SAND2021-14095C

Valuation of Behind-the-Meter Energy Storage in Hybrid Energy Systems

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***Abstract*—Many remote communities are subject to poor electric service, which low power quality and reliability being common concerns. To compensate, many isolated communities employ diesel generation units to bolster utility inputs or to fully support key loads in the event of an outage. While this is effective, it can be a very expensive mode of operation requiring oversized units to ensure reliable power. Declining prices of both renewable generation and energy storage systems have the potential to improve this situation, though careful planning is needed to make these hybrid energy systems financially attractive. This paper presents analytical methods to enable informed decision making with respect to future planning incorporating renewables and energy storage systems to enhance system reliability and reduce operating costs. These methods are demonstrated in a case study for the San Carlos Apache Tribe, which is located in a sparsely populated region next to Coolidge, Arizona that has limited power generation and transmission resources. Currently, the energy tariffs are high and the system suffers from frequent power interruptions, adding up to an average of around 100 power interruptions per year. To reduce electricity costs and improve power quality, the tribe is currently installing solar photovoltaic arrays in several sites inside of the reservation. We have analyzed the potential benefits and optimal of energy storage systems associated with solar power generation to reduce the tribe's costs with electricity and contribute to improve reliability of critical loads. Results show that energy storage has the potential to reduce electricity costs significantly and provide backup power for critical loads during several hours.**

***Index Terms*—Behind-the-meter, energy storage, optimal sizing, solar photovoltaic.**

I. INTRODUCTION

REMOTE communities in the USA often suffer from unreliable power supply. The frequency of power interruptions has been found to decrease for an increased number of customers per line mile, a metric correlated with population density [1]. Sparsely populated areas, including rural and insular communities, sometimes need to be equipped with local generation assets to produce their own power when the transmission system fails, or to achieve some level of energy independence. Diesel generators (DGs) are often chosen due to their controllability and cost-effectiveness in long-term backup power applications, but systems could also include other resources such as solar, wind, hydro power, or energy storage [2]–[4].

Systems powered by renewable energy resources (RESs) or conventional DGs can both benefit from the integration with energy storage systems (ESSs) into hybrid energy systems (HESs). DGs supplying power continuously or during long periods are often required to run suboptimally. Integration of DGs with battery ESSs (BESSs) could reduce fuel consumption by enabling the generators to run at their most efficient operating point more frequently. Highly controllable BESSs can also help operations with RESs by absorbing or injecting power to balance intermittent generation from RES and loads. Furthermore, BESSs can provide many other services, including peak shaving, renewable energy time-shift generation, to name a few [5]. Grid-tied storage located behind the meter (BTM) can also provide cost reductions by participation in net energy metering (NEM) programs and reduction of energy and demand charges [6]. In addition to the technical benefits, the falling price of lithium-ion batteries pushed by the increasing electric vehicle market [7] has started to make the integration of BESS to the power grid an economical investment.

However, prior to investing in a BESS project, it is necessary to perform a comprehensive valuation study to ensure that well-informed project decisions can be made and resulting systems have positive financial impacts. Sizing and estimating the value provided by BESS into a given power system can be done though mathematical optimization, such as mixed-integer linear programming (MILP) [2], [5], [8]–[10]. Those often rely on simplifying assumptions such as globally optimal BESS dispatch under perfect load and RES generation forecast [8], [9].

In this paper we present valuation methods for BESSs for grid-connected, BTM HESs incorporating DG and solar photovoltaic (PV) generation. These methods are demonstrated in a case study for the San Carlos Apache Tribe, which operates an energy system that supports a remote hospital in Arizona that suffers from severe power supply reliability

This work was supported by the U.S. Department of Energy, Office Electricity, Energy Storage program. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy National Nuclear Security Administration under contract DE-NA0003525. SAND2021-XXXX X.

problems from the electric utility and therefore must operate the DGs regularly. The benefits of a BESS integrated into the hybrid energy system (HES) are evaluated using a mixed-integer quadratic programming (MIQP) method. We model three revenue streams that are relevant for BTM operation of HES: reduction of demand costs, fuel savings, and decrease of solar power curtailment.

The remainder of the paper is organized as follows. Section II introduces the problem formulation, including technical constraints and models for the DGs, BESS and specifics about the electricity cost structure to which the load is subject to. Specifics of the rate schedule and load profile are discussed in Section III. The results are presented in Section IV and the conclusion in Section V.

II. Problem Formulation

The San Carlos Apache reservation is located in a sparsely populated region of southeastern Arizona. Its 1.8 million acres are home to approximately 17,000 tribal members. The Tribe is powered by three regional power utilities, some of which have limited power generation and transmission assets. The power line that serves the community surrounding the regional hospital is outdated and prone to outages. Consequently, tribal members report more than 100 outages per year, especially during the monsoon season (June through September). The tribe is considering the installation of a multi-megawatt solar PV system for independent power support to be co-located with the hospital. The local utility, however, does not have an NEM program, which means that there is no tangible benefit for injecting power into the grid.

To avoid service interruptions and medical equipment failure, the hospital's load is shifted to the backup power system when bad weather is expected. The backup power system is composed of three DG units of 1.25 MW each. This redundant setup is designed to supply power during the peak load of the hospital complex even if one of the units has to be offline. A drawback of this system is that the DGs often operate at very low loads, which is inefficient and can lead to premature engine failure. Sustained low-load operation causes wet stacking, sludge formation, adverse emissions, and loss of efficiency because of blow-by of combustion gases [11], [12]. To avoid some of these unwanted effects, DG manufacturers often recommend running systems at over 30% of their capacity [13]. Appropriately integrated PV and BESS systems could be used to reduce these concerns and improve the system's technical and economic performance.

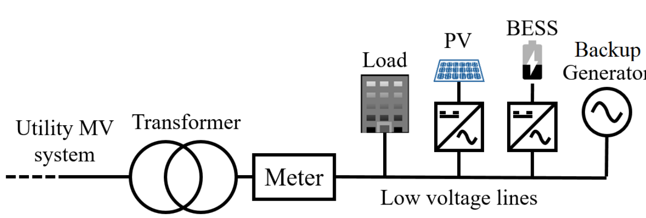

Fig. 1. Simplified behind-the-meter schematic of the HES.

To estimate the savings due to operation of BTM storage and generation, we consider the optimal sizing and operation of BESS with perfect foresight of PV output and load over the desired time horizon. This provides an upper bound on the possible savings with optimal scheduling of BESSs for given load and solar generation profile. This problem is formulated as net present value (NPV) maximization problem, whose objective function is described by (1).

$$\max_{q_t^c, q_t^d, \overline{q^m}, \overline{S}, q_t^g, q_t^{sc}} \sum_{k=1}^{n_y} \frac{R_k}{(1+i_r)^k} - C_{in}, \forall t \in \Omega^t, \forall g \in \Omega^g \quad s.t. (2)-(18) \tag{1}$$

The first term of the objective function is the present value of the cost-savings R_k for each year k over the time horizon of n_y years given a yearly rate of return i_r. The second term C_{in} is the investment cost of purchasing a BESS. The solution to the optimization problem depends on finding the optimal dispatch schedule of the three components of the HES as well as the size of BESS that maximizes the objective function above. More specifically, it is necessary to find the discharge (q_t^c), charge (q_t^d) dispatch schedule for the BESS at each time step t, as well as its power ($\overline{q^m}$) and energy ($\overline{S}$) capacities. The generator dispatch consists in finding the optimal power output $q_t^g, g \in \Omega^g = \{1, 2, 3\}$ for all generators at each time step t. Finally, the last variable to determine is the amount of solar energy curtailed q_t^{sc}.

A. Cost Savings and Capital Cost

Cost-savings are the difference between baseline costs, $\overline{C_j}$, and the costs of operation after installation of BESS, C_j, for each month j within the optimization horizon, as shown in (2). In addition to the electricity demand D_j and energy E_j costs paid to the local utility, the total cost C_j (3) of operating the system also includes the cost of fuel consumed in the same period, F_j (9).

$$R_k = \sum_{j \in \Omega_k^m} \left(\overline{C_j} - C_j \right), \forall k \in \{1, 2, ..., n_y\} \tag{2}$$

$$C_j = D_j + E_j + F_j, \forall j \in \Omega^b, \tag{3}$$

Since the analysis focuses on the benefits of BESS only, the cost of investment is equal to the cost of a BESS. This capital cost can be estimated by the cost of power (p_{kW}) and energy (p_{kWh}) capacity of the BESS, (4).

$$C_{in} = p_{kW} \cdot \overline{q^m} + p_{kWh} \cdot \overline{S} \tag{4}$$

B. Electricity Rate Structure

The hospital is subject to the same utility tariff applied to industrial customers because of its high peak demand [14]. At each billing period j the consumer is charged for their peak demand D_j, (5), and total energy consumption E_j, (8). The energy consumed during billing period is defined as (7).

$$D_j = p_d \cdot \max\{\underline{d}, \overline{d_j}\}, \forall j \in \Omega^b, \tag{5}$$

$$\overline{d_j} = \max(d_t), \forall t \in \Omega_j^m, \forall j \in \Omega^b \tag{6}$$

$$e_j = \sum_{t \in \Omega_j^b} d_t \cdot \Delta t, \forall j \in \Omega^b \quad (7)$$

$$E_j = \underline{E} + p_e \cdot e_j, \forall j \in \Omega^b \quad (8)$$

where $\overline{d_j}$ is the largest demand recorded in the billing period, $p_d = \$7/kW$ is the demand tariff and $\underline{d} = 1,000kW$ is the base for the demand charge calculation. A service tariff $\underline{E} = \$250$ is charged and $p_e = \$0.0718/kWh$ is the cost of energy. The power meters used for billing measure net demand at each time step d_t as the average power consumed during a 15-minute period. Other periods can be specified in contract. A time step (Δt) of one hour is considered instead to reduce the size of the optimization problem and to match the granularity of data for load and solar PV profiles.

C. Fuel Costs

Monthly diesel costs are a function of the hourly fuel consumption f_t^g for each generator g given by (9).

$$F_j = \sum_{t \in \Omega_j^b} \sum_{g \in \Omega^g} f_t^g, \forall j \in \Omega^b \quad (9)$$

A quadratic constraint based on a curve fit of the manufacturer's power to fuel consumption tables was used in the algorithm as:

$$f_t^g = A_2 \cdot (q_t^g)^2 + A_1 \cdot q_t^g + A_0 \cdot \alpha_t^g, \forall t \in \Omega^{t_0} \quad (10)$$

where α_t^g is a binary parameter indicating whether or not the generator g is online at time t.

D. Hybrid Energy System Operational Constraints

Inequality constraints for the maximum power output of generators are included in the formulation in (12). Furthermore, wet stacking, a harmful operating condition that can occur at low loads and accelerate aging, should be avoided with these generators. To avoid this issue the generators should operate a minimum, no-zero output whenever they are operational. It is typically recommended that generators operate at $K_{low} = 30\%$ or more of their maximum rated output (q_{max}) to avoid this condition. This is modeled in the algorithm as:

$$q_t^g \geq K_{low} \cdot q_{max} \cdot \alpha_t^g, \forall t \in \Omega^{t_0} \quad (11)$$

$$q_t^g \leq q_{max} \cdot \alpha_t^g, \forall t \in \Omega^{t_0} \quad (12)$$

In a BTM system, the power purchased from the utility is equal to the net power consumed by the complex d_t, as shown in (13). For this HES, the net power consumed is equal to the difference between the load l_t and the power injected by the HES, which is the sum of power injected by the BESS and the power produced by the solar PV q_t^s (14), and all generators.

$$d_t = l_t + q_t^c - q_t^d - q_t^s - \sum_{g \in \Omega^g} q_t^g, \forall t \in \Omega^t \quad (13)$$

$$q_t^s = \overline{q_t^s} - q_t^{sc}, \forall t \in \Omega^t \quad (14)$$

where $\overline{q_t^s}$ is the maximum power output the solar PV generator can produce at time t. During business hours during the monsoon season, 4 days a week, we consider that the site has to work as a microgrid, i.e. no power will be purchased from the utility ($d_t = 0$).

The ability of the BESS to charge and discharge is limited by the system's power capacity (15). The dynamics of the state-of-charge S_t at each time step are given by (16) for known charge, discharge, and self-discharge efficiencies γ_c, γ_d and γ_s, respectively. Limits on S_t are imposed by the energy capacity of the BESS $\overline{S}$ and the energy reserve $\underline{S}$. To simplify the optimization problem, S_t is set to 50% of its maximum at the first hour of each month, as given by (18).

$$0 \leq q_t^c, q_t^d \leq \overline{q^c}, \forall t \in \Omega^t \quad (15)$$

$$S_{t+1} = \gamma_s \cdot S_t + \gamma_c \cdot q_t^c - \frac{q_t^d}{\gamma_d}, \forall t \in \Omega^t \quad (16)$$

$$\underline{S} \leq S_t \leq \overline{S}, \forall t \in \Omega^t \quad (17)$$

$$S_t = 0.5 \cdot \left(\overline{S} - \underline{S}\right), \forall t \in \Omega^{t_0} \quad (18)$$

III. Case Study

In this analysis the goal is to estimate the potential benefit provided by integrating a BESS into a current system, therefore it is necessary to establish a baseline of system operation costs without BESSs, $\overline{C_j}$, over the time horizon of $n_y = 10$ years. The rate of return i_r was set to 3%. To simplify the analysis, we assume that load and solar PV generation do not change significantly from one year to the next within the optimization time horizon. Monthly energy consumption was disclosed by the hospital operators and load profiles were obtained from OpenEI [15]. PV profiles were obtained from [16], PV cost parameters are found in [17].

TABLE I
PARAMETERS OF PRE-BESS ENERGY SYSTEM.

Asset	Capacity
Solar Photovoltaic Generator	2 MW
Diesel Generators	1.25 MW (x3)
Grid Connection	2 MW

To evaluate the capacity of the BESS to reduce fuel consumption we have analyzed two scenarios. In the first one, all three generators operate simultaneously during microgrid operation. In the second scenario, it is assumed that the BESS is sized such that one generator can remain in standby while load is supplied by the two remaining units, solar power, and the BESS. For each scenario, the tests were rerun for 6 Lithium-ion NMC-based BESS costs: low, medium and high obtained from surveys of recent BESS projects (2020 prices) and the same three ranges for estimated 2030 BESS prices [18]. Pyomo [19] optimization framework was employed to calculate the results presented in this paper. The MIQP problem is solved using Gurobi Optimizer [20].

IV. Results

The results of the optimizations are shown in Table II for the case with 2 generators and Table III for the case with 3 generators. It can be seen that in all cases the BESS system is able to reduce significantly the total annual costs of operation.

As can be seen here, one of the largest impacts that energy storage could have in this scenario would be to reduce the number of generators needed to run for reliability concerns. Again, three generators are used such that if one generator were to fall offline, the energy supply would not be interrupted. This however increases fuel consumption given the minimum load requirement of the generators to avoid wet stacking concerns. In fact, many of the hours in which all three generators are operated to ensure power stability also coincide with peak solar generation. However, given the critical nature of the loads, all three are still kept in operation in the event of a sudden decline in solar power or generator failure because a single generator would not be sufficient to cover the peak load of the facility.

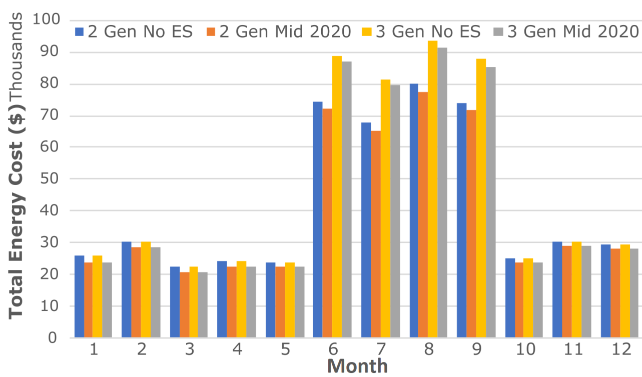

Fig. 2. Total monthly costs with BESS and changing generator number.

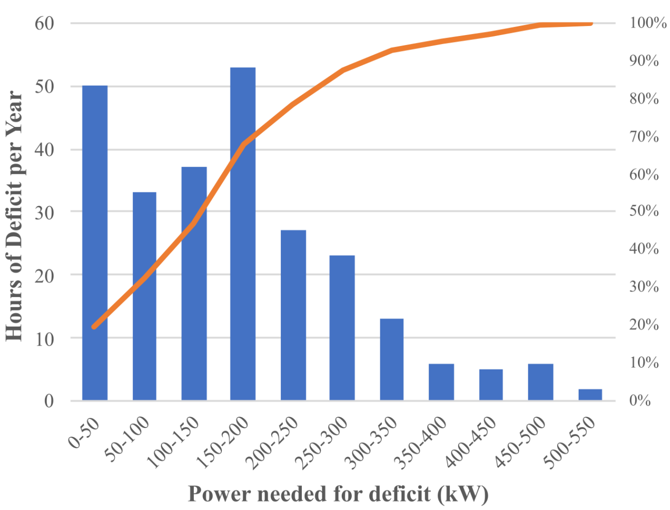

Fig. 3. Shortages in power throughout the year.

Energy storage could be used here to allow a buffer period to activate a generator without interrupting power supply in the event of a generator failure. If an energy storage system was of sufficient size and left a sufficient energy reserve, the number of generators run consistently during the monsoon season could be reduced while still ensuring energy stability. Besides additional benefits of increasing solar utilization, this alone would result in a significant reduction in fuel costs as shown in Fig. 2. It is important then to estimate the size of the energy storage system, in terms of power output and reserve energy requirements, needed to provide this functionality. To do this, we looked at the when the solar array and a single generator would not be sufficient to cover the demand throughout the year because this would dictate the size of the ESS for an n-1 generation scenario if only two generators were run for reliability typically. Fig. 3 shows the additional power needed in the hours of the year that solar and a single generator (1250kW) were not sufficient to cover demand.

In the worst case, the additional power needed would be 529 kW and in this case 132 kWh of reserve energy would be needed to give 15 minutes to activate a backup generator. This is approximately 300 kW more installed power than is recommended for the optimal ESS size considering energy costs alone at 2020 average prices, which implies that additional power would be needed for reliability concerns to reduce the number of generators run consistently. However, this power deficit would be rare throughout the year and typically a much smaller system would be sufficient. In fact, a system of approximately 300-350kW would cover 95% of the potential deficit, which is only approximately 100 kW larger than the recommended size at 2020 prices, and less than the recommended size at 2030 prices. To capture the value of reducing generator fuel consumption by reducing redundancy, a careful study balancing the potential savings versus risks, installed system costs, and alternate options such as load shedding in the event of a generator failure would be needed, but this is indeed another tangible source of benefits using ESS in combination with diesel systems.

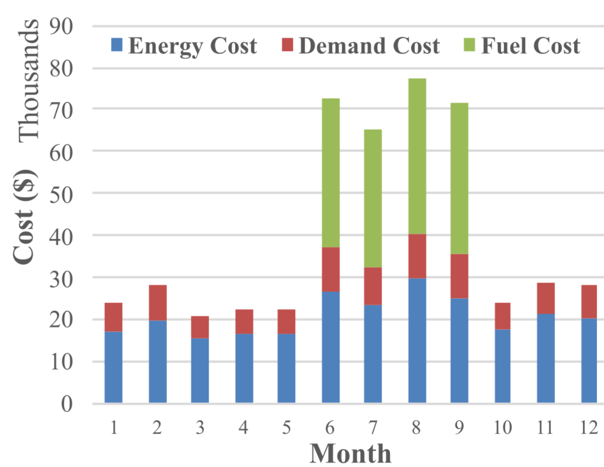

Fig. 4. Monthly Energy Costs - 2 Generators, 2020 ES pricing.

V. Conclusion

Due to recent price decrease of Lithium-ion batteries, integration of BESS to HES of remote communities has a potential

TABLE II
SUMMARY OF RESULTS WITH 2 GENERATORS

$/kW	$/kWh	Price Source	ES kW	ES kWh	Energy Cost	Demand Cost	Fuel Cost	Total Annual	ESS Cost	10-Year NPV
No ES		---	---	---	**$ 254,340**	**$ 108,694**	**$ 144,601**	**$ 507,635**	**$ -**	**$ -**
106	248	Low 2030	468	1098	$ 240,457	$ 77,467	$ 136,276	$ 454,200	$ 322,000	$ 133,807
126	285	Mid 2030	423	837	$ 243,685	$ 81,467	$ 137,647	$ 462,799	$ 291,769	$ 90,694
138	332	High 2030	287	425	$ 248,804	$ 90,098	$ 140,541	$ 479,443	$ 180,633	$ 59,852
140	344	Low 2020	281	409	$ 248,998	$ 90,478	$ 140,669	$ 480,144	$ 180,104	$ 54,399
156	408	Mid 2020	211	307	$ 250,247	$ 93,824	$ 141,539	$ 485,609	$ 158,340	$ 29,544
171	467	High 2020	126	184	$ 251,828	$ 99,023	$ 142,689	$ 493,541	$ 107,488	$ 12,738

TABLE III
SUMMARY OF RESULTS WITH 3 GENERATORS

$/kW	$/kWh	Price Source	ES kW	ES kWh	Energy Cost	Demand Cost	Fuel Cost	Total Annual	ESS Cost	10-Year NPV
Reference		Price Source	0	0	**$ 254,340**	**$ 108,694**	**$ 200,133**	**$ 563,167**	**$ -**	**$ -**
106	248	Low 2030	457	1038	$ 238,715	$ 78,313	$ 196,876	$ 513,904	$ 305,922	$ 114,299
126	285	Mid 2030	368	661	$ 244,092	$ 84,840	$ 197,483	$ 526,415	$ 234,908	$ 78,594
138	332	High 2030	281	409	$ 247,823	$ 90,485	$ 198,029	$ 536,337	$ 174,530	$ 54,334
140	344	Low 2020	279	405	$ 247,874	$ 90,590	$ 198,039	$ 536,502	$ 178,521	$ 48,931
156	408	Mid 2020	210	305	$ 249,419	$ 93,926	$ 198,377	$ 541,721	$ 156,931	$ 26,004
171	467	High 2020	111	161	$ 251,696	$ 100,062	$ 199,064	$ 550,822	$ 93,969	$ 11,332

to be an economical project. In this work, we estimate that with optimum operation and sizing of modern, cost effective and efficient BTM BESS, it is possible to obtain positive NPV based on cost-savings over the course of a decade for a hospital profile. Most of the savings come from reduction of demand-related charges, but there are additional fuel-savings and reliability benefits if the BESS is sufficiently large.

ACKNOWLEDGMENT

The authors would like to thank Dr. Imre Gyuk, Director of the Energy Storage Program, for his continued support. The authors would like to thank Dr. Alvaro Furlani Bastos for the technical review.

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