure 3. The average value of each bin and the corresponding probability is given in table III.

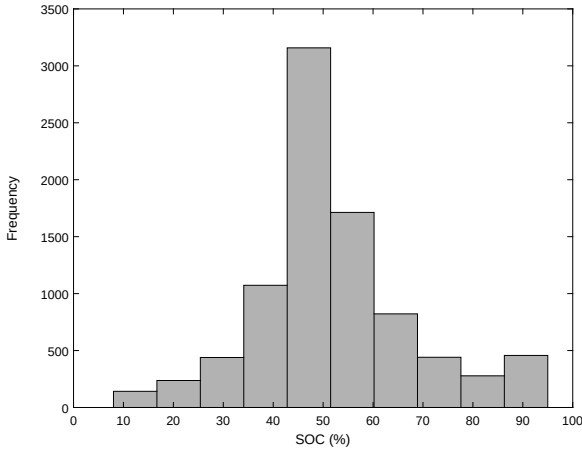


Fig. 3. Histogram of SOC for a year

TABLE III
ESS SOC VALUE AND STATE PROBABILITY

State No.	1	2	3	4	5
Average SOC (%)	19	27	35	43	51
Probability	0.0337	0.0381	0.0783	0.1572	0.3692
State No.	6	7	8	9	10
Average SOC (%)	59	67	75	83	91
Probability	0.1332	0.0715	0.0402	0.0296	0.0491

2) *Reliability Improvement*: First, the sequential MCS is performed on the base case (without ESS) to estimate the reliability indices and the interruption cost. The results are shown in table IV.

The evaluation of a 20 MW, 20 MWh ESS at five selected load buses (bus 6, 9, 10, 13 and 18) are performed; the system

TABLE IV
RELIABILITY INDICES OF THE BASE CASE

Base Case	LOLP	EDNS (MW/year)	Interruption cost (\$/year)
Value	0.0026	0.23504	4,719,762

TABLE V
RELIABILITY IMPROVEMENT WITH THE ESS

Bus No.	LOLP	EDNS (MW/year)	Interruption cost (\$/year)
6	0.0026	0.22895	4,597,234
9	0.0026	0.22905	4,599,175
10	0.0026	0.22904	4,599,133
13	0.0026	0.22915	4,601,397
18	0.0026	0.22907	4,599,724

reliability improves more when the ESS is installed on these buses [11]. The SOC value at the beginning of the outage event is represented by the multi-state model as given in table III. The results for these five cases are shown in table V. The improvement on the other buses are very small. The reliability indices and interruption costs are almost the same as in the base case, therefore, they are not displayed here. From the results, we can see that the LOLP is not improved and the EDNS and interruption costs are reduced. This happens as the ESS does not have enough capacity to compensate the loss of load. Thus, the ESS cannot reduce the number of outage events. However, it is still significant in improving system reliability, since it can reduce the number of interrupted customers and the interruption cost.

3) *Revenue from Arbitrage and Regulation Markets*: The simulation runs on a daily basis ($T_m = 24$), and an additional constraint: $SOC_{24} - SOC_0 = 0$ is considered to ensure that the initial and the final states are consistent [29], i.e., SOC at the beginning of a day is the same as the SOC at the end of the previous day. The SOC_0 is assumed to be 50% for the case studies.

Figure 4 illustrates the optimal amount of capacity participated in the arbitrage and regulation markets and the variation of SOC for one day with no outage event.

The outage events and durations are tracked in the sequential MCS. For these hours, the ESS is unavailable to generate revenue from the arbitrage or the regulation market. The results for each day are obtained by solving the quadratically constrained linear programming. The revenue for each month and the whole year are calculated and listed in table VI.

4) *Stacked Revenue*: Table VII presents the stacked revenue for a year. From the results, it can be concluded that the regulation market generates more revenue than the arbitrage market since the ESS purchases energy from the arbitrage market but sells most of the energy to the regulation market, where the revenue is higher.

D. Estimated Income

This part discusses the total estimated income an ESS can generate. The total expenditure for an ESS can be broken down

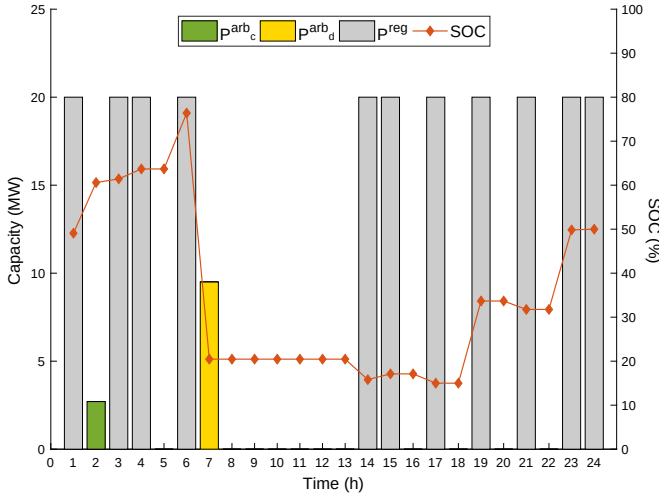


Fig. 4. Capacity and SOC for an example day

TABLE VI
REVENUE FROM ARBITRAGE AND REGULATION MARKET

Month	Arbitrage Market (\$)	Regulation Market (\$)
January	5,423	178,075
February	2,790	134,877
March	11,242	132,593
April	4,466	132,593
May	5,771	204,478
June	8,461	183,584
July	8,460	250,559
August	10,189	232,081
September	5,010	246,339
October	4,967	231,261
November	3,826	197,093
December	6,970	160,945
Annual	77,575	2,300,486

TABLE VII
STACKED REVENUE FOR A YEAR

Bus No.	Outage Mitigation (\$)	Arbitrage Market (\$)	Regulation Market (\$)	Stacked Revenue (\$)
6	122,528	77,575	2,300,486	2,500,589
9	120,587	77,575	2,300,486	2,498,648
10	120,629	77,575	2,300,486	2,498,690
13	118,365	77,575	2,300,486	2,496,426
18	120,038	77,575	2,300,486	2,498,099

into capital and operation and maintenance (O&M) costs. Typically, the capital cost and O&M costs for a Redox flow BESS can be assumed to be \$900/kWh and \$5.7/kWh per year [27], respectively. The cost for O&M has been considered as an average value since it changes over the years. The cost increases as the battery ages, since more maintenance is required to keep the performance of the degrading battery at a constant level. Hence, for the BESS considered in this paper, the installation cost is estimated to be \$18 M with an additional \$0.114 M (average) per year for operation and maintenance.

Table VIII below summarizes the cycle life, capital cost and O&M cost of redox flow batteries [1], [27].

TABLE VIII
PARAMETERS OF REDOX FLOW BATTERY

Parameter	Calendar Life [1]	Cycle Life [27]	Capital Cost (\$/kWh) [27]	O&M Cost (\$/kWh/yr) [1]
Value	10 years	13,000	900	5.7

In this study, the number of discharge cycles (η_{cyc}) is restricted to 3.5 cycles per day, thus it can be used for 10 years. Then the approximate stacked income can be calculated by subtracting the installation and O&M cost from the total stacked revenue of the 10 years. Table IX tabulates the estimated income when an ESS is installed at bus 6.

TABLE IX
ESTIMATED INCOME

Parameter	Value
Annual Stacked Revenue (M\$)	2.5
Lifespan (year)	10
Total Revenue (M\$)	25
Total Installation and O&M (M\$)	19.14
Total Income (M\$)	5.86

E. Discussion

From the results of the case studies, it can be observed that the ESS generates the majority of its profit from the regulation market. However, participating in the regulation market also leads to frequent cycling. Operators need to consider the cycling constraint when they make decisions for bidding. In addition, the prices for the regulation markets have declined over the years and as the trend continues, the utilities should keep in mind this factor while estimating their revenue from the applications of an ESS.

Although the value derived from the mitigation of outages is smaller than revenues from the markets, it bears an intangible but significant value in terms of customer satisfaction. It helps the utility to build positive reputation among its customers by providing a reliable power supply. The value of improving reliability can be higher if the ESS is able to serve some critical loads, such as schools and hospitals.

VI. CONCLUSION

This paper has presented a method for quantifying the benefits of stacking up the applications of an ESS. Three applications (outage mitigation, energy arbitrage, and frequency regulation) were considered. Several case studies were performed to evaluate the reliability indices and the cost benefits. Sequential MCS was used to track the charging and discharging performance of the ESS and also the outage events in the system while evaluating the reliability indices and interruption cost. The variable behavior of load demand and the forced outages of generators were also captured by the sequential MCS. A quadratically constrained linear

programming model was established to estimate the potential revenue from arbitrage and regulation markets. The paper presents several benefits from installing an ESS and utilizing it for the applications stated above. The approach described in this paper can be utilized by industries including utilities and manufacturers to build business cases when they want to install an ESS for their facilities. Future work includes the development of a more comprehensive framework and converting the benefits from other applications mentioned in section II to monetary profits and stacking them up to estimate the maximum revenue. Also, a detailed and comprehensive methodology on the revenue generated over a longer period of time, e.g., ten years, considering the improvement of the ESS technology, the variability of market price and the trade-off between cycle life and profit, is under development.

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