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Feasibility of 100% Renewable-Energy-Powered Microgrids Serving Remote Communities

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***Abstract*—This paper presents an analysis of the size of solar photovoltaic (PV) generation and battery energy storage system (BESS) necessary to power a remote community through renewable self-generation with minimum or no use of fossil-fuel-based generation. We analyze the case of an island in the coast of Maine, which is currently served by an aging subsea cable and a set of back-up diesel generators, and subject to very high electricity costs. We formulated an optimization problem to determine the optimal dispatching of the PV, BESS, and diesel generators to meet the hourly demand requirements at all times while minimizing the need for back-up diesel power generation. This dispatch problem is solved for multiple PV power sizes and BESS storage capacities. The results show that, under historical load and solar generation profiles, the island can be powered almost exclusively by renewable energy sources using at least a 400-kW PV and a 2-MWh BESS. We also analyzed the impact of prolonged periods of low solar generation in systems with an ultra-high share of renewable resources penetration. It was shown that these periods are the root-cause of the rising marginal costs in displacing fossil fuel generation as the penetration of renewable sources increases.**

***Index Terms*—battery energy storage system, microgrid, remote community, renewable energy, solar photovoltaic**

I. Introduction

Electric power distribution networks in remote communities oftentimes are not connected to the main grid due to their relatively low electricity consumption and geographical isolation. The demand at these locations usually is supplied through self-generation resources, such as diesel generators. However, a confluence of factors in the past decade has driven some of these communities to reassess their current power infrastructure; these factors include uncertainty about the cost of fossil fuels, decreasing cost and improved performance of renewable energy technologies, environmental concerns, and state/federal policies [1]–[4]. In this new environment, stand-alone microgrids with 100% renewable generation from solar photovoltaics and battery energy storage systems (called 100% PV+BESS microgrid throughout this paper) has become a promising alternative to supply their electricity demand [5].

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. This work was supported by the U.S. Department of Energy, Office Electricity, Energy Storage Program. 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.

Previous studies have shown that 100% PV+BESS microgrids are operationally feasible using existing technologies, where the BESS ensures the continuity of power supply by mitigating the instantaneous mismatch between solar generation and demand [1]. They rely on grid-forming inverters and proper controls to provide inertial response and avoid stability/reliability issues [6], [7]. Further, these stand-alone microgrids require a form of back-up power (such as diesel generators) to meet the demand during periods at which both PV and BESS resources are unavailable or scarce.

However, significant challenges have been reported for scenarios approaching 100% penetration of renewable energy resources. These challenges include the need for large storage capacity to accommodate the temporal mismatch between demand and generation, and a non-linear increase in the marginal costs to achieve the last few percent of ultra-high renewable energy penetration [1], [6], [8]–[11].

In this paper, we analyze the optimal dispatch of a mix of energy resources (PV, BESS, and diesel generators) to meet the demand from a remote community. The goal is to investigate whether 100% renewable generation is easily achievable or allowing for a partial fulfilment of that requirement results in a more promising design from a financial perspective. The demand profile used in this study consists of one year of hourly measurements from an actual remote community, as described in Section II. The problem formulation is described in Section III, whereas Section IV and Section V present the results and discussion, respectively.

II. Background Information

Isle au Haut (IaH) is a small island in the coast of Maine, U.S., nearly seven miles from mainland. Currently, it is connected to the mainland power infrastructure via a subsea cable, which was installed in 1983, as well as backup diesel generators to supply electricity during mainland service interruptions. The island's electricity consumption is around 285 MWh/year and it has not experienced a significant load growth for multiple successive years. On a daily basis, the demand profile reaches its largest peak around 10 PM and a relatively smaller peak around 10 AM. Additional details on the historical demand at IaH are available in [12].

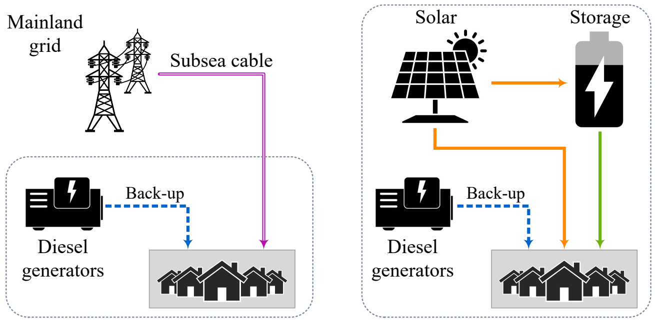

Fig. 1. Illustration of the IaH's power infrastructure with (current) and without (planned) interconnection to the mainland grid.

Due to the increasing failure likelihood of the aging subsea cable and the high cost of electricity at the island (as of 2020, it is 3.5 times the national average), the local utility has started exploring alternatives to supply the island's demand. The current back-up diesel generators can meet the entire island's demand, but that is not a viable long-term solution because it would increase the electricity costs even further. A previous study showed that it is technically feasible to replace the current power infrastructure at IaH with a microgrid, such that the island's demand would be met through renewable self-generation from solar photovoltaic arrays and a battery energy storage system, as shown in Fig. 1 [12]. This framework would result in a truly islanded microgrid once the aging subsea cable becomes inoperative; thus, any surplus of solar generation cannot be exported to the mainland grid.

The goal in this paper is to extend the previous analyses of the IaH's PV+BESS microgrid to ascertain whether such 100% renewable self-generation microgrids are economically optimal for remote communities. The proposed problem formulation minimizes the yearly usage of back-up diesel generators, while taking into account the trade-off between increasing the share of renewable resources and the corresponding higher capital costs due to the BESS.

III. Problem Setup and Formulation

The analysis presented in this paper aims at sizing a PV+BESS stand-alone microgrid such that the demand is met at all times throughout the year, while also minimizing the use of non-renewable energy resources (back-up diesel generators in this case). The hourly dispatch schedule is formulated as an optimization problem where the objective function involves minimizing the yearly usage of diesel generators for various combinations of solar array and BESS sizes. The optimization problem contains constraints to model the BESS operation (such as lower/upper bounds on charge and discharge powers) as well as to guarantee the supply-demand balance at all times.

Under this dispatch formulation, daytime loads are supplied directly by daytime solar generation, whereas evening loads are supplied by BESS discharging and possibly back-up diesel generators if the BESS resources are insufficient to meet the demand. Further, surplus of solar generation is used for charging the BESS during the day. Note that the BESS charges/discharges on a daily basis and it provides a means to shifting daytime solar generation to supply evening loads.

A. Assumptions

The following assumptions have been made in this problem formulation; they represent a trade-off between model accuracy and complexity.

- Load and solar generation profiles are based on historical time series and are known with perfect foresight. This simplification is reasonable in the present analysis, as it does not include real-time control of the microgrid components nor real-time electricity market prices.
- BESS's efficiencies are constant, rather than varying with the BESS's state-of-charge (SoC) or power output.
- BESS's self-discharge efficiency is set to 100%, as BESS's self-discharge rate is relatively low and unlikely to affect systems that cycle on a daily basis.
- Ramp-up and ramp-down constraints for the BESS and the back-up diesel generators are neglected.
- Degradation of the microgrid components (such as PV degradation, BESS's capacity fading, and BESS's round-trip efficiency reduction) are neglected.

B. Nomenclature

The following lists define the load and energy resources parameters (inputs to the optimization problem) and decision variables (outputs of the optimization problem), which are used in the problem formulation in the next section.

– Load and energy resources parameters:

- P^{load}: historical load data, in kW
- P^{PV}: historical solar generation data, in kW
- $\overline{P}_{\text{BESS}}$: BESS's rated power, in kW
- $\overline{S}_{\text{BESS}}$: BESS's energy storage capacity, in kWh
- γ_{s}, γ_{c}, γ_{d}: BESS's efficiencies (self-discharge, charge, and discharge, respectively)
- n_{g}: number of diesel generator units
- $\overline{P}^{\text{g}}_k$: rated power of diesel generator k
- $\eta^{\text{g}}_{\text{min}}$, $\eta^{\text{g}}_{\text{max}}$: minimum and maximum load levels for the diesel generators when they are running
- δ_t: time step, in hours
- n_t: time horizon, i.e. number of optimization periods
- t: set of optimization periods, i.e., $\{1, \ldots, n_t\}$

– Decision variables:

- P^{s}_t: actual solar generation at time t (after curtailment)
- P^{c}_t, P^{d}_t: BESS's charge and discharge powers at time t
- S_t: BESS's SoC at time t
- $P^{\text{g}}_{k,t}$: output power of diesel generator k at time t
- $\alpha_{k,t}$: status of diesel generator k time t, i.e., *on* or *off*

C. Optimization Problem

Based on the previous discussion, the optimization problem for dispatching the mix of resources in the PV+BESS stand-alone microgrid is formulated as follows.

– Objective function, which corresponds to minimizing the total yearly electricity provided by back-up diesel generators:

$$\min \sum_{t=1}^{n_t} \sum_{k=1}^{n_\mathrm{g}} P_{k,t}^{\mathrm{g}} \tag{1}$$

– Supply-demand balance constraint:

$$P_t^{\mathrm{load}} + P_t^{\mathrm{c}} = P_t^{\mathrm{s}} + P_t^{\mathrm{d}} + \sum_{k=1}^{n_\mathrm{g}} P_{k,t}^{\mathrm{g}}, \quad \forall t \tag{2}$$

– Bounds on the actual solar generation constraint:

$$0 \leq P_t^{\mathrm{s}} \leq P_t^{\mathrm{PV}}, \quad \forall t \tag{3}$$

– BESS's SoC constraints:

$$S_t = \gamma_{\mathrm{s}} S_{t-1} + \delta_t \gamma_{\mathrm{c}} P_t^{\mathrm{c}} - \delta_t P_t^{\mathrm{d}} \gamma_{\mathrm{d}}^{-1}, \quad \forall t \tag{4}$$

$$0 \leq S_t \leq \overline{S}_{\mathrm{BESS}}, \quad \forall t \tag{5}$$

$$S_0 = S_{n_t} = \overline{S}_{\mathrm{BESS}}/2 \tag{6}$$

where the last constraint represents a zero-net charging requirement, so that the SoC values at the first and last optimization periods are equal to each other.

– BESS's charge/discharge powers constraints:

$$0 \leq P_t^{\mathrm{c}} \leq \overline{P}_{\mathrm{BESS}}, \quad \forall t \tag{7}$$

$$0 \leq P_t^{\mathrm{d}} \leq \overline{P}_{\mathrm{BESS}}, \quad \forall t \tag{8}$$

– Diesel generators constraints:

$$\alpha_{k,t} \eta_{\mathrm{min}}^{\mathrm{g}} \overline{P}_k^{\mathrm{g}} \leq P_{k,t}^{\mathrm{g}} \leq \alpha_{k,t} \eta_{\mathrm{max}}^{\mathrm{g}} \overline{P}_k^{\mathrm{g}}, \quad \forall k, \forall t \tag{9}$$

$$\alpha_{k,t} \in \{0,1\}, \quad \forall k, \forall t \tag{10}$$

Note that these two constraints ensure that the diesel generators are either offline or the power generated by them is between their minimum and maximum load levels.

D. Microgrid Specifications

Table I depicts the sizes and other specifications of the stand-alone microgrid components under consideration in this analysis. The number and size of the back-up diesel generators as well as the BESS's rated power were determined in [12]. Note that these specifications result in 404 scenarios with different combinations of PV and BESS sizes.

TABLE I
100% PV+BESS STAND-ALONE MICROGRID SPECIFICATIONS

System	Parameter	Value
Solar array	Module type	Standard
	Array type	Fixed (open-rack)
	DC system size	250, 400, 500, and 600 kW
	Tilt angle	44 degrees
	Azimuth angle	180 degrees
	Nominal efficiency	15%
	Inverter efficiency	96%
	System losses	14.08%
	DC-to-AC size ratio	1.2
BESS	Storage capacity	0 to 2.5 MWh, in 25 kWh steps
	Rated power	200 kW
	Round-trip efficiency	86%
Diesel generators	Number of units	5
	Rated power (per unit)	20 kW
	Minimum load level	60% of nameplate rating

IV. RESULTS

This section presents the results of the optimal dispatch for the 100% PV+BESS stand-alone microgrid as formulated in the previous section. The main result is presented in Fig. 2, which depicts the annual summary of two quantities for multiple combinations of PV and BESS sizes (each column represents one combination of sizes): mix of resources supplying the hourly demand (top plots) and breakdown by usage of the total solar generation (bottom plots).

It is evident that a large share of the total annual demand can be met through the PV and BESS, as long as the BESS capacity is sufficiently large. For example, consider the scenario with a 400-kW solar array and a 1-MWh/200-kW BESS. In this case, the mix of resources supplying the annual electricity consumption is as follows: solar generation directly supplying daytime loads (41.6%), discharging of the BESS (55.2%), and back-up diesel generators (3.2%). Further, the breakdown by usage of the total solar generation is as follows: directly supplying daytime loads (21.3%), charging of the BESS (32.9%), and surplus (45.8%).

Interestingly, back-up diesel generators are still need to supply over 3% of the annual electricity consumption, even though almost half of the potential solar generation is curtailed. This result highlights the important role that chronology plays on the optimal dispatch of renewable energy and BESS resources. The BESS cannot store all of the surplus of solar generation due to its capacity constraints, resulting in curtailed solar generation; on the other hand, the BESS is not able to supply the entire demand during long periods (multiple days) of low solar generation.

This fact is illustrated in Fig. 3, which includes a 5-day period with low solar generation. On ordinary days, the BESS discharges from early evening (around sunset time) up to early morning (usually between 6 AM and 7 AM, depending on the season of the year). At that time, solar generation starts to increase and meets most, if not all, of the demand. By early afternoon, solar generation reaches its peak and excess of solar generation is used to charge the BESS. However, this cycle breaks if solar generation is rather low for multiple consecutive days. In that case, the BESS cannot charge during the day (or even worse, it may discharge during the day to meet the full demand), and its SoC decreases continually until the back-up generators are brought online to supply the demand.

Still with respect to Fig. 2, one can observe that it is possible to completely eliminate the usage of the back-up diesel generators for any scenario with at least a 400-kW solar array, as long as the BESS's storage capacity is sufficiently large. Further, it is evident that the 100% PV+BESS stand-alone microgrid is subject to the phenomenon of decreasing returns, i.e., as the deployed BESS capacity increases, there

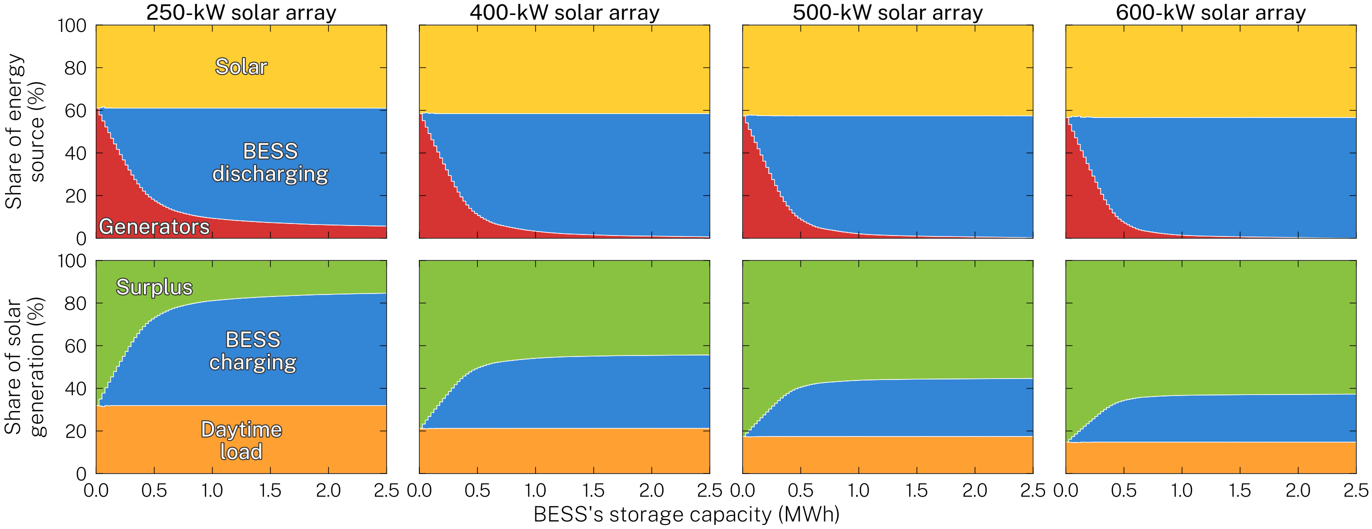

Fig. 2. Annual summary of the optimal hourly dispatch for the 100% PV+BESS stand-alone microgrid for multiple solar array sizes. Top: mix of resources supplying the demand. Bottom: breakdown by usage of the solar generation.

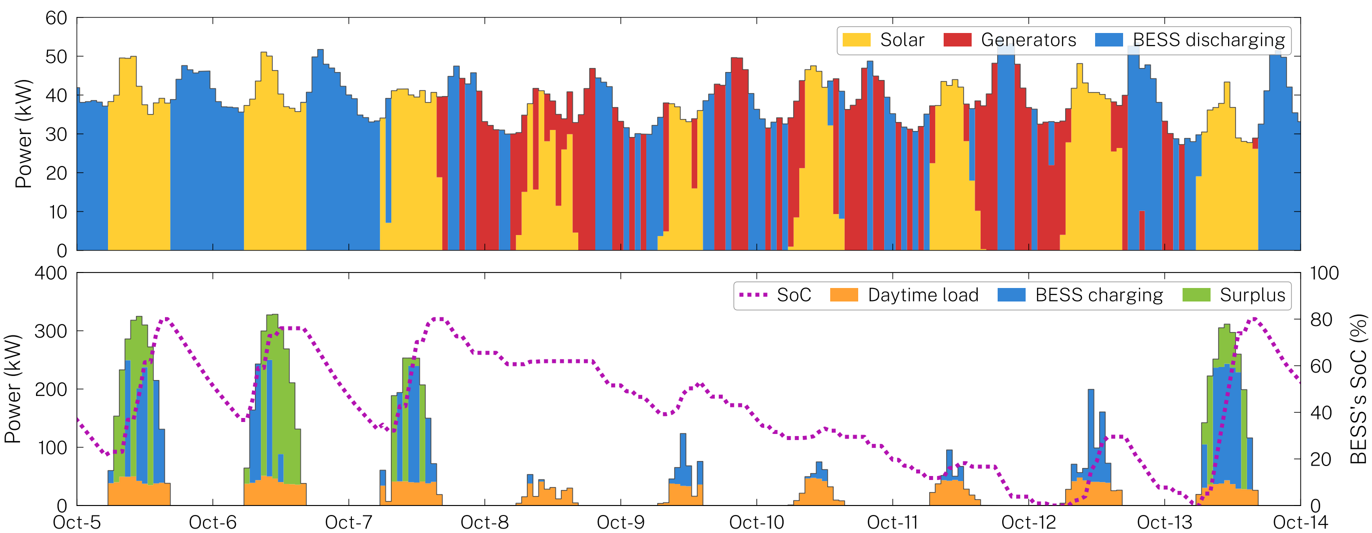

Fig. 3. Optimal dispatch schedule for a long period of low solar generation considering a 400-kW solar array and a 1-MWh/200-kW BESS. Top: mix of resources supplying the hourly demand. Bottom: breakdown by usage of the hourly solar generation and the corresponding BESS's SoC.

is a declining marginal value on the reduction of back-up diesel generators usage. In other words, the need for storage capacity grows sharply at ultra-high penetration of renewable generation. For example, in the 400-kW solar array scenario, increasing the storage capacity from 0 to 0.5 MWh reduces the share of diesel generators by 47.8 percentage points (from 58.5% to 10.7%); on the other hand, with an additional 0.5 MWh in the storage capacity (i.e., increasing it from 0.5 MWh to 1 MWh), the share of diesel generators reduces by only 7.5 percentage points (from 10.7% to 3.2%).

The declining returns at larger storage capacities can be better observed in the top panel of Fig. 4, which depicts the marginal value (in percentage points reduction in diesel generators usage per kWh of additional storage capacity) at each BESS's storage capacity. The diminishing improvement on the reduction of back-up diesel generators usage is conspicuous, and the marginal value roughly flattens out at a value close to zero for storage capacities beyond 750 kWh.

On the other hand, increasing the storage capacity yields a lower BESS's utilization ratio[1], as it would not be *fully* charged/discharge each day. This behavior is illustrated in the bottom panel of Fig. 4. Although shallower cycles might decelerate the BESS degradation, the additional storage capacity is an expensive resource that is idle for most part of the year.

The effective utilization of solar generation (i.e., the amount of solar generation that is actually dispatched to supply daytime load and charge the BESS) also experiences decreasing returns as the size of the solar array increases. As before, this

[1]BESS's utilization ratio is defined as the average number of daily cycles.

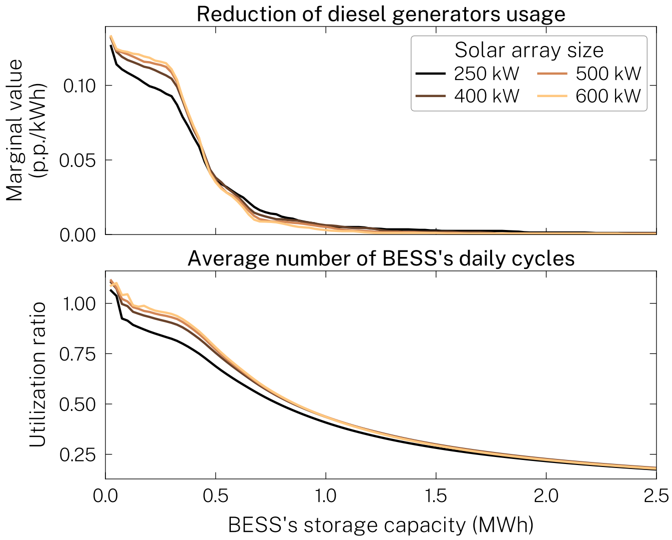

Fig. 4. Marginal value in the reduction of diesel generators usage and BESS's utilization ratio for multiple storage capacities.

phenomenon is also due to the storage capacity constraints. As the BESS gets fully charged on almost all ordinary days, most of the increased solar generation potential is curtailed; the only advantage of oversizing the solar array is aiding on meeting the supply-balance constraint on the few days throughout the year that have low solar generation.

V. Discussion/Conclusion

The analysis presented in this paper showed that 100% PV+BESS stand-alone microgrids are technically feasible, but there are challenges to maintaining the balance of supply and demand at all times. As illustrated in Fig. 2, a 0.5-MWh BESS would allow a renewable resources penetration of about 90%; on the other hand, the storage capacity would need to be increased by 4-5 times to displace the remaining 10% of fossil fuel generation. This result is due to the need of supplying the demand during long periods of low solar generation and it shows that achieving the last few percentage points of renewable penetration can be quite expensive. Therefore, aiming to achieve 100% renewable generation in remote communities might not be the best financial option. Instead, partial fulfillment (such as 90% PV+BESS) makes stand-alone microgrids more promising and achievable because capital costs are significantly reduced, while still displacing a large share of fossil fuel generation.

Further, it has also been observed that all scenarios yield excessive solar generation at times, which has to be curtailed. Solar curtailment reached up to 60% of the annual potential solar generation even for scenarios with a relatively low usage of back-up diesel generators.

The feasibility analysis presented in this paper is location-dependent, mostly being contingent on the weather characteristics at the location of interest, such as the duration and frequency of long periods with low solar generation. Other factors such as frequency stability and system protection should also be considered in the operation and control of stand-alone microgrids with ultra-high penetration of renewable resources. These are active research topics nowadays.

Finally, it is important to emphasize that the insights provided in this analysis do not necessarily transfer to large, interconnected systems. The mix of energy resources in those systems are likely to be more diverse (such as including at least solar and wind resources, which usually have a relatively low temporal correlation) and deployed at distinct regions (such as solar arrays deployed at multiple regions that experience unfavorable weather conditions at different times, allowing import/export of solar generation between the regions as necessary). The main benefit of this diversity – either geographical or of type of resources – is the reduction of the amount of storage capacity needed to meet the supply-demand balance constraint at all times.

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