To Shift or not to Shift?

An Energy Storage Analysis from Hawaii

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***Abstract*- As island power systems increase adoption of variable renewable energy (VRE), grid planners and operators are increasingly utilizing battery energy storage systems (BESS) as a tool to integrate renewable energy and maintain grid stability. While the cost of BESS technology is still expensive relative to other forms of system flexibility, island power systems are at the forefront of economic deployment of BESS technologies.**

The objective of this analysis was to quantify the benefits of varying BESS configurations and determine what size, as well as power to energy ratio, may be best for the Oahu (Hawaii) island grid. This allows for a direct comparison between energy shifting (high energy, low power applications) and reserve (high power, lower energy) assets.

Keywords*- *battery energy storage; wind and solar; variable renewable energy; island power system; Oahu, Hawaii

I. INTRODUCTION

As island power systems increase adoption of variable renewable energy (VRE), grid planners and operators are increasingly utilizing battery energy storage systems (BESS) as a tool to integrate renewable energy and maintain grid stability. While the cost of BESS technology is still expensive relative to other forms of system flexibility, island power systems are at the forefront of economic deployment of BESS technologies.

Island grids are unique; reserves (regulation and contingency) have high premiums relative to mainland power systems. A BESS can provide a number of services such as energy shifting, system ramp management, frequency regulation and contingency reserves. However, a common misconception assumes that as solar generation increases, energy storage should charge surplus energy in the middle of the day and discharge during evening peak. Not so fast… a better understanding about the proper sizing and utilization of BESS technology is warranted to ensure system reliability and economic efficiency. This understanding requires analysis that is system specific, and especially necessary for the unique nature of island grids. An illustrative example of the multiple use cases for energy storage is provided in Figure 1.

BESS technology is highly customizable and scalable. The power (MW) and energy rating (MWh) of the BESS are designed based on the application it is intended to serve. For example, a BESS employed for an energy shifting or capacity application needs, on average, 4 hours or more of storage at its rated power. On the other hand, a BESS used for frequency regulation or fast frequency response (FFR) applications may only need 15-30 minutes of storage at rated power. In practice, an energy storage asset can provide multiple services at different times, depending on system needs. The appropriate power and energy rating of the BESS depends on the service or combination of services it provides.

The objective of this analysis was to quantify the benefits of varying BESS configurations and determine what size, as well as power to energy ratio, may be best for the Oahu (Hawaii) island grid. This allows for a direct comparison between energy shifting (high energy, low power applications) and reserve (high power, lower energy) assets.

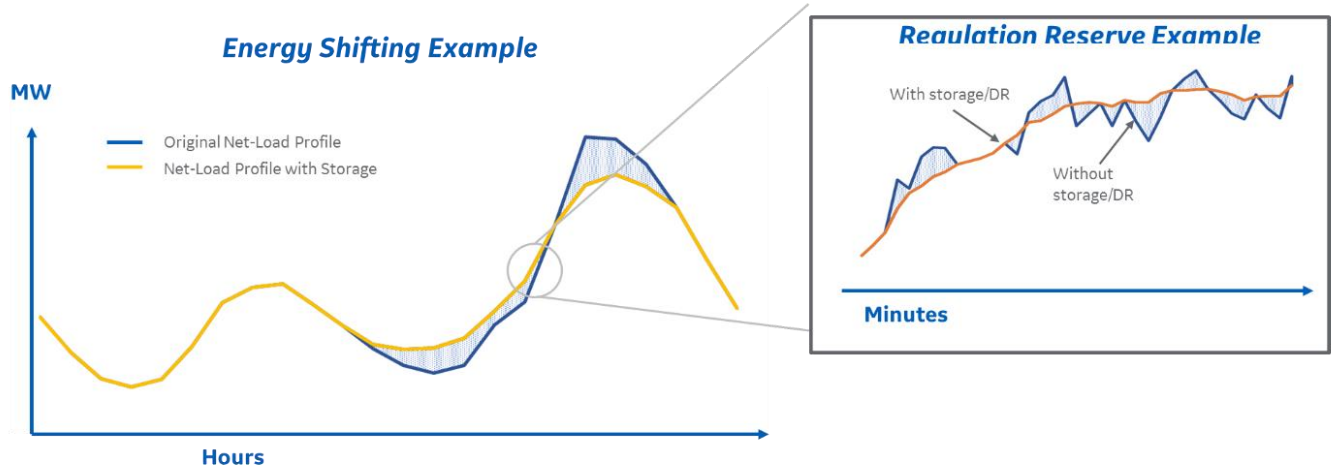

Figure 1. Illustrative Example of Multiple Use Cases for Energy Storage

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II. METHODOLOGY

To perform this analysis, a PLEXOS® based production cost model was developed for the Oahu power grid. The production cost model allows for a chronological simulation of the power grid at 10-minute intervals to accurately capture changes to system load and variability in wind and solar resources. The simulation develops a security-constrained commitment and dispatch schedule of each generator to minimize system cost. The model also takes into account technical constraints on the system, including ramp rates, startup and shutdown times (and costs), minimum up and down times for generators, contingency and regulation reserve requirements, planned and forced outage events, and solar and wind forecast errors. This model has been routinely benchmarked and validated in prior analyses [1].

To understand the role of energy storage for renewable integration, a future resource mix of the Oahu power grid was modeled. This included a 50% annual renewable penetration as a percentage of load. The future resource mix was developed to reflect HECO's April Power Supply Improvement Plan (PSIP) in the year 2040 [2]. This includes 565 MW of wind capacity, 565 MW of utility-scale PV solar capacity, and 840 MW of distributed rooftop PV (DPV) solar capacity. In addition, system load was increased to 8,450 GWh mostly due to increased electric vehicle penetration. All other system assumptions, including installed thermal capacity, load profiles, and operating conditions were maintained from current operations. An overview of the future 50% wind and solar system assumptions are provided in Table 1, which also includes the current power grid overview for reference.

The production cost model was used to quantify the benefits of a BESS in providing energy shifting relative to other ancillary services such as regulation and fast-frequency response. This was analyzed by first running a one-year simulation without a BESS included in the model to serve as a reference point (Base Case). Afterwards, scenarios were simulated assuming different configurations of BESS applications. The configurations ranged from high power, low energy (30-minute duration at rated power) to high energy, low power (4-hour duration at rated power). Table 2 shows the power and energy ratings for the BESS considered in this analysis. In this table, the power rating ranges from 25MW to 200MW and the energy rating ranges from 125MWh to 800 MWh depending on the hours of storage. Hours of storage is the amount of time the BESS can charge or discharge at max power rating.

TABLE I. OVERVIEW OF FUTURE GRID SCENARIO ASSUMPTIONS

	Current Power System	50% Wind and Solar System
Peak Load (MW)	1,225	1,225
Annual Energy (GWh)	7,734	8,450
Electric Vehicles (GWh)	44	791
Wind & Solar Capacity (MW)	809	1965
Utility-Scale Wind	123	565
Utility-Scale Solar	148	565
Distributed PV	538	840
Available W&S (GWh)	1547	4225
Available W&S (% of Load)	20%	50%

TABLE II. POWER AND ENERGY RATINGS OF BESS CONFIGURATIONS

Energy (MWh)		Power (MW)			
		25	50	100	200
Storage (Hrs)	0.50	12.5	25	50	100
	1.00	25	50	100	200
	2.00	50	100	200	400
	4.00	100	200	400	800

It was assumed that each BESS application was able to shift energy and provide reserves. Energy shifting was limited to the amount of MWh available in the BESS configuration. Reserve provision was limited to the power rating and the minimum duration of response required (30-minutes). It was also assumed that the BESS could provide reserves when charging, sitting idle with a state of charge, or discharging below maximum output. The production cost model optimized the storage charging and discharging to minimize system operating cost.

The system benefits of the BESS technologies were calculated by comparing the change to production cost when each BESS is added to the grid (in isolation), relative to the Base Case without any BESS added. Production costs included in the analysis include fuel costs, variable operations and maintenance cost (VO&M), and generator startup cost. It was assumed that all wind and solar generation was priced as a fixed take-or-pay power purchase agreement. Thus, any reduction in wind and solar curtailment was a direct savings to the system. Any changes to system operations and associated production costs can be directly attributed to the BESS integration.

III. ANALYTICAL RESULTS

A. *Understanding Storage Utilization and Impact on Grid Operations*

Including the additional BESS technology on the system changes the way the grid is committed and dispatched. The BESS acts as a load when it charges and as a generator when it discharges. One of the applications of BESS is to charge when there is excess renewable generation (zero marginal cost resource) and discharge during peak load hours or when the system must meet fast (up) ramps in net load. Even if there is no surplus wind and solar generation, the BESS may still charge to capture available energy from lower cost, baseload generators and discharge to avoid the use of expensive peaking units. Once charged, the BESS can also provide ancillary services such as regulation and fast-frequency response (contingency reserves). It may also be possible to provide these services while the BESS is charging or discharging. For example, the BESS could provide up reserves by quickly reducing its load during the charge process or increasing its rate of generation during the discharge process if it is operating below its maximum power capability and there is sufficient energy remaining to sustain the response for the required amount of time based on operating rules.

The results of the production simulations are provided in Figure 2, which shows the change in annual generation due to the addition of a BESS with varying power and energy

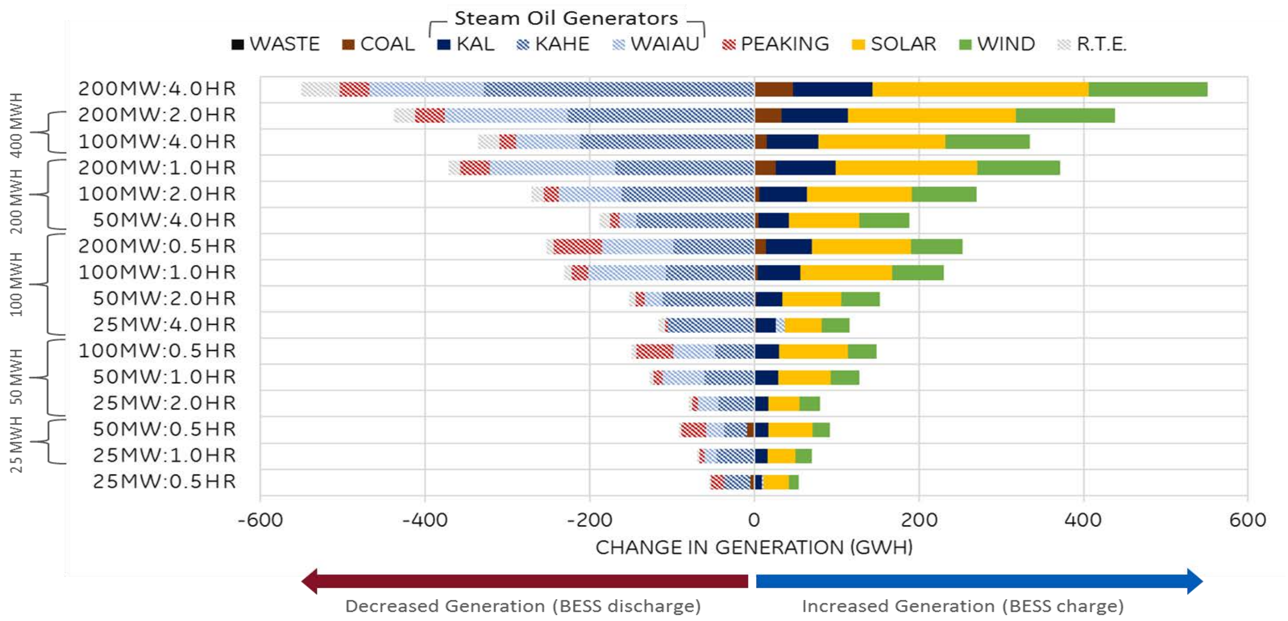

Figure 2. Impact of BESS on Annual Energy Generation by Type

ratings in the 50% renewable energy scenario. The change is relative to a Base Case with 50% renewable penetration but without any BESS available to the grid. The right-hand side of the figure shows the generators whose energy increases due to the addition of the BESS. The figure illustrates that more energy is delivered from zero marginal cost resources (wind and solar plants). This increase is due to a reduction in curtailment, which occurs for two reasons;

- The BESS charges with otherwise curtailed wind and solar energy and increases the system's load during hours of surplus wind and solar energy shifting to hours when it can be used to reduce the energy required from expensive oil-fired generation,
- The BESS can provide reserves (regulation and FFR) that otherwise would have been provided by conventional thermal units. This frees up additional space on the grid that was previously occupied by reserve generators operating at their minimum power.

This is an important observation as it illustrates how even a high power, low energy BESS that has limited ability to shift energy from one time to another can still significantly decrease curtailment.

It can also be observed that the lower cost AES coal and Kalaeloa combined cycle plants generate more energy with the addition of BESS, particularly with large storage (MWh) capacity. This occurs because the BESS allows these lower cost units to operate at more efficient loading during hours of low net load rather than be backed down to lower operating points or cycled off-line entirely. While the price differential between these two plants is not as significant as zero marginal cost wind and solar resources, they are still lower cost than the rest of Oahu's thermal generating fleet and thus provide net production cost benefits to the system.

When the BESS discharges, it displaces energy from other less efficient plants. As described earlier, the BESS could discharge during the peak load hour to mitigate large ramps in net system load or to provide up reserves. Figure 2 shows that most of the displacement occurs in more expensive oil-fired steam plants (Kahe, Waiau) and peaking plants. This results in lower fuel costs and emissions. The round-trip efficiency (R.T.E.) represents the losses that occur during the charge and discharge cycle and was assumed to be 90%. Including RTE in the figure ensures that the total increase in generation balances the total decrease in generation, accounting for losses.

B. Decoupling Energy Shifting and Reserve Value

Throughout this analysis, it was assumed that the BESS could provide both reserves (FFR and regulation) and energy arbitrage (shifting energy from one time-period to another), as long as multiple reserve services were not provided at the same time. The results presented in the previous sections indicate that a short duration BESS can provide significant value even without much ability to shift energy. This raises an important question; for the longer duration BESS, which value stream is larger; providing reserves, or energy arbitrage?

In order to decouple the combined value of these services, an additional sensitivity was conducted on the four-hour BESS configuration by removing the ability for the BESS to provide reserves (either FFR or regulation). When included with the original cases (presented previously), this creates three sets of simulation results to isolate the value of reserves and energy arbitrage.

- Energy Shifting: 4.0 HR BESS assumed unable to provide reserves. This represents an 'energy arbitrage' only storage system, which cannot provide FFR or regulation reserves (additional sensitivity case),
- Reserves: 0.5 HR BESS, which represents a 'reserve only' storage system (previously presented results),
- Combined: 4.0 HR BESS, assumed able to provide reserves. This represents the combined reserve and energy arbitrage storage system (previously presented results).

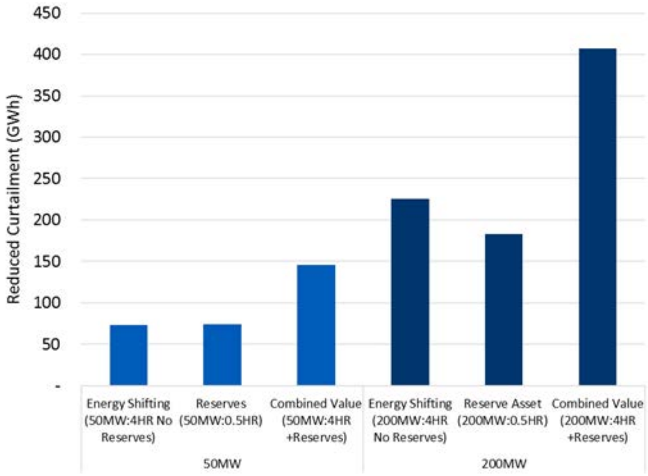

Figure 3. Annual Curtailment Reduction by BESS Use Case

The additional sensitivity allows for a direct comparison of the avoided cost and curtailment reductions relative to the case without energy storage. The sensitivity was conducted on the high renewable scenario for two power ratings, 50 MW and 200 MW. The total annual production costs and savings are provided in Table 3, while the reduction in annual curtailment is provided in Figure 4.

This comparison shows that in both the 50 MW and 200 MW power rated BESS, a reserve only asset has more value compared to the energy shifting asset, but the difference between the two use cases is relatively small. This is true even in the high renewable scenario that has significant levels of curtailment and quantifies observations made in previous sections of the report, which identified the high value of reserves (both FFR and regulation) for the Oahu grid. It can also be observed that the combined value of a reserve and energy shifting asset is significantly higher than either use case in isolation. However, the two use cases are not completely additive; the combined value of reserves and energy shifting is less than the two isolated use cases summed together. This is because the BESS cannot always provide multiple services at the same time (i.e. when the BESS is discharging at its max power rating it loses ability to provide up-regulation and FFR).

The results of this sensitivity highlight that significant value (both in production cost savings and curtailment reduction) can be achieved even with a relatively short duration reserve battery. The results also highlight that the combined value of a reserve and energy shifting asset is significantly higher than one use case in isolation. Thus, the co-optimized utilization of BESS technologies is important to fully capture the potential benefits of storage.

TABLE III. PRODUCTION COST SAVINGS BY BESS USE CASE

Power Rating	Energy (MWh)	BESS Use Case	Annual Production Cost (k$)	Annual Savings (k$)
Base Case	N/A	N/A	451,222	
50 MW	25 MWh	Reserves	434,706	16,516
50 MW	200 MWh	Energy Shifting	436,151	15,071
50 MW	200 MWh	Combined	429,949	21,273
200 MW	100 MWh	Reserves	409,224	41,998
200 MW	400 MWh	Energy Shifting	411,614	39,608
200 MW	400 MWh	Combined	383,646	67,576

IV. CONCLUSIONS

While many people assume the best way to incorporate storage is to shift solar energy from the middle of the day to evening peak hours, there are other options available to grid operators. Results of this analysis indicate that a short-duration (low energy), high power rating reserve asset can be more effective and economic way to integrate solar energy, reduce curtailment, and decrease system production cost. The short-duration BESS can be installed with a lower CapEx while providing similar system benefits. This is because a short-duration reserve BESS configuration can provide valuable grid services, which allows other conventional generators to shut down during high wind and solar periods. This saves significant fuel costs and allows to the grid to accept more renewables.

This finding is likely amplified on island power systems where reserves have high premiums relative to mainland power systems. However, in the future high renewable energy mainland grids will require ancillary services from new technologies. Storage is one of these technologies, but similar services are available from demand response and the wind and solar technologies themselves. To the extent that these technologies can replace ancillary services from conventional generators, additional renewable energy can be integrated into the grid. In most systems today, there are additional mitigations available to integrate more wind and solar into the grid, even during high generation events like the middle of the "duck curve." It is not necessary, nor prudent, to require energy shifting of renewable energy until these other forms of flexibility have been exhausted.

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