ORIGINAL RESEARCH

Integration of energy storage with diesel generation in remote communities

Rodrigo D. Trevizan and Stanley Atcitty Sandia National Laboratories, Albuquerque, NM, USA,
Alexander J. Headley, and Robert Geer Department of Mechanical Engineering, The University of Memphis, Memphis, USA,
Imre Gyuk, U.S. Department of Energy, Washington, DC, USA

Address all correspondence to Rodrigo D. Trevizan at rdtrevi@sandia.gov

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ABSTRACT

- *Battery energy storage may improve energy efficiency and reliability of hybrid energy systems composed by diesel and solar photovoltaic power generators serving isolated communities.*
- *In projects aiming update of power plants serving electrically isolated communities with redundant diesel generation, battery energy storage can improve overall economic performance of power supply system by reducing fuel usage, decreasing capital costs by replacing redundant diesel generation units, and increasing generator system life by shortening yearly runtime.*
- *Fast-acting battery energy storage systems with grid-forming inverters might have potential for improving drastically the reliability indices of isolated communities currently supplied by diesel generation.*

This paper will highlight unique challenges and opportunities with regard to energy storage utilization in remote, self-sustaining communities. The energy management of such areas has unique concerns. Diesel generation is often the go-to power source in these scenarios, but these systems are not devoid of issues. Without dedicated maintenance crews as in large, interconnected network areas, minor interruptions can be frequent and invasive not only for those who lose power, but also for those in the community that must then correct any faults. Although the immediate financial benefits are perhaps not readily apparent, energy storage could be used to address concerns related to reliability, automation, fuel supply concerns, generator degradation, solar utilization, and, yes, fuel costs to name a few. These ideas are shown through a case study of the Levelock Village of Alaska. Currently, the community is faced with high diesel prices and a difficult supply chain, which makes temporary loss of power very common and reductions in fuel consumption very impactful. This study will investigate the benefits that an energy storage system could bring to the overall system life, fuel costs, and reliability of the power supply. The variable efficiency of the generators, impact of startup/shutdown process, and low-load operation concerns are considered. The technological benefits of the combined system will be explored for various scenarios of future diesel prices and technology maintenance/replacement costs as well as for the avoidance of power interruptions that are so common in the community currently.

Keywords efficiency · energy generation · energy storage · storage

Discussion

In several cases, energy storage can provide a means to promote energy equity by improving remote communities' power supply reliability to levels closer to what the average urban consumer experiences at a reduced cost compared to transmission buildout. Furthermore, energy equity represents a hard-to-quantify benefit achieved by the integration of energy storage

to isolated power systems of under-served communities, which suggests that the financial aspects of such projects should be questioned as the main performance criterion. To improve battery energy storage system valuation for diesel-based power systems, integration analysis must be holistic and go beyond fuel savings to capture every value stream possible.

Introduction

Although most electricity consumers receive power from large regional power supply networks, there are many remote localities, including small rural¹ and insular² communities that have to supply their own power with local generation assets. In these cases, the local electric power system (EPS) is commonly based on diesel-fueled generators but might also include renewable energy resources such as solar, wind, or hydro power.^{1–6} When one or more of such technologies are combined with some form of energy storage, these systems are called hybrid energy systems (HESs). In small scale and remote HESs, electricity costs are often high, power quality is inadequate, and fuel supply and equipment maintenance logistics are challenging.⁷ Therefore, solutions that can prolong the life of equipment and reduce costs can have a significant impact for local populations.

Energy storage systems (ESSs) can play a particularly impactful role in systems of which primary power source is uncontrollable or intermittent, such as power systems that rely heavily on non-dispatchable renewable energy sources. The flexibility and controllability of ESSs, which can absorb or inject energy in the network, can help to balance intermittent generation and fluctuating loads. Further, fast-acting storage devices such as battery ESSs (BESSs) can provide spinning reserves, regulate system frequency, time-shift renewable generation, improve grid resiliency, and help compliance with the operating limitations of generation sources, to name a few of their benefits,^{4,8,9} and many have focused on the application of ESSs for renewable power grids.

However, fossil fuel-based HESs may also benefit from the flexibility of energy storage, particularly in remote locations. In many isolated communities, diesel generators (DGs) continuously supply power for time-varying loads, which can be highly variable with limited load aggregation. Often this necessitates running generators at sub-optimal operation points for some time. Integration with BESSs could reduce fuel consumption by enabling the generators to run at their most efficient operating point more frequently. In,¹ a scheme for minimizing fuel consumption of an HES composed of a DG and a battery to power rural residences and base transceiver stations was proposed. This work showed alternating between running the generator at its most fuel-efficient point while charging the battery and shutting down the generator to power loads exclusively using the BESS could reduce daily fuel consumption by 6–8%. BESSs have also been used to provide spinning reserves to self-sustaining communities.⁴

The functionality of BESSs comes with a cost though. In spite of the significant cost reductions driven by electric vehicles,¹⁰ investments in BESS can still be expensive. Furthermore, control and management of BESSs can be difficult, especially if battery capacity is limited, and should involve forecasting algorithms to maximize benefits.¹¹ To balance costs and benefits from BESSs, optimal sizing algorithms have been proposed. These methods are typically based on

mathematical optimization algorithms, such as mixed-integer linear programming (MILP)^{1,4,8,9} or heuristics, like genetic algorithms.⁵

In this paper, we present contributions to the modeling of HESs containing BESSs, renewables, and diesel generation using a mixed-integer quadratic programming (MIQP) approach. We identify and analyze four revenue streams that are relevant for remote communities: reliability improvements, fuel savings, decrease of operation and maintenance (O&M) costs, and DG replacement deferral. We include models for operational constraints of diesel-based electrical generators that comply with industry standards for operation, optimal sizing of BESS, and system life. Further, we propose indices to help predict the value of a BESS and explain the results of the optimization solutions. To illustrate the importance of these novelties, a case study of a self-sustaining and electrically isolated community, the Levelock Village of Alaska is presented and extrapolated to show how these results could apply to other remote EPSs.

Assessing applications of energy storage

There are many applications in which energy storage could have an impact on remote EPSs. Here, we will expound upon the major benefits that could be had with BESSs and how to assess the potential impact.

Reliability improvements

Power interruptions are typically caused by EPS component failures, protection equipment activity, or manual control by systems operators. Interruptions cause financial and non-material losses to customers, the severity of which depends on factors such as the frequency of interruptions, their duration, and the type of consumers affected.¹²

Reducing the costs of interruptions is normally achieved through EPS hardening investments. For example, buried power lines are less vulnerable to weather events than overhead transmission and battery backup systems can be installed to reduce power interruptions.¹² As reliability investments increase, their cost eventually surpasses the benefits they provide. A sensible investment strategy should minimize total reliability-related costs.¹³

Grid reliability can be measured in terms of the system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI), which are calculated from the duration and frequency of service interruptions¹⁴:

$$SAIDI = \frac{\sum_{i=1}^K D_i N_i}{N_{tot}}, \quad (1)$$

$$SAIFI = \frac{\sum_{i=1}^K N_i}{N_{tot}}, \quad (2)$$

where K is the number of interruptions within a given year, N_i is the number of affected customers in the i th interruption, D_i

Figure 1. Sample Generator Fuel Usage and Efficiency Curves for a 100 kW DG.¹⁶

is the duration of the i th system interruption, and N_{tot} is the number of customers served by the system.

Accurately estimating the cost of interruptions and the benefits of reliability investments is challenging. While residential customers typically experience little inconvenience from short interruptions, similar events can cause industrial customers to restart production processes. Customer direct interruption costs are used for value-based reliability planning and can be estimated using different methods.¹³ Survey-based methods are the most reliable but are often costly to conduct. Alternatively, databases and tools exist to estimate the costs of interruptions, such as the Interruption Cost Estimation (ICE) calculator.¹⁵ Given the reliability indices and load characteristics, the improvement in reliability indices from system enhancements can be estimated and one can estimate the potential savings from a project using these tools.

Fuel usage

One of the main aims of incorporating BESSs in any diesel-based EPS would be to reduce fuel consumption. Barring an overall load reduction, the only way to reduce the fuel consumption would be to increase the efficiency of the DGs being used. This can be done with the addition of a BESS by charging and discharging the system as needed to optimize the operating point of the DG. A sample of the power output versus efficiency curve of a DG is shown Fig. 1.

Generators typically operate more efficiently close to their rated power output. A properly sized battery can act as a buffer to swings in demand, while the generator remains at its optimal operating point. When demand is low and the battery is sufficiently charged, the generator can be shut down entirely while the battery supports the load.¹

However, the effectiveness of this strategy is highly dependent on the variability of the demand and how much the efficiency of the generator changes with power output. Furthermore, as

ESSs do not produce power, the scale of the load relative to the generator capacity will predominantly determine how efficiently it can be run unless the battery is large enough to fully support the electrical demand for extended periods of time.

Valuation of ESSs is often posed as an optimization problem with a cost function defined by the financial performance of the given scenario and appropriate constraints to reflect the physical limitations of the system.⁹ Often linear programming or MILP is used to represent a given scenario for optimization. Typically, power generation is considered an external input, and the timing of the dispatch of the ESS is optimized to minimize costs for the given market scenario (e.g., minimizing peak power).

When assessing the use of energy storage to reduce fuel consumption from associated DG, the cost function should include generator fuel consumption as this is the main operational cost. This necessitates that constraints should be added to reflect fuel consumption with the power output of the generator(s). However, unlike many other ESS valuation scenarios, fixed efficiency assumptions for the generators are insufficient as exploitation of efficiency differences across the operating range is the goal. This consideration will be discussed further in the case study section of the paper.

Regardless, a few major trends are expected with the application of ESSs with DGs. First, an ESS will be most effective for reducing fuel consumption when there is a significant amount of variation in the load. In a high variability demand case, combustion engines working alone would be forced to operate across a large section of their rated operating range, meaning that some low-efficiency operation would be required unless a buffer between the load and generation (e.g., a battery) was used.

Second, the fuel savings that could be derived are limited by the size of the battery. If the load would necessitate extended operation in the low-efficiency operating range of the generator, a larger battery would be needed to service low-efficiency

periods or charge for a significant amount of time to shift generator operating points to a more efficient level. This suggests that a similar concept to that of the hybridization factor (HF), a value combining the maximum power of the battery to that of the generator found in some hybrid electric vehicle (HEV) studies, would be relevant to HES studies as well. Lukic et al. found that fuel economy improvements are related to both the control scheme used to dispatch the generator / battery system as well as the HF, which they defined as follows¹⁷:

$$HF = \frac{P_{EM}}{P_{EM} + P_{ICE}}, \quad (3)$$

where P_{EM} is the power rating of the electric components and P_{ICE} is the power rating of the internal combustion engine. They found that increasing the HF improves fuel economy to a point, after which further increases yielded no additional benefits.

Similar trends can be expected in the case of electrical supply for isolated communities, with some key differences. The component power ratings are more important than energy ratings in hybrid electric vehicles because driving loads have large fluctuations and a significant portion of the energy used for acceleration is stored in the form of kinetic energy that can be recovered through regenerative braking. For micro-grid applications that lack comparable inertial storage, the energy rating is also an important factor, and “hybridization” should be scaled in terms of power and energy to assess different designs.

There is then some need to quantify the variations in the demand that the system will need to be supported to assess the savings potential of a given scenario. To this end, we suggest the use of an energy opportunity ratio (EOR) based on the expected load profile:

$$EOR = \frac{\sum |P_{\max, \text{eff}} - P_{\text{dem}}| \Delta t}{\sum P_{\text{dem}} \Delta t} = \frac{\sum |P_{\max, \text{eff}} - P_{\text{dem}}|}{\sum P_{\text{dem}}} = \frac{E_{\text{low eff}}}{E_{\text{dem}}}, \quad (4)$$

where $P_{\max, \text{eff}}$ is the power output of the generator at the maximum efficiency setpoint and P_{dem} is the demanded power. The EOR as defined here scales the amount of energy that would need to be supplied away from the maximum efficiency setpoint of the generators ($E_{\text{low eff}}$) to the total energy requirement of the system for a given time period (E_{dem}).

Essentially, the EOR suggests that if power would need to be supplied inefficiently for a significant amount of time, the potential for fuel savings from battery hybridization increases. In the case of grid-servicing applications for remote communities, the EOR should be considered on a case-by-case basis, and there is likely potential for improvement using ES in the following situations:

- (1) Highly variable grid demand
- (2) Diesel generation is used for ramping support
 - (a) In this case, demand would likely be sporadic and span the power range of the DGs.
- (3) The generator is oversized for the typical demand of the system

- (a) This can be caused by a mismatch from changing grid architecture, infrequent loads, or reductions in load after generator purchases
 - (b) This could also be the result of generator sizing for an infrequent but essential worst-case scenario
- (4) Other sources of generation exist on the network
 - (a) Wind and solar particularly increase variability
 - (b) Generators used for backup power with another base load (e.g., hydro^{4, 6}) can often benefit as well.

The EOR captures all these points if the net power requirement of the DGs is investigated, including the contributions of the alternate sources of power. The utility of this calculation for pre-screening demand scenarios will be shown in the case study section of the paper.

Maximizing savings from solar and wind installations

The potential for fuel savings with BESS hybridization alone is often limited. For instance, a case study for a 600-person forward operating base suggested that diesel consumption would only be reduced by approximately 3% with optimal dispatch of an ESS in conjunction with DGs.¹⁸ However, wind and solar generation can greatly reduce fuel consumption, and ES pairings with these resources can further increase their impact. With reductions in the costs of both wind and solar power, combined renewable generation and diesel systems are already being deployed or considered for remote communities in various climates.^{19,20} However, renewable penetration is often limited to avoid underloading DGs and increasing their wear, particularly in colder climates. These effects can be counteracted with ES to increase the ability to house renewables without damaging DGs. As a result, if a remote community is considering a significant amount of renewable generation to support their electricity demands, pairing with ESSs should be considered to balance operations and allow more renewables to be installed without low DG load concerns. This will be explored further in the following case study as well.

Extending generator life and reducing O&M costs

Generator sets that function as a primary source of electric power for an isolated community must operate continuously and provide electrical power for variable loads. This operation regime matches the definition of prime-rated power (PRP) described in the standard ISO 8528-1.^{21,22} This standard defines operational constraints generators should meet.

If the demand for a community is highly variable or the generation capacity must be sized for a peak that is considerably higher than the typical load, the potential value for an ESS increases. This is not only true because of the potential to reduce fuel consumption. There are also a number of degradation concerns associated with “High Idle” operation (low load/low temperature) of DGs that must be corrected for.^{23,24}

Low-load (30% or less of maximum continuous power rating (MCPR)) and/or varying load operations of a DG can affect degradation by exposing the DG to non-ideal conditions such as lower operational temperatures and lower cylinder pressure.²⁵ Optimal operating conditions are easiest to maintain between 40 and 80% of the MCPR of the generator. If low-load operation is required for an extended period, running at high load (80%-90% MCPR) can counteract some of the negative outcomes from the low-load operation.²⁶ For instance, Caterpillar recommends loading generators at a minimum of 30% load for 30 min for every four hours spent at an extremely low load.²⁵ However, large swings in the load can increase mechanical stresses on the crankshaft if deceleration occurs. If a low-load operation occurs frequently, sludge formation, wet stacking, and loss of efficiency because of blow-by of combustion gases are all major concerns, among others.²³ Adverse emissions are also a concern at low loads.²⁴

These are known issues, and many corrective methods have been used in industry for decades such as increasing back pressure, capacity modulation, intake preheating, and exhaust gas recirculation to name a few.²³ Capacity modulation in particular, or “artificially” increasing the load on the generator to an acceptable minimum level, is one common approach. Load banks are often used to increase the load on a generator to avoid wet-stacking concerns²⁷ by activating a resistor when the generator load falls below some predetermined minimum level. Although this avoids the added degradation concerns, it comes at the expense of increased fuel consumption. An ESS could provide this benefit without an excessive increase in fuel consumption by using the generator to charge to avoid underloading and discharge during times of higher demand. Alternatively, if an ESS is sufficiently large, it can fully support loads while generators are shut down.

However, the effects of potential change on the operational parameters should be carefully considered. For instance, cold start effects are a wear concern in extremely cold environments and planning operations to include frequent shutdowns because of battery availability could accelerate generator aging. Lower ambient temperatures can increase intake air density and power output but also reduce peak pressures and compression temperatures. Combined with fuel injection delays, self-ignition speeds can degrade, potentially leading to malfunctions. In addition, prolonged low-temperature operation can promote residue in the crankcase, potentially blocking the blow-by system and overpressurizing the crankcase.²⁵ If the prescribed ES dispatch alters operations to increase the number of cold starts in particularly cold ambient conditions, care should be taken to ensure that the overall system cost including maintenance would not ultimately worsen with the addition of ESS.

If appropriately sized and controlled, however, ESS can be used to extend the life and reduce maintenance of diesel systems in scenarios where operations are suboptimal. Many manufacturers specify not only the proper operating range of their devices relative to the power rating of the system but also the amount of

time outside of that range that can be sustained without damage. This leads to a similar opportunity cost consideration that can help assess the potential of ES to avoid these issues. Here we additionally define a low-power opportunity ratio LOR as follows:

$$LOR = \frac{\sum \text{if}(P_{\text{dem}} < P_{\text{low}}) \Delta t}{\sum P_{\text{dem}} \Delta t} = \frac{E_{\text{low power}}}{E_{\text{dem}}}, \quad (5)$$

where P_{low} is the desired lower limit of the generator. The LOR as defined here scales the amount of energy ($E_{\text{low power}}$) that would need to be supplied at a power output below P_{low} to the total energy requirement of the system for a given time period (E_{dem}). Often P_{low} is defined as 30% of the rated power of the generator. Although some amount of time can typically be spent below this limit if a significant amount of time is spent at higher loads,²⁶ if a large proportion of generator run hours at low load would be required, the potential for ES to be used to recover lost fuel (due to low-efficiency operation or load bank utilization) and avoid accelerated aging increases, as does the LOR.

Quantifying potential project value

The decision to invest in a BESS can be evaluated with respect to the financial benefits it can offer and balanced against the benefits of other options. For the following analyses, it is assumed that the EPS is in need of upgrades and there are two mutually exclusive investment options: (1) replacing all DGs with new generators of the same power ratings and (2) installing one less new generator and a BESS. For the case studies in this paper, the present value (PV)¹ of the project costs is the main evaluation criterion. The PV is a discounted cash flow technique that estimates the value added by an investment over a time horizon (e.g., N years) considering a given discount rate (r) and expected cash flows (CO_y).^{28,2}

$$PV = - \sum_{y=1}^N \frac{CO_y}{(1+r)^y}. \quad (6)$$

We model the cash flows CO_y at each year y as the differences between revenue and capital expenses (CAPEX) as well as O&M costs of the project. To limit the scope of the analysis, we have not considered utility revenues from billing consumers. Instead, we focus on the operational costs of alternative projects for the isolated electric system. Therefore, the benefit of one project with respect to the other is characterized in terms of the PV of

¹ PV was used instead of net present value (NPV) because we do not consider cash inflows (e.g., revenue from billing customers).

² In the case study, all assets have a life of about 10 years; therefore, the PV framework does not require further adjustments. Otherwise, the equivalent annual charge method could be used instead.

cost savings throughout project life. The revenue streams identified are the reduction in fuel costs, reduction in O&M costs, deferral of generator replacement, and reliability improvement.³ The PV of both options should be compared to estimate which would be the best use of capital and lead to the lowest operating costs over the time horizon.

Let us start by look at the PV of investment option (1), i.e., costs of a system powered exclusively by N_D DGs:

$$PV_D = - \sum_{g=1}^{N_D} C_g - \sum_{g=1}^{N_D} \frac{D_g}{(1+r)^{t_g}} - \sum_{y=1}^N \frac{F_y + O_y}{(1+r)^y}, \quad (7)$$

where, PV_D : PV of the DGs only project (\$); C_g : cost of purchasing a new DG g (\$), a linear function of rated power (kW); D_g : cost of replacing or overhauling a DG g (\$); F_y : fuel costs at year y (\$); O_y : system O&M costs at year y (\$), a function of rated power (kW) and output (kWh); t_l : generator expected life (hours); t_g : capacity factor of generator g (hours/year); N : number of years considered in the analysis.

The PV of costs of investment option (2) differs somewhat because of differences in installed costs, as well as changes in fuel consumption and O&M costs:

$$PV_B = - \sum_{g=1}^{N_D-1} C_g - C_B - \sum_{g=1}^{N_D-1} \frac{D'_g}{(1+r)^{t'_g}} - \sum_{y=1}^N \frac{F'_y + O'_y}{(1+r)^y}, \quad (8)$$

where PV_B : PV of the costs of the project with BESS (\$); C_B : capital cost of BESS (\$), a linear function of rated power (kW) and energy capacity (kWh); D'_g : deferred cost of replacing or overhauling DG g ; F'_y : fuel costs of system with BESS at year y ; O'_y : O&M costs of system with BESS at year y ; t'_g : generator capacity factor when operated with BESS (hours/year).

As both projects are mutually exclusive, we must obtain a metric to identify which one is best. Subtracting (7) from (8) yields

$$PV_B - PV_D = \overbrace{C_{N_D} - C_B}^{CAPEX} + \overbrace{\frac{D_{N_D}}{(1+r)^{t_{N_D}}} + \sum_{g=1}^{N_D-1} \frac{D_g}{(1+r)^{t_g}} - \frac{D'_g}{(1+r)^{t'_g}}}^{Generator\ investment\ deferral} + \sum_{y=1}^N \overbrace{\frac{F_y - F'_y + O_y - O'_y}{(1+r)^y}}^{Fuel\ and\ O\&M}$$

The equation above provides quantitative criterion for deciding which project is the best fit. If (9) is positive, then the project with BESS has a smaller cost and should be selected. If it is negative, then a DG-only EPS would be the best choice.

Generator replacement deferral

The expected life of a DG set depends on several factors, including load factor, application, maintenance schedule, and others. For this analysis, DGs have an expected life of 25,000 h.²⁹ The operation of DGs in tandem with BESS can reduce the time generators stay online, which allows postponing the investment

on generator replacement or overhaul. The economics of this investment are similar to those of transmission upgrade deferrals.⁹ The PV of generator investment deferral can be estimated as follows:

$$PV_{\text{deferral}} = \frac{D_{N_D}}{(1+r)^{t_{N_D}}} + \sum_{g=1}^{N_D-1} \frac{D_g}{(1+r)^{t_g}} - \frac{D'_g}{(1+r)^{t'_g}}. \quad (10)$$

The non-linearity of this savings option is too severe to add to an MIQP optimization algorithm, but that does not imply that the benefit of reducing generator run hours cannot be added to the optimization procedure. A simpler generator run time-based linear penalty can be used instead (see (11) in the coming section).

Case study of the value of ES to the Levelock village of Alaska

The application of the analyses presented above will be presented through a case study of the Levelock Village of Alaska. The village's electric power is supplied exclusively by DGs which have proved unreliable and costly, with fuel costs 20% higher than the national average. As such, there is an ongoing interest in the community to improve reliability and reduce the operation costs of the power facility.

The power plant serves 40 residential and 38 non-residential customers. To cover the 94 kW peak load and provide system redundancy, the existing power system has 3 DGs: one rated at 100 kW and two at 67 kW. This redundant configuration can meet peak load even if one of the units is offline. This investigation will explore the relative financial benefits of two options for upgrading/renewing the current system:

1. Replacement of all three generators with new units with the same rated power output;
2. Replacement of the system with two new generators and a BESS.

Comparisons of these two options will be shown to highlight the impact of a BESS. For this study, lithium-ion batteries were selected due to their higher technological maturity and modularity, which enables them to be shipped and deployed in a practical manner.

Four potential revenue streams for the inclusion of a BESS were assessed in the economic analysis:

1. Reduction in costs caused by service interruptions.
2. Avoided cost due to reduction in fuel consumption.

³ Disposal costs and revenue from salvage could not be estimated and are left out of the analysis.

Table 1. Summary of reliability indices for Levelock, AK, the state of Alaska, and the United States.

	SAIFI	SAIDI
Levelock, historical est. ^a	42	10.50 h-(630 min)
Levelock est. (2020) ^b	67.23	17.76 h (1065.59 min)
Levelock, improved ^c	17.93	10.87 h (652.13 min)
Alaska (2019) ³⁰	3.28	4.95 h (297.27 min)
U.S. (2019) ³⁰	1.44	4.45 h (267.13 min)

^aConsidering accounts from tribal members.

^bEstimation based on measurements over 163 days. Extrapolated to a full year for comparison.

^cConsidering that the restoration time can be reduced by 15 min through automatic restoration or BESS backup for 15 min.

Figure 2. Histogram of the duration of power interruptions.

3. Reduction of generator O&M costs due to BESS operation.
4. Generator investment deferral.

We will break down the impact of these potential revenue streams within the context of the current load of the village, and further present implications for other scenarios in the following sections.

Reliability concerns and improvement with BESS

Historically, the villagers reported 3 to 4 power interruptions per month, but recently the number of interruptions has increased due to the poor condition of the generators. Data logged during 163 days captured 69 power interruptions totaling 9.97 h of interrupted service; 30 of those were sustained

interruptions lasting for a total of 7.93 h.⁴ If extrapolated to a full year, those would result in annualized SAIFI and SAIDI indices of 67.23 and 17.76 h (1065.59 min), respectively.⁵ These indices are much larger than averages for the USA and the state of Alaska in 2019³⁰ shown in Table 1. A histogram with the duration of those power interruptions is shown in Fig. 2.

⁴ A “sustained interruption” is the loss of power for five minutes or more.¹⁴

⁵ The reliability indices were based on data recorded at the power plant, which means that only total system interruptions are accounted for. Power interruptions at the consumer level could not be measured; therefore, these numbers might underestimate the true indices.

Figure 3. Histograms of estimated unserved power and energy load. Colors in histogram (a) indicate the number of times a power interruption with an estimated unserved load (kWh) and peak power (kW) were recorded. (b) Is a cumulative histogram of (a) where the colors provide probability that a given outage (i.e., a point in graph) is larger in terms of power and energy unserved than any other outage.

An analysis of Fig. 2 shows that 95% of recorded interruptions lasted less than 35 min and about 87% of them were shorter than 15 min. Time-series linear interpolation was used to estimate the unserved load during power interruptions events, which are presented in detail in Fig. 3. The first graph (Fig. 3a) shows a two-dimensional histogram of unserved load (in kWh) and peak power (kW) of all interruptions recorded in the period obtained by discretizing the range of those variables in two-dimensional bins and then counting the frequency of those faults, which is represented in the color code. A two-dimensional sample cumulative mass probability distribution (Fig. 3b) was obtained from this two-dimensional histogram. The contour lines of this second graph permit sizing a BESS capable of providing backup power and energy for a given fraction of the recorded power interruptions.

Reducing costs by improving reliability

Automation could improve reliability indices through fast restoration of service. The power plant is not continuously manned; therefore, travel is often necessary to manually restart the generation system. Precisely quantifying reliability gains in terms of improvements of SAIFI and SAIDI is a very challenging task because the causes of the power interruptions are not entirely known.

A backup BESS would have to hold an energy reserve to restore service once a power outage was detected. The desired backup capacity for a target reliability improvement could be estimated using historical power interruption information. Covering 100% of all recorded outages would require a system

larger than 71.24 kW and 54.62 kWh, the maximum estimated unserved peak load and energy. If a compromise between reliability and cost is achieved, a smaller system could be utilized. For instance, a 70 kW/11 kWh system would have enough power to back up more than 95% of the recorded interruptions (see Fig. 3) and sufficient energy for to eliminate the average 15-min power interruption. This BESS would reduce SAIDI to 10.87 h (652.13 min) and SAIFI to 17.93. Table 1 shows a comparison with U.S. and Alaska's averages.

With additional data from the Village, it is possible to use the ICE calculator¹⁵ to estimate the reliability improvement cost savings shown in Table 2.

These estimated savings are much larger than all other revenue streams (detailed in next section) and would justify investments of almost 6 million dollars. However, the ICE calculator was developed with a limited number of studies as the base data sources, which might not include cases similar to Levelock. Despite this uncertainty, these results reassert the importance of considering reliability as a revenue stream.

Table 2. Cost of interruptions and cost savings of reliability improvement estimated using the ICE tool.¹⁵

Levelock est. (2020)	Levelock, improved	Cost savings (year)	PV of cost savings (10 years)
\$988,151.88	\$311,118.06	\$677,033.82	\$5,729,044.50

Table 3. Summary of BESS parameters.³¹

BESS parameters	Value
Chemistry	Lithium-ion
Round trip efficiency	86%
Calendar life	10 years
Cycle life (C_l)	2000 cycles
Marginal capital cost of rated power (average)	140–171 (156) \$/kW
Marginal capital cost of energy capacity (average)	344–467 (408) \$/kWh
Fixed annual O&M costs (average)	3.96–4.84 (4.40) \$/kW-year
Variable O&M costs (function of power throughput)	0.5125 \$/MWh

Fuel, O&M cost, and generator deferral savings

Batteries can also be used for (1) reduction in fuel consumption, (2) reduction in operations and maintenance costs of the DGs, and (3) deferral of generator replacement or refurbishment by reducing run hours. To investigate the potential impact of a battery system in these capacities, we performed analyses emulating the load of the Levelock Village and optimizing the dispatch of the generators and BESSs of various sizes with a MIQP. Further details on the analyses performed are below.

Optimization algorithm

The goal in this application is to minimize fuel usage, reduce generator maintenance, and reduce generator run hours to maximize the PV of the system. Ideally, the PV equation (9) would be used directly in the objective function, but the non-linearity of generator deferral term makes it unsuitable for the optimization algorithm. However, the goals of minimizing fuel consumption and generator run hours can be reflected more simply with appropriate costs associated with each term. For the analyses presented below, the following cost function was used:

$$\min_{P_{g,t}, P_{C,t}, P_{D,t}} \underbrace{C_f \sum_{g=1}^{N_D} \sum_{t=1}^{8760} F_{g,t}}_{\text{Fuel Costs}} + \underbrace{\sum_{g=1}^{N_D} \sum_{t=1}^{8760} \alpha_{g,t} \Delta t \left(\frac{K_{O\&M} \times P_{g,\text{rated}} \times C_{\text{gen}}}{t_{\text{life}}} \right)}_{\text{Run Time Cost}}$$

Load data

The analyses were based on annual simulations (8760 h) of the Levelock system. Generator voltage, power output, and frequency data were measured over 5 months in 2020 using three energy loggers at the power plant. These data were used to represent the total load as well as to extrapolate the load profiles for the remaining 7 months of the year. Total monthly energy consumption data from the previous year were used to extrapolate the load profiles from the data loggers for the seven months without direct measurements, producing a yearlong load profile with resolution (Δt) of one hour. To simplify the analysis, it was assumed that the load of the village will not change significantly in subsequent years.

where C_f is the cost of diesel fuel in \$/gal and C_{gen} is the cost of a new generator in \$/kW, $F_{g,t}$ is the fuel consumption of generator g at time t , and $\alpha_{g,t}$ is a variable indicating that generator g is active at time t . The second term applies a generator run time cost by acknowledging that every hour a generator is active is one hour closer to the estimated system life, t_{life} , and requiring a full overhaul, which is estimated to cost $K_{O\&M}$ percent of the cost of a new system. This gives the optimization function a cost to both fuel and run hours to balance one goal to the other. Other O&M costs were calculated in post-processing as they were found to be relatively minor contributors in preliminary simulations. The parameters used for the following analyses are shown in Tables 3 and 4.

Constraints were added to the optimization to reflect the proper operations of the DGs and BESS:

Table 4. Summary of reciprocating DG set parameters.²⁹

Reciprocating DG set parameters	Value
Generator expected life (t_{life})	25,000 h
Marginal capital cost for new unit (C_{gen})	800 \$/kW
Cost of generator overhaul as percentage of capital cost ($K_{O\&M}$)	65%
Fixed annual O&M costs	10 \$/kW-year
Variable O&M costs (function of power output)	0.10 \$/MWh

$$P_{dem,t} = P_{gen,t} + P_{D,t} - P_{C,t} - P_{curtail,t} \quad (a)$$

$$S_t = S_{t-1} + \left(\eta_C P_{C,t} - \frac{P_{D,t}}{\eta_D} \right) \quad (b) \quad (12)$$

where (12a) sets the power balance for the system and (12b) is the state-of-charge (S) model of the battery. The subscripts dem, gen, D, C, and curtail relate to power demand, sum of all generator outputs, BESS discharge, BESS charge, and curtailment (e.g., from a load bank) at each time step. The charge and discharge efficiencies of the BESS are η_C and η_D , respectively. Furthermore, the BESS charge and discharge power are constrained to be less than or equal to the rated power of the BESS ($\bar{P}$). The state of charge is similarly constrained to be within the rated state of charge for the BESS ($\bar{S}$) being simulated.

$$|P_{C,t}| \leq \bar{P}, |P_{D,t}| \leq \bar{P} \quad (a)$$

$$0 \leq S_t \leq \bar{S} \quad (b) \quad (13)$$

A constraint on BESS life was implemented by limiting the system throughput based on estimated battery cycle life. To match the framework of the annual optimization, we have limited the number of equivalent cycles on an average yearly basis, as shown in (14).

$$\sum_{t=1}^{8760} P_{D,t} \Delta t \leq \bar{S} \cdot \frac{C_l}{N} \quad (14)$$

For the generators, quadratic correlations between the fuel consumption and power output of the DGs were used based on manufacturers' curves for the generators in the village as shown in Fig. 4.

This was modeled in the algorithm using the coefficients of the best fit trendlines for each generator as quadratic functions:

$$F_{g,t} = \left(A_{2,g} \cdot (P_{g,t} \times P_{g,t}) + A_{1,g} \cdot P_{g,t} \right) \Delta t, \quad (15)$$

where A_2 and A_1 are the quadratic and linear coefficients of the second-order curve fit of the generator efficiency curves as shown in Fig. 4.

Additional constraints were imposed defining the desired operating limitations of the generator to avoid accelerated degradation due to wet stacking at the lower end or overloading:

$$P_{g,t} \geq K_{low} P_{g,max} \alpha_{g,t}$$

$$P_{g,t} \leq K_{high} P_{g,max} \alpha_{g,t} \quad (16)$$

These constraints ensure that if a generator is active, its output remains between K_{low} and K_{high} percent of its rated power. For this case study, K_{low} was set to 30% to avoid wet-stacking concerns, and K_{high} to 110% to allow for some overloading per manufacturers' specifications. Furthermore, manufacturers specified that the average power output should remain below 70% of the rated power over a 12-h window. Additional constraints were imposed to calculate the average power over this time span for each generator and ensure that this did not exceed the 12-h average limitation:

$$P_{g,avg,t} = \sum_{t=12}^t \frac{P_{g,t}}{12}$$

$$P_{g,avg,t} \leq 0.7 P_{g,rated} \quad (17)$$

Dispatch optimization was performed for each month. Another constraint ensured continuity between months by enforcing 50% state of charge at the first hour of each month.

Figure 4. Comparison between efficiency of a 67 kW and a 100 kW DG.

Figure 5. USA Diesel Price Forecast Scenarios. Source: EIA 2020 AEO.

The mixed-integer, quadratic program was coded in Python using PYOMO³² and solved using Gurobi.³³

Additional assumptions

The study is performed under the assumption of perfect load foresight. This means that the results are mathematically optimal in terms of system performance and represent the upper bound on cost savings potential. Due to difficulties in quantifying precisely the revenue from reliability improvement, only revenue streams from fuel savings and generator deferral were considered.

Assumptions also need to be made with regard to costs. A major source of risk in the future for a diesel generation facility is the price of diesel. Given that cost savings achieved by coordinated operation of diesel generation and BESS can be marginal (e.g., 5% of fuel consumption), the price of fuel becomes extremely relevant. For this study, we used historical fuel costs cited by the Levelock system operators (approximately \$3.65/gal), but this cost could increase significantly in coming years, based on Energy Information Administration's (EIA) 2020 Annual Energy Outlook (AEO) Fig. 5:

The reference fuel cost is significantly less than what can be obtained in Levelock, but future prices could increase or decrease significantly as shown. The same can also be said for battery prices as well. The following analyses are based on current nominal prices. Future price changes could of course alter the cost benefits shown below, but trends are likely to remain unchanged. Benefits are also affected by the load being served and BESSs will have more impact in some cases than others. To highlight these trends, we analyze a few different load cases with varying "opportunity ratios" as were introduced above. We will show the applicability of BESS pairings with diesel generation in these various scenarios below.

Case I: Levelock base scenario

We will start with the impact of BESS on fuel consumption and generator run hours with the current load profile in the Levelock Village. In this base scenario, the major benefit of the battery would be to reduce run hours of the generators, in fact at the expense of increased fuel consumption. This is because the load in the village is fairly steady, with very little time with the demand being less than the wet-stacking limit of the smallest generators. As such, the EOR and LOR in this scenario, 0.393 and 0.00011, respectively, are simply too small to have a significant savings potential for reductions in fuel consumption or reducing load bank operation for wet-stacking concerns.

Instead, the only benefit that could be achieved would be to use the battery to allow generators to shut down periodically throughout the year, thereby deferring replacement or refurbishment of the generators. However, this benefit would come at the expense of slightly increased annual fuel consumption because of efficiency losses with additional battery usage. This is highlighted in Fig. 6, which shows changes in fuel costs and run hours with varying battery sizes:

In the event that the battery is being used to replace a generator, this value stream alone can lead to positive PVs for a 10-year project duration for smaller battery sizes where the installed cost can be less than the cost of a new generator. Below is a plot of the PV of the battery system in the base case for Levelock (Fig. 7).

This suggests that there is little or no PV for any system larger than 100 kWh for the base scenario. The question remains; however, whether a small battery could effectively replace a generator without sacrificing the system redundancy benefit of a third DG given the limited capacity. To obtain the value projected would require full utilization of the battery

Figure 6. Fuel (a) and Generator Run Hour (b) Savings versus Increasing Battery Capacity with Current Load. Results are shown for BESS power capacities of 25 kW, 50 kW, and 100 kW.

Figure 7. PV of generator replacement with a battery versus battery capacity, estimated with (9). Results are shown for BESS power capacities of 25 kW, 50 kW, and 100 kW.

capacity, meaning that batteries would have to be larger still for the reliability concerns cited in the previous section. Ideally, multiple benefits would be seen with the battery, which would increase confidence in proceeding with a project and larger batteries would have positive PVs to expand the possible number of uses and increase its value as a redundancy asset. To this end, the following sections investigate what other cases would lead to higher BESS values in combination with diesel generation.

Case II: high variability load

Part of the reason for the limited battery impact in Levelock is that their load is fairly steady. This means that the generators can run at a fairly constant output and without any conflicts with wet-stacking limitations, meaning that the EOR and LOR are both low. However, in other remote communities, the load could be much more variable, which would increase the opportunity

for improvement with a coupled battery system. This was first emulated by adding zero mean, uncorrelated, and independently distributed noise at each time step to the measured load profile of increasing strength. This kept the total kWh consumption identical over the timeframe in question but simulated a load with much higher hour-to-hour variability, thereby increasing the utility of a battery to alter the operating point of the generator to maximize efficiency and the likelihood of operation below the wet-stacking limit. Figure 8 shows how increasing the variability of the load affects the opportunity ratios.

For this load, after an added noise of 30 kW, the EOR and LOR increase significantly, leading to corresponding increase in the potential for fuel savings and generator run hours with a battery. For the following analyses, we will look at results with varying levels of energy capacity for a 50 kW battery for a modified case for Levelock, AK. Figures 9 and 10 show the effect of load variability on potential fuel and generator run hour savings.

Figure 8. EOR and LOR versus noise strength.

Figure 9. Fuel Savings with 50 kW BESS (a) versus noise strength and (b) versus EOR.

These figures show a steep increase in the potential benefits of a battery as the EOR increases past approximately 0.4 and the LOR becomes non-zero. Note that the total kWh being delivered annually is the same in all cases. The benefits associated with battery operations result from the increased variability allowing for modulation of the load to operate generators more efficiently and avoiding wet-stacking concerns by charging the battery rather than using a load bank. In these scenarios, the PV of using a battery instead of a third generator increases significantly and becomes positive even for much larger systems as shown in Fig. 11:

This analysis suggests that DG demand cases with EORs greater than 0.4-0.5 and positive LORs would benefit the most from pairing with larger batteries. As the EOR increases with load variability (as shown in Fig. 8), this suggests that the value of a battery to diesel operations increases dramatically for cases where the demand is highly variable.

Case III: increasing solar penetration

In this section, the effect of solar installations in Levelock's EPS is investigated. Solar was simulated for this case using solar generation data for Levelock, AK from the NREL PVWatts

Figure 10. Generator Run Hour Savings with 50 kW BESS (a) versus noise strength and (b) versus EOR.

Figure 11. PV versus EOR for 50 kW BESS.

Calculator.³⁴ Despite the relatively low annual irradiance, solar installations could still reduce fuel requirements for the community, and additionally, pairing with a battery could yield further benefits. The following plot shows how solar penetration would affect the opportunity ratios (Fig. 12):

The EOR increases linearly with solar installation, because any solar augmentation reflects additional energy being supplied below the peak efficiency of the generators given the

net decrease in load. Solar installation of course comes with a decrease in the total annual energy and, therefore, reduction of diesel consumption, as shown in Fig. 13.

The trends are similar for this case again, in that with an EOR exceeding approximately 0.5, the potential for additional fuel and run hour savings with a battery increases significantly. This again leads to larger PVs when substituting a generator

Figure 12. EOR and LOR versus solar penetration.

Figure 13. (a) Fuel savings and (b) generator run hour savings with a 50 kW BESS versus EOR with increasing solar penetration.

with a battery in conjunction with diesel generation as shown in Fig. 14.

In summary, a BESS with 50 kW and 25 kWh exemplifies a reasonable tradeoff between financial performance and capacity to provide redundancy. Figure 15 shows a breakdown of

contributions from each revenue stream (excluding reliability) plus CAPEX savings for (a) a case without solar arrays, with PV of \$34,512, and (b) a scenario with 50 kW of solar, with PV of \$39,376. Clearly, combining solar and storage offers larger opportunity for saving fuel.

Figure 14. PV for battery with solar versus EOR with a 50 kW BESS versus EOR with increasing solar penetration.

Figure 15. PV for 50 kW/25kWh BESS without solar (a) with 50 kW of solar (b), calculated with (9).

Conclusions

BESSs can offer multiple benefits to systems using DG as the primary energy source such as communities isolated from the electric grid. Given their ability to perform instantaneous backup power operations in the event of a generator outage, a sufficiently large battery can have major reliability implications on reducing SAIDI and SAIFI. Additionally, in systems utilizing

multiple generator configurations, a battery can be a good alternative to replacing an aged-out generator in some cases given the benefits that they can bring for could be found for the rest of the system. A BESS can reduce run hours on the remaining generators while providing system redundancy in the event of a generator trip while providing additional benefits such as reducing fuel consumption and deferring generator overhaul.

However, the potential for a battery system to provide these additional benefits differs from one case to the next, and the system needs to be properly sized to provide all of the full range of utility. Larger batteries can do more to reduce operating costs during day-to-day operations while maintaining the appropriate reserve for reliability benefits, but large BESSs can come with significant installation costs. Furthermore, the load profile for which a battery would be applied has a major effect on the financial benefits they could provide and needs to be assessed fully to understand the cost-to-benefit implications of BESS installation. Ideally, a larger battery could be applied to a given scenario and have a positive net value to justify the system costs directly through significant reductions in fuel consumption in addition to the indirect reliability benefits, but this is not always clear.

To this end, in this paper, we introduced the concept of energy storage “opportunity ratios” to quickly identify potential scenarios in which a battery could bring large benefits to isolated diesel generation systems. We showed the utility of these opportunity ratios through case studies of a remote tribal community of Levelock, AK. Here, we looked at the PV of operating their EPS with three generators versus using two generators and BESSs of varying sizes. It was found that in the base scenario, only a small, inexpensive battery system would have any positive PV relative to the all-diesel case as the opportunity ratios for their load was limited.

To investigate cases where a battery would have a larger positive impact, we modulated the load to simulate changes in “opportunity” for this community by increasing the variability of their load and simulating increasing levels of solar installations. It was found that cases with energy opportunity ratios (EORs) in excess of approximately 0.5 led to significant benefits from BESS pairing with diesel. This increased EOR could result from highly variable loads, as is the case for some communities, or from increasing solar penetration, which has its own benefit with regard to fuel reductions also increases the potential for additional savings with batteries. The methods presented here could be of use to other diesel power based communities in assessing the potential for BESS for their operations.

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Declarations

Conflict of interest The authors declare no conflicts of interest nor competing interests.

Data availability

The study contains private data.

Code availability

The code used to produce results will not be made available online.

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