

Reliability and Environmental Benefits of Energy Storage Systems in Firming up Wind Generation

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Abstract—This paper presents a method to evaluate the reliability and environmental benefits of energy storage systems (ESSs) applied in firming up grid connected wind farms. Due to the variability and uncertainty of wind energy, ESSs have the potential to play a significant role in firming up the output power of wind farms. In this context, determining the size of ESSs in terms of rated power and energy is a crucial factor. In this paper, a method to quantify the necessary ESSs to firm up wind generation or to meet a certain reliability target is discussed. Also, this paper presents a method to evaluate the monetary benefits of both reliability improvement and emission reduction. Sequential Monte Carlo simulation and optimal power flow calculations are carried out in evaluating system reliability and the monetary benefits. The proposed method is demonstrated on the IEEE reliability test system (IEEE-RTS) to determine the reliability and environmental benefits from a wind farm with energy storage system.

Index Terms—Energy storage system, environment, reliability, sizing and siting, wind generation.

I. INTRODUCTION

Integration of renewable energy sources into power grids has several advantages, such as reductions in emission and cost. However, the intermittent nature of these sources leads to a number of concerns, such as stability, peak load capability, and generation adequacy. Also, maintaining the efficiency and reliability of the grid, especially with high penetration of variable generation, has become a challenging task. Consequently, energy storage systems (ESSs) are being deployed nowadays as a practical solution to overcome these challenges allowing increased renewable energy integration. Also, ESSs are expected to improve system reliability and stability, provide flexibility in managing unit commitment challenges, and participate in electricity market to avoid negative spot prices. However, determining the size of ESSs is a challenging task. Also, it is necessary to determine their economical, environmental, and reliability benefits in the planning phase.

Large storage facilities, including pumped hydro storage (PHS) or compressed air energy storage (CAES) have been developed since 1920s. In particular, PHS is widely used and accounts for around 95% of the entire storage capacities (MW) [1]. Battery storage systems (BESSs), such as sodium-sulfur BESS, lead-acid BESS, lithium-ion BESS, vanadium redox flow BESS and others have been applied in power grid starting

from the mid 1980s. Although the power and energy capacities of BESSs are not comparable with PHS systems, with the development of battery technology, the capacity of BESSs is on the rise. 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 Dec 31, 2020) [1].

An ESS can be utilized in a large number of applications. Reports from several organizations and national laboratories have been published, describing the applications of ESSs in power systems [2]–[4]. Besides these, an ESS can also be used for the benefit of the environment. For example, the carbon dioxide and nitrous oxide emissions from peaking generation are significantly higher than that of combined cycle power plants. Incidentally, these also make up a large portion of existing gas fired generation today. ESS might be used to counter these ill-effects of peaking generation. For example, some economic dispatch models with environmental objectives or constraints have been studied in [5]–[7]. It presents an intelligent economic dispatch (ED) model which aims to minimize emission and operation costs (including wind power cost, fuel cost, and battery cost). In [8], a simultaneous perturbation method for Lagrangian relaxation is proposed for economic dispatch problems applying environmental aspects as constraints. The impact of ESS on reliability is analyzed in [9]–[11]. A quantitative method to determine the size of energy storage systems to meet specified reliability targets was proposed by the authors in [9], [10]. The work presented in [11] extends this method to quantify the size of the required energy storage to firm up wind power and improve system reliability to a specific target. These works show the benefits of energy storage system from the point of view of improving system reliability and firming of wind generation.

In planning of energy storage system projects, the investment cost is a crucial factor. Several researchers have investigated the cost of integrating ESS into the power grid and shown that it depends on several factors including the size of the ESS and also the technology being used [12]. With the improvement of energy technology, it is expected to foresee the reduction in price and expansion of ESS. Here, only the

benefits from reliability improvement and emission reduction are considered, while a discussion on the type of ESS to be used and its capital cost are beyond the scope of this paper.

This paper discusses the quantification of ESSs in firming up wind energy and evaluates their reliability and environmental benefits. The environmental aspects of integrating ESSs with wind generation is provided and the benefits of reliability improvement and emission reduction is monetized. The sizes and locations of ESSs are determined based on the capacity value of wind power and the sensitivity of system reliability indices with respect to wind farm location. Sequential Monte Carlo simulation is carried out in evaluating system reliability and the monetary benefits.

The remainder of this paper is organized as follows. Section II briefly discusses about the methodology for quantifying energy storage. Section III explains the mathematical models, including the objective and constraints. Section IV describes the method to evaluate benefit of reliability improvement and emission reduction. Section V presents the case studies and the results. Section VI provides some concluding remarks about the research and its findings.

II. QUANTIFICATION OF ENERGY STORAGE

In this section, the methodology for quantifying the energy storage is briefly discussed. A power system is considered in which the wind farm under consideration provides supply to a load with availability ρ_0 . Now, it is assumed that a part of the load curtailment, P_L , can be directly attributed to the variability of wind power. This quantity can be determined from the difference between the nameplate capacity and the capacity value of the wind farm. The capacity value is the amount of load the wind farm can reliably support, given the variability of wind. Firming the wind output consists of adding a storage system that is sufficient to increase the availability of supply to ρ_1 , which is what would be available if there were firm (dispatchable) generation instead of wind. Thus, the power capacity of the required storage unit should be at least P_L . The energy capacity can then be determined as follows.

The unavailability reduction ratio α can be defined as:

$$\alpha = \frac{1 - \rho_1}{1 - \rho_0}. \quad (1)$$

The unavailability reduction ratio can be explained as follows. Let $\rho_0 = 0.999$ and it is required to increase the availability by an additional “9,” i.e., to $\rho_1 = 0.9999$; then, $\alpha = 0.1$.

It is assumed that the storage system which will improve the system reliability to ρ_1 can sustain a load of P_L for time t_A . Then, service interruption occurs when grid supply is down and the storage has been depleted. The probability of this event can be described by (2).

$$\begin{aligned} P\{L_s\} &= P\{R > t_A\} \cap L_{\bar{s}} \\ &= P\{R > t_A \mid L_{\bar{s}}\} P\{L_{\bar{s}}\} \\ &= \left(\int_{t_A}^{\infty} f_R(r) dr \right) P\{L_{\bar{s}}\}. \end{aligned} \quad (2)$$

The variables in (2) are defined as follows.

$L_{\bar{s}}$: event that the load is curtailed in the absence of storage;
 L_s : event that the load is curtailed in the presence of storage;
 R : random variable representing the down time (outage duration);

$f_R(r)$: probability density function of R .

In (2), $P\{L_s\}$ is clearly $1 - \rho_1$, and $P\{L_{\bar{s}}\} = 1 - \rho_0$. From (1) and (2), it is clear that

$$\int_{t_A}^{\infty} f_R(r) dr = \alpha. \quad (3)$$

Equation (3) represents the basic relation that quantifies the required energy capacity of the storage system. However, the storage unit itself may not be perfectly reliable. In order to compensate for this, the storage device should have an energy capacity that enables it to provide the required power (P_L) for a period of time (t_S) that is given by (4).

$$t_S = \frac{t_A}{A_S}, \quad (4)$$

where A_S is the availability of the storage system. Therefore, the power capacity of the selected storage unit should be at least P_L , and the energy capacity should be at least $P_L t_S$.

The solution to (4), given by t_A , is the length of time for which the storage unit can support the load not served by wind, and it can be directly calculated from Monte Carlo simulation. Therefore, the power capacity of the selected storage unit should be at least P_L , and the energy capacity should be at least $P_L t_S$. Solutions of (3) for different system down time distributions, such as exponential and Weibull distributions, are given in [9] and are not reproduced in this paper.

III. MATHEMATICAL MODELING

In this section, the objective function and the constraints of the system model for reliability and emission evaluation with energy storage system are described. In composite reliability evaluation studies, repetitive solutions of an optimization problem with an objective function of minimizing interruption cost are performed. This section describes the formulation and incorporation of the optimization problem using the AC power flow model. Sequential Monte Carlo simulation is used to emulate the behavior of the system and estimate system reliability indices. This consists of sequential assessments of the reliability of the states that the system assumes in successive time steps over the planning horizon. For these states, the objective is to determine a dispatch that minimizes the interruption cost, subject to system constraints.

A. Objective Function

Numerous factors may affect system reliability such as random unit breakdowns, huge variations in demand, scheduled maintenances and so on. All these factors may lead to load and financial losses. During 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

mitigate the outage completely. However, for such an event, it can shorten the interruption duration or reduce the number of customers interrupted.

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 [13]. The value depends on the type of customer served. For example, 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 such as the interrupted energy assessment rate (IEAR) in \$/kWh to evaluate the monetary loss as a function of the energy not supplied. The equation below shows the objective function of the system model as minimizing the interruption cost, $Cost_t^{int}$, at each time period t .

$$\text{Minimize } Cost_t^{int} = \left(\sum_{i=1}^{N_b} C_i \times IEAR_i \right) \quad (5)$$

where C_i is the load curtailment at bus i and $IEAR_i$ is the Interrupted Energy Assessment Rate at bus i .

When a fault occurs in the power system, such as a generation loss or a transmission line tripping, the load demand may not be satisfied. In the sequential Monte Carlo Simulation (MCS), the 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, generation, and transmission adequacy. Then, a feasible dispatch is sought by solving for minimum load curtailment subject to the equality and inequality constraints of the power system operation limits and the availability of system components.

B. Power System Constraints

The above mentioned objective function is bounded by the following constraints, including the equality constraints of power balance, the inequality constraints of equipment capacity, power quality, and the availability of system components.

$$\begin{aligned} P(V, \delta) - P_D + C &= 0 \\ Q(V, \delta) - Q_D + C_Q &= 0 \\ P_G^{min} &\leq P_G \leq P_G^{max} \\ Q_G^{min} &\leq Q_G \leq Q_G^{max} \\ V^{min} &\leq V \leq V^{max} \\ |F(V, \delta)| &\leq F^{max} \\ \delta &\text{ unrestricted.} \end{aligned} \quad (6)$$

where 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 ($N_t \times 1$), F^{max} is the vector of power rating limits of the transmission lines ($N_t \times 1$). In the foregoing description, N_b is the number of buses, N_t is the number of transmission lines, and N_g is the number of generators.

C. ESS Operation Constraints

The operation of an ESS can be modeled by its energy storage capacity, charging and discharging power limits, and storage and conversion efficiencies. The energy storage state of charge (SOC) at the end of each period depends on the SOC of the previous period and the current charging/discharging operation. The SOC (S_t) at time t is formulated as follows.

$$SOC_t = (1 - \alpha)SOC_{t-1} + \gamma_c E_t^{Chr} - E_t^{Dis}, \forall t \in T \quad (7)$$

where α is the self-discharge rate of the battery, $1 - \alpha$ is the storage efficiency (%), γ_c is the conversion efficiency (%). E_t^{Chr} and E_t^{Dis} are the charged and discharged energy (MWh) in the current period, respectively.

During the operation period, an ESS is subjected to the following constraints.

$$\begin{aligned} SOC_{min} &\leq SOC_t \leq SOC_{max}, \forall t \in T \\ 0 &\leq P_t^{Chr} \leq P_{max}^{Chr}, \forall t \in T \\ 0 &\leq P_t^{Dis} \leq P_{max}^{Dis}, \forall t \in T \end{aligned} \quad (8)$$

where SOC_{min} and SOC_{max} are the lower and upper bounds of SOC of the energy storage devices, P_t^{Chr} and P_t^{Dis} are the charging/discharging power rates at time t , and P_{max}^{Chr} and P_{max}^{Dis} are the maximum charging/discharging rates, respectively.

IV. EVALUATION OF RELIABILITY AND ENVIRONMENTAL IMPACTS

In this section, the evaluation of reliability improvement and the cost benefit of emission reduction is presented.

A. Reliability and Interruption Cost

In order to capture interruption times and state of charge of the storage system, all indices are determined from sequential MCS.

a) *Loss of load probability (LOLP)*: The LOLP index can be estimated as follows.

$$LOLP = E[\theta]; \quad \theta = \frac{1}{T} \sum_{i=1}^{N_c} T_i^{down} \quad (9)$$

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

b) *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.

$$EDNS = E[\hat{d}]; \quad \hat{d} = \frac{1}{T} \sum_{i=1}^{N_c} (T_i^{down} \sum_{j=1}^{N_b} C_j) \quad (10)$$

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

$$\text{Interruption cost} = E[\hat{\beta}] \quad (11)$$

where

$$\hat{\beta} = \frac{1}{T} \sum_{i=1}^{N_c} (T_i^{down} \sum_{j=1}^{N_b} C_j \times IEAR_j)$$

B. Emission and Emission Cost

Once a feasible dispatch has been attained using the above mentioned system model, the corresponding emissions for each hour Em (Lbs/hour) from the conventional units can be obtained using (12).

$$Em_j = \sum_{i=1}^{Ng} f_{ij} (a_{ij} + b_{ij} P_{G_i} + c_{ij} P_{G_i}^2) \quad (12)$$

where f_{ij} is the emission factor of generator i for type j air emission in Lbs/MMBTU ($j = 1, 2, 3$ or 4 for the CO_2 , CO , SO_2 or NO_x emissions respectively), a_{ij} , b_{ij} and c_{ij} are heat rates (MMBTU/MWh).

The total emission cost is calculated as follows.

$$Em_{cost} = \sum_{j=1}^{N_{em}} \eta_j \times Em_j \quad (13)$$

where N_{em} is the total number of emission types and η_j is the emission cost rate of emission type j .

V. CASE STUDIES AND RESULTS

In this study, the IEEE RTS is used to demonstrate the proposed framework. 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 given in [14] and the single line diagram of this test system are given in Fig. 1. Also, the IEAR values for this test system is presented in Table I [15]. The emission coefficient data is shown in Table II. Here the emission cost is calculated for CO_2 only and the emission cost rate is considered as 30 \$/tons [16], [17].

A wind farm with 200 MW capacity is added to the system at the load buses assuming that all WTGs are identical (100 WTGs with nameplate capacity of 2 MW each) [11]. Actual observed wind speed data sets are used to calculate the output of WTGs [18].

Two case studies are performed to show the benefit from a wind farm with an ESS as follows:

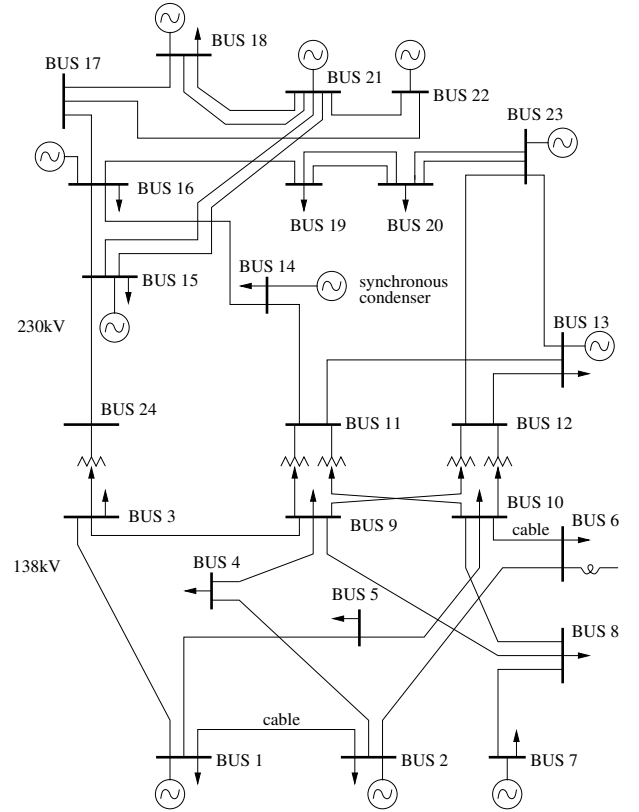


Fig. 1. Single line diagram of the IEEE RTS

TABLE I
IEEE RTS-24 IEAR VALUES

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

- 1) Case study 1 (Base case): The reliability indices, interruption cost, emission, and emission cost are evaluated for the original IEEE-RTS without wind farm or ESS.
- 2) Case study 2: The evaluations are performed on the system which is the original IEEE-RTS with one 200 MW wind farm and an ESS at the selected load bus.

A. ESS Size and Location

The sizes and locations of the ESS, which are determined using the method presented in section II, are listed in Table III for the five selected load buses [11].

TABLE II
UNIT EMISSION DATA

IEEE-RTS Unit Group	20	12, 100, 197	76, 155, 350
Unit type	GT	ST	ST
Fuel type	FO2	FO6	Bituminous Coal
Fuel sulfur content (%)	0.2	Unit-Specific	Unit-specific
Emissions Rate			
SO_2 (Lbs/MMBTU)	0.2	Unit-specific	Unit-specific
NO_x (Lbs/MMBTU)	0.5	0.5	Unit-specific
Part (Lbs/MMBTU)	0.036	0.1	Unit-specific
CO_2 (Lbs/MMBTU)	160	170	210
CH_4 (Lbs/MMBTU)	0.002	0.002	0.001
N_2O (Lbs/MMBTU)	0.004	0.004	0.004
CO (Lbs/MMBTU)	0.11	0.04	0.02
VOCs (Lbs/MMBTU)	0.04	0.007	0.003

TABLE III
ENERGY STORAGE AT DIFFERENT BUSES

Bus No.	Capacity (MW)	t_S (hour)
6	153.3	3
9	153.3	3
10	153.3	3
13	153.3	4
18	153.3	4

B. Results

Results of the two case studies are presented in this section.

a) *Case Study 1*: The sequential MCS is performed on the base case (without wind farm or ESS) for the reliability and emission evaluation. Table IV lists the LOLP, EDNS, and interruption cost and Table V presents the CO_2 , CO , SO_2 , and NO_x emissions and emission cost.

TABLE IV
RELIABILITY EVALUATION OF THE BASE CASE

Base Case	LOLP	EDNS (MW/year)	Interruption Cost (\$/year)
Value	0.0016	0.2184	6,021,000

TABLE V
EMISSION EVALUATION OF THE BASE CASE

CO_2 (tons/year)	CO (tons/year)	SO_2 (tons/year)	NO_x (tons/year)	Emission Cost (\$/year)
11,497,811	2,002	11,988	29,970	344,934,330

b) *Case Study 2*: The evaluation of the reliability improvement and emission reduction when a wind farm and an ESS are installed at five load buses (bus 6, 9, 10, 13 or 18) are performed. The self-discharge rate (α) and conversion efficiency (γ_c) are 0.15 and 0.98, respectively [19], [20]. Table VI shows the reliability and emission results for the five selected buses. Figure 2 shows the emission reduction for the four types of gases compared with the base case.

From the comparison between cases 1 and 2, it can be concluded that, by applying ESS with wind generation, not

TABLE VI
CASE STUDY 2 RESULTS

Bus No.	Emission Cost (\$)	Interruption Cost (\$)
6	338,217,474	2,271,053
9	336,836,930	2,247,226
10	339,209,705	2,256,938
13	337,504,240	2,142,487
18	340,132,737	2,079,729

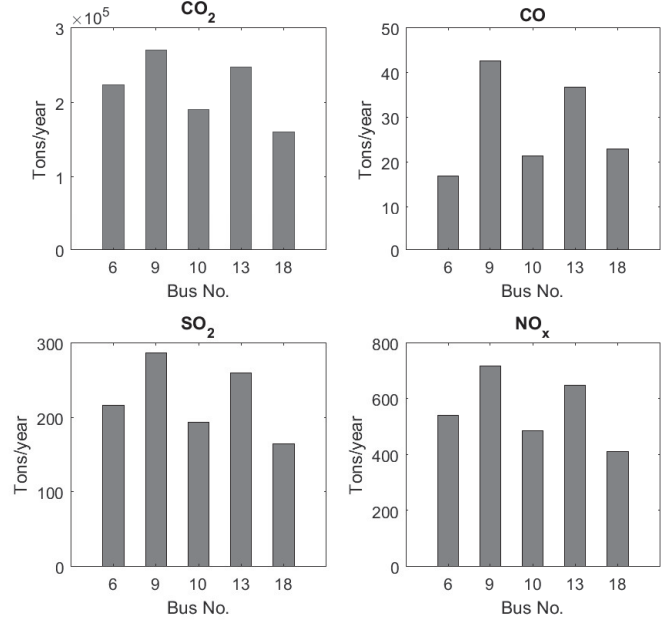


Fig. 2. Emission Reduction.

only the system reliability can be enhanced, but also the emission can be reduced.

VI. CONCLUSION

This paper has presented a method to quantify the environmental and reliability benefits from the wind generation and energy storage systems. Sequential Monte Carlo simulation (MCS) was used to track the charging and discharging performance of the ESSs and also the outage events in the system while evaluating the reliability indices and interruption costs. The variable behavior of load demand and the forced outages of generators are also captured by the sequential MCS and considered in the optimal power flow model. The results show significant improvement in system reliability and emission reduction after the integration of the ESSs and wind generation.

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