

Oahu Grid Stability Study

Phase 4: Battery Energy Storage Analysis

Prepared for

**Hawai'i Natural Energy Institute
School of Ocean and Earth Science and Technology
University of Hawai'i**

Report prepared by

GE Energy Consulting

December 2017



HNEI
Hawai'i Natural Energy Institute
University of Hawai'i at Mānoa





HNEI

Hawai'i Natural Energy Institute

School of Ocean and Earth Science and Technology
University of Hawai'i at Mānoa

Oahu Grid Stability Study

Phase 4: Battery Energy Storage Analysis

Prepared for: Hawaii Natural Energy Institute

Prepared by: GE Energy Consulting

Date: December 2017

Foreword

In the fall of 2015, GE Energy Consulting and the Hawaii Natural Energy Institute began a technical assessment of the Oahu power grid, with a goal of utilizing power system models to understand and quantify the impact of increasing variable renewable energy technologies, specifically distributed photovoltaic (DPV) energy, on system stability, reliability, and economics.

This report is the third of a multi-faceted project that will cover several topics of renewable integration. This report outlines the methodology, analysis and key findings of the analysis related to “Part 4: Battery Energy Storage Analysis.” While this report is meant to be a stand-alone document and can be read independently of the other project parts, it should be viewed in a larger context. This report will not address all questions or topics related to grid stability and renewable integration, but will refer readers to additional scope that will be the subject of future analysis.

This report was prepared by General Electric International, Inc. (“GEI”); acting through its Energy Consulting Group (“GE Energy Consulting”) based in Schenectady, NY, and submitted to the Hawaii Natural Energy Institute (“HNEI”). Questions and any correspondence concerning this document should be referred to:

Technical Contact

Derek Stenlik
Manager, Power Systems Strategy
GE Energy Consulting

General Electric International, Inc.
One River Road
Building 53
Schenectady, New York 12345
Phone: 518-385-7438
E-Mail: derek.stenlik@ge.com



Project Team

GE Energy Consulting

Derek Stenclik

Matthew Richwine

Richard Piwko

Christopher Cox

Sundar Venkataraman

Phillip deMello

Hawaii Natural Energy Institute

John Cole

Richard Rocheleau

Kevin Davies

Technical Review Committee

Hawaii Public Utilities Commission (HPUC)

Hawaiian Electric Company (HECO)

Department of Business, Economic Development, and Tourism (DBEDT)

Division of Consumer Advocacy

Brendan Kirby

Sebastian Nola

Note: While the Technical Review Committee was involved in regular status update meetings and reviews of the project methodology, the findings and results presented in this analysis do not constitute endorsement by the parties listed above.



TABLE OF CONTENTS

FOREWORD	I
TABLE OF CONTENTS	III
LIST OF FIGURES	IV
LIST OF TABLES	IV
1 INTRODUCTION	1
1.1 Objective of the Analysis	1
1.2 Key Assumptions	2
1.3 Scenarios Analyzed	3
1.4 Study Scope & Limitations	5
2 IMPACT OF BESS ON SYSTEM OPERATIONS	6
3 IMPACT OF BESS ON SYSTEM ECONOMICS	11
3.1 BESS Description	11
3.2 BESS Cost components	13
3.3 Benefit Cost Analysis	20
4 KEY FINDINGS	27

LIST OF FIGURES

Figure 1: Various Applications of a Battery Energy Storage System.....	2
Figure 2: Impact of BESS on Annual Energy Generation by Type	7
Figure 3: Thermal Plant Commitment and Dispatch with and without BESS (one week).....	8
Figure 4: Generation Dispatch with and without BESS (one week)	9
Figure 5: Charge-Discharge profile and State of Charge of BESS (one week).....	10
Figure 6: State of charge duration curves for various capacities of BESS	10
Figure 7: Example 10MW/40MWh (4-hour) BESS Unit.....	11
Figure 8: Example BESS Power Conversion System	12
Figure 9: Controls and Communications Diagram for a Renewables + Storage Plant.....	13
Figure 10: Degradation Assumptions Effect on Total Replacement Costs	16
Figure 11: Total CapEx (M\$) Estimate for Four BESS Configurations	18
Figure 12: Total CapEx (\$/kWh) Estimate for Four BESS Configurations	18
Figure 13: CapEx for all BESS Configurations Analyzed.....	19
Figure 14: Total Production Cost by BESS Configuration in a 50% Renewable Scenario	20
Figure 15: Benefit-Cost ratio of BESS configurations in a 50% Renewable Scenario	21
Figure 16: Production Cost Savings vs Annual Capital Cost by Configuration	22
Figure 17: Benefit Cost Analysis by BESS Configuration and Scenario	23
Figure 18: Sensitivity of Key Assumptions on Benefit-Cost Ratio	24

LIST OF TABLES

Table 1: Power and Energy Rating of BESS Considered in the Analysis.....	3
Table 2: Overview of Assumptions for Two Scenarios Analyzed.....	4
Table 3: Assumed Capital Cost Estimates for BESS.....	17



1 INTRODUCTION

As Hawaii's energy mix transitions to a high renewable grid, the penetration of wind and solar generation will increase significantly. This transition will require a significant change to grid operations and a new framework to ensure the system is operated efficiently, reliably, and securely. It may be necessary for new emerging technologies, including distributed energy resources (DERs), including PV, demand response, energy storage, and other emerging technologies to provide grid support and other essential reliability services in a way they are not currently utilized. Earlier analysis performed as a part of this study (Phases 1, 2 and 3) identified the ancillary services that may be necessary in the future grid, as well as possible approaches to procure them. In this task, a benefit-cost analysis of using a battery energy storage system (BESS) for providing a few of the grid support and essential reliability services was performed.

BESS is an emerging technology that can provide multiple services. Some of these services can be monetized via existing ancillary service procurement mechanisms, while others require additional mechanisms. BESS technology is also highly configurable and modular. Systems can be designed, sized, and configured to fit the unique requirements of the grid where they are deployed. With proper communications and controls, many distributed BESS (as well as load control and demand response) can be aggregated to provide similar services as larger utility-scale configurations.

Therefore, it is essential to understand all the benefits, as well as costs associated with this emerging technology. Different configurations, which vary by power rating (MW) and energy rating (MWh), as well as cell chemistry, will differ in the way they are utilized by the grid and the services provided. In addition, the way energy storage is utilized and the benefits provided to the grid will change as renewable penetration increases. There is no "one-size fits all" BESS configuration that will work across all grids and use cases. Robust engineering and economic analysis can provide a framework to understand the appropriate sizing and configuration for the grid.

1.1 Objective of the Analysis

A BESS can provide a number of plant-level and system-level services such as energy shifting, system ramp management, frequency regulation and contingency reserves as shown in Figure 1. 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 optimal 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 net benefits of varying BESS configurations and determine what size, as well as power to energy ratio, may be best for the Oahu system. In this analysis, production simulation modeling was used to quantify the benefits of BESS in

Battery Energy Storage System Analysis

providing energy shifting and other ancillary services such as regulation and fast-frequency response (highlighted in green in Figure 1). A benefit cost analysis was then performed by comparing the production cost savings with the total capital cost of BESS for different combinations of power and energy ratings. Using the results of the benefit-cost analysis, a BESS size (power and energy rating) is recommended for further consideration.

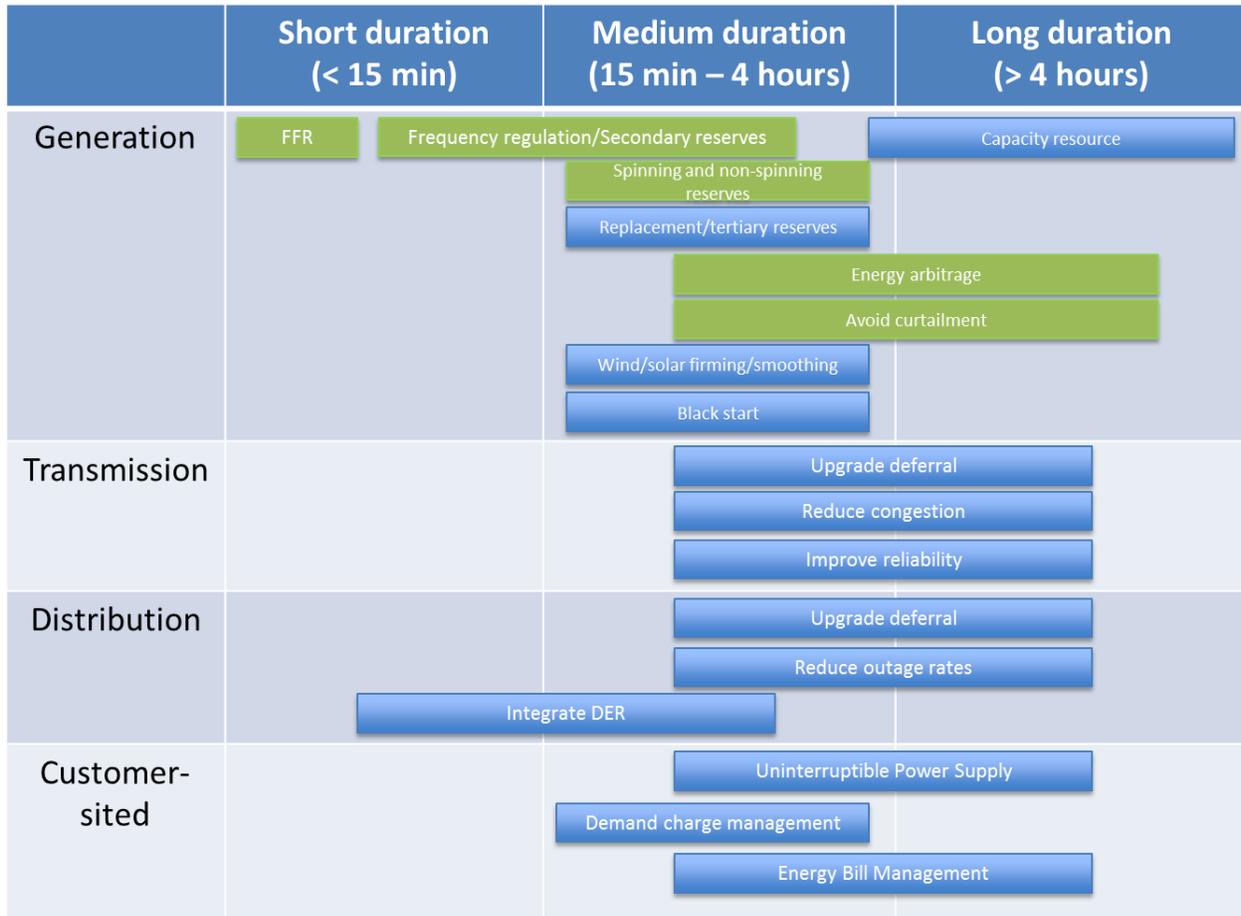


Figure 1: Various Applications of a Battery Energy Storage System

1.2 Key Assumptions

As mentioned before, a BESS is defined by two key parameters: a power rating and energy rating. Table 1 shows the power and energy ratings for 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.

Battery Energy Storage System Analysis

Table 1: Power and Energy Rating of BESS Considered in the Analysis

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

Other key assumptions made in the operational and benefit cost analysis are listed below.

- It is assumed that the power purchase agreements associated with the wind and solar resources are take-or-pay. In this case, the system operator is paying for energy based on expected operation even if it is curtailed. Therefore, there is an incentive for the operator to capture the curtailed energy for use later and this value is attributable to the addition of the BESS.
- It is assumed that the BESS will be used for energy arbitrage, as well as providing essential reliability services such as regulation reserves and contingency reserves (FFR). It is also assumed that the BESS will be able to provide FFR or regulation services while charging, idle with some state of charge (SoC), or discharging below its maximum rating.
- An overall BESS round trip efficiency of 85% is assumed in this analysis. This efficiency is inclusive of the battery roundtrip efficiency, as well as the losses associated with the balance of system components such as the inverter and the transformer.
- It is assumed that the BESS provides only energy arbitrage and essential reliability services mentioned above. Other services that could be provided by BESS such as transmission and distribution upgrade deferral, voltage support etc., are not evaluated in this analysis but may provide additional value to the system if deployed correctly.

1.3 Scenarios Analyzed

The benefit of energy storage is calculated under two renewable penetration scenarios: 1) representing the near-term (2018) renewable portfolio on Oahu (“Current W&S”) and 2) assuming additional renewable resources equal to 50% available annual renewable energy penetration as a percent of load (“50% W&S”). To achieve the renewable penetration identified in Scenario 2, the production simulation model includes the buildout from HECO’s April Power Supply Improvement Plan (PSIP)¹ in the year 2040. This includes 565 MW of wind capacity, 565 MW of utility-scale PV solar capacity, and 840 MW of distributed rooftop PV

¹ Due to the timing of this study and concurrent work being conducted by the utility, the resource mix assumed in Scenario 2 does not reflect the renewable expansion plan proposed in the latest PSIP. However, it is representative of a solar-centric renewable grid currently being proposed.



Battery Energy Storage System Analysis

(DPV) solar capacity. In addition, system load was increased from 7,734 GWh in Scenario 1, to 8,450 GWh in Scenario 2 mostly due to increased electric vehicle penetration.

The thermal capacity and assumed fuel price modeled in the production simulation was held constant between the two scenarios to simplify the comparison between the two scenarios. Both assumptions reflect what is currently in operation or under construction (in 2017) and the approximate delivered oil price.

As a long-term planning study, most of the analysis presented in this report is for Scenario 2, the 50% wind and solar available energy scenario. However, in some instances the results of a selection of BESS configurations analyzed in Scenario 1 are also presented to compare the utilization and benefits of a particular BESS on the current system versus a system with more renewable energy. An overview of the fuel price, load, and renewable capacity assumptions are provided in Table 2.

Table 2: Overview of Assumptions for Two Scenarios Analyzed

	SCEN 1 (Current W&S)	SCEN 2 (50% W&S)
Fuel Price (\$/bbl)	\$60/bbl WTI = ~\$11/MMBtu	
Thermal Resources	Existing Units, No Adds or Retires	
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%



1.4 Study Scope & Limitations

The objective of this study is to evaluate the relative benefits of different battery energy storage configurations on the Oahu power system as additional wind and solar is added to the grid. While this study significantly expands the technical analysis into areas not examined in previous studies, it does not cover all possible risks and mitigations for grid strength. The following points highlight the scope and potential limitations of the study:

- This study does not replace existing analysis conducted by the utility, state regulators, or other stakeholders in Hawaii. Instead, it is intended to supplement those studies with additional technical analysis and findings.
- The analysis presented herein provides an in-depth assessment and quantification of several storage services (i.e. regulation reserves, fast-frequency response, ramping and load following, energy arbitrage, and curtailment). However, it does not cover all services that can be provided by a BESS. Additional value is likely available from other services.
- The capital cost estimates developed in the benefit-cost analysis is for a representative lithium-ion based battery system. Depending on the configuration, battery cell chemistries will vary and impact the cost of the BESS. This level of precision was not included in this study but should be evaluated when selecting specific project technologies.
- Battery energy storage technology is one of many emerging technologies that can facilitate renewable integration. The objective of this study was to compare and contrast different battery configurations to determine which ones are most valuable to the Oahu system. This analysis did not compare the efficacy of BESS technology versus other technologies such as conventional thermal generation, wind and solar generation, or demand response.

2 IMPACT OF BESS ON SYSTEM OPERATIONS

The impact of BESS on operations was studied using a production simulation software. The production simulation software performs a least-cost, security-constrained unit commitment and economic dispatch. It commits and dispatches the most efficient set of generators to meet load for each 10-minute interval of the simulation year as load, wind, and solar fluctuate over time. In addition, the software also ensures that generators hold sufficient reserves (regulation and contingency reserves) during each hour of operation. Battery energy storage systems are modeled using their power and energy ratings, as well as their round-trip efficiencies. In addition, the capability of the BESS to provide various ancillary services is also modeled.

The BESS acts as a load when it charges and as a generator when it discharges. In large energy systems, 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.

Figure 2 shows the change in annual generation due to the addition of BESS with varying power and energy 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;

- 1) The BESS charges with otherwise curtailed wind and solar energy and increases the system's load during hours of surplus wind and solar energy and shifts it to hours when it can be used to reduce the energy required from expensive oil-fired generation,
- 2) 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)

Battery Energy Storage System Analysis

capacity. This occurs because the BESS allows these lower cost units to operate at higher, more efficient, loading online 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, Waiiau) 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.

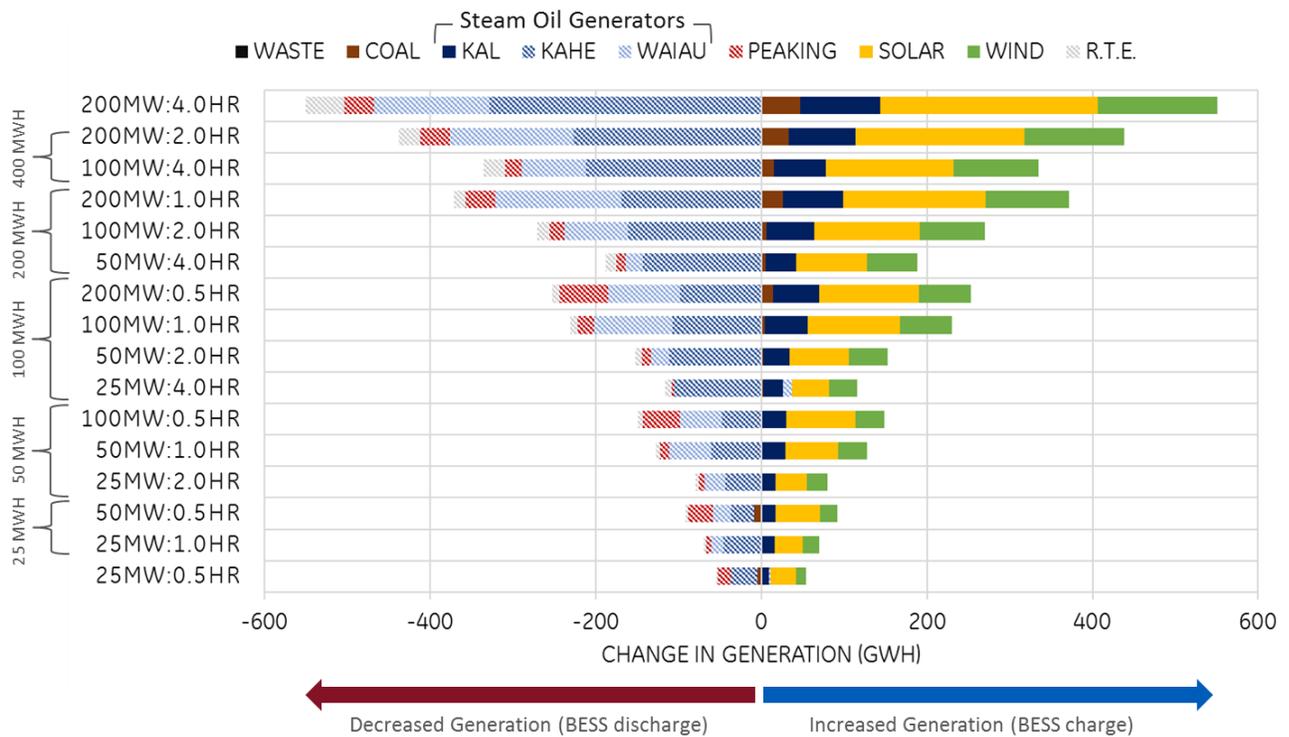


Figure 2: Impact of BESS on Annual Energy Generation by Type

To better understand the underlying cause of the changes in generation presented in Figure 2, the impact of BESS on the commitment and dispatch of thermal plants is further analyzed. Figure 3 shows the cumulative hourly commitment (blue line) and dispatch (shaded blue area) of thermal power plants with and without a 200MW-2hr BESS for a one-week period. During the hours of high renewable generation, typically middle of the day, the thermal units are backed down to their minimum value. These units are not cycled off due to the need for regulation and FFR reserves, to avoid a start cost, or due to minimum up and minimum down-

Battery Energy Storage System Analysis

time constraints. The BESS enables some of the energy from the PV solar plants that would have otherwise been curtailed to be delivered. This can be observed by comparing the energy from renewable generation (green area), which peaks above the system load (black line) in the BESS case. Those periods represent battery charging, which increases the system load.

It should be noted that the decrease in solar curtailment is larger than what the BESS could absorb via charging and energy shifting alone. As indicated earlier, this is achieved when the BESS lowers the capacity of thermal plants that are committed. This is because some of thermal plants that were committed in the base case for the specific purpose of providing ancillary services are no longer needed as much since the BESS can provide this service. It can be observed that the addition of BESS results in an average reduction of 200 MW in thermal unit commitment during this example week of operations. With fewer thermal units committed, there is more available on the grid to be served by solar energy.

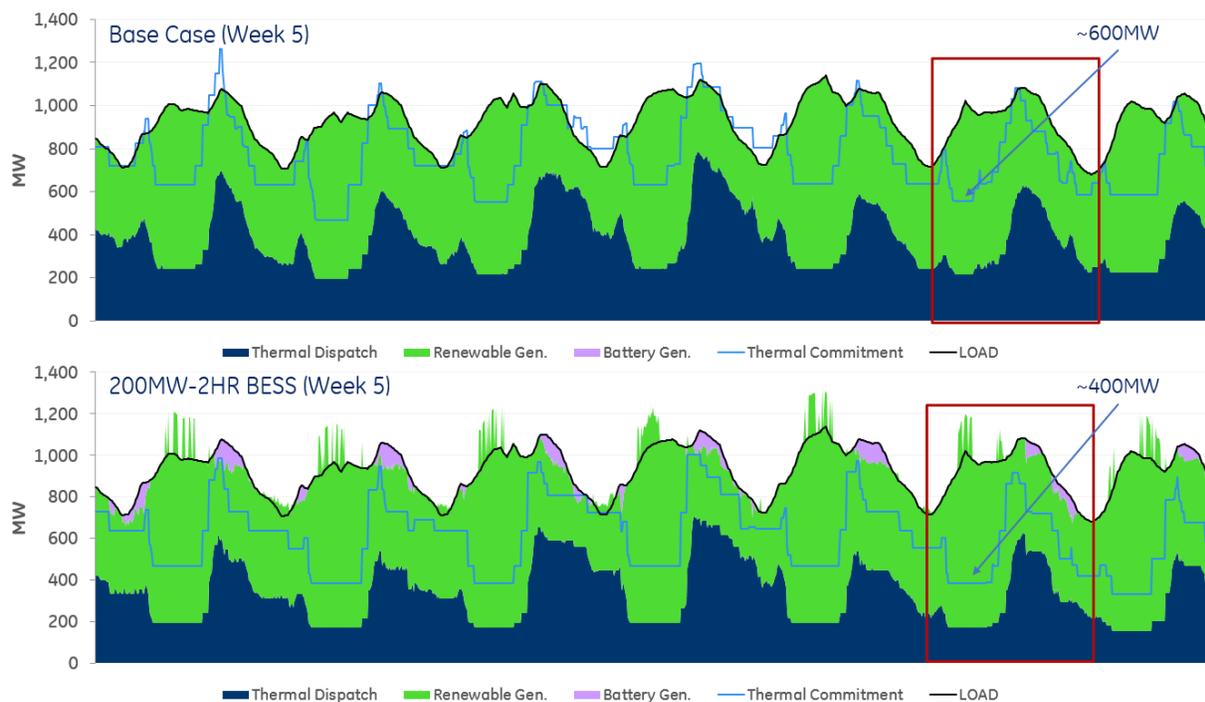


Figure 3: Thermal Plant Commitment and Dispatch with and without BESS (one week)

Figure 4 shows the chronological dispatch of the solar and wind generation, as well as the generation from each thermal power plant grouping. The dispatch of peaking units is lower with energy storage than under the base case. It can also be observed that more efficient units such as AES and Kalaeloa are dispatched more in the case with energy storage. Those units also ramp less and operate at more stable operating points as illustrated by slightly fewer “jagged” edges.

Battery Energy Storage System Analysis

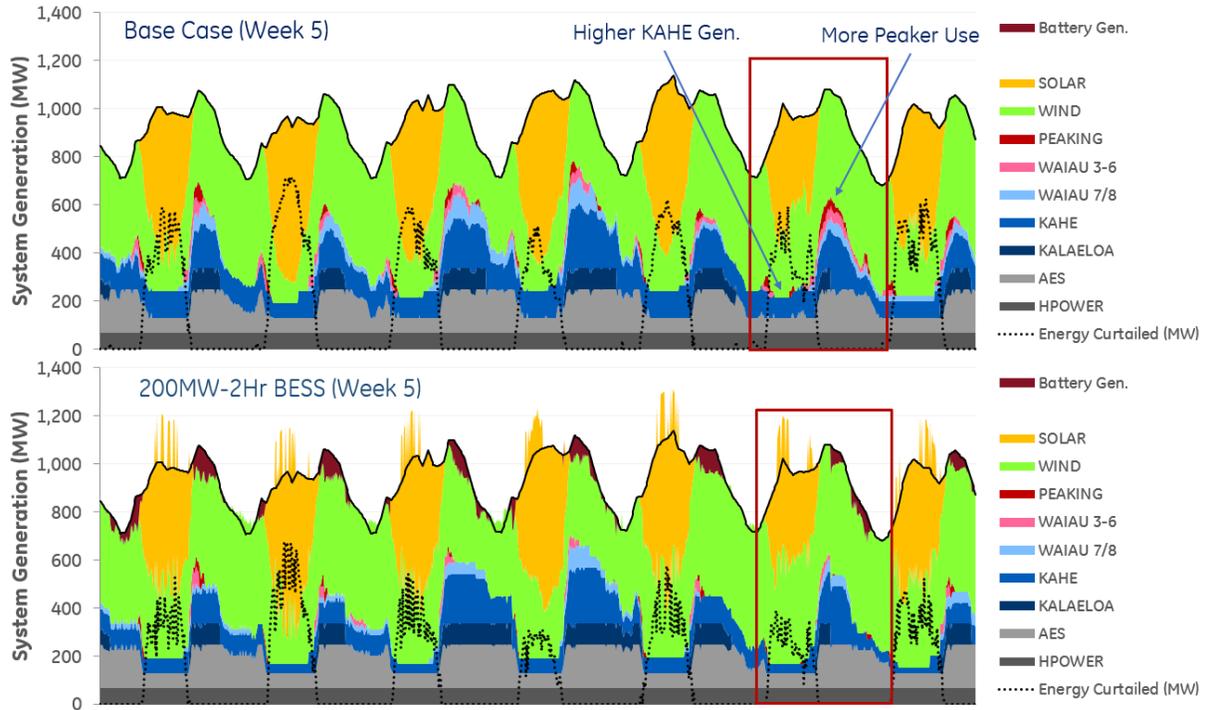


Figure 4: Generation Dispatch with and without BESS (one week)

Figure 5 shows the charge-discharge profile of the BESS during the same week, as well as the State of Charge (SoC) of the 200 MW, 400 MWh BESS. The area shown in green represents the energy used for charging the BESS and the area in blue represents energy returned to the grid from the BESS. The figure also shows the state of charge (SoC) of the battery. The SoC is similar to the fuel gauge in a car and represents the amount of energy stored in the battery at any given time as a fraction of the capacity of the battery. If a battery is charged, then its SoC goes up. Conversely, when it's discharged, its SoC goes down. The SoC of the BESS is optimized by projecting its operations one day into the future. This ensures that the BESS has sufficient energy to meet the charge-discharge requirements of the following day, based on forecasted load and renewable generation.

From Figure 5, it is evident that the BESS charges primarily during the middle of the day using the excess energy from PV solar generation. Excess wind energy is also used to charge the BESS during early morning (12am to 3am) hours. It is also evident from the figure that the BESS primarily discharges during later afternoon, peak-load, hours (6pm to midnight). This is the peak load period of the day with the lowest reserve margin (available surplus capacity). As a result, the BESS is also serving as a valuable capacity resource during this period (a benefit that is not quantified in this report). The BESS also discharges during the morning peak (6am to 9am). The overall SoC of the BESS is also managed such that it is capable of providing ancillary services such as regulation reserves and FFR.

Figure 6 shows the SoC duration curves for four batteries with different power and energy ratings. The SoC duration curve for each battery was obtained by sorting the hourly SoC values for one year from high to low. In this figure, the high energy batteries (2 hours of storage) are shown in solid lines and low energy (0.5 hours) in dotted lines. It can be

Battery Energy Storage System Analysis

observed from this figure that within each power class, BESS with higher energy ratings spend more time at a lower SoC. This is because the lower energy BESS needs to maintain sufficient SoC in order to provide various ancillary services. This is observed as the “plateaus” of SoC in the duration curves, which show the minimum SoC required to provide the reserve and is based on the required duration of reserve response (assumed to be 30 minutes). As a result, it is often economic to keep the BESS SoC at or above that level. In the next section, the impact of BESS operations on production costs will be investigated further.

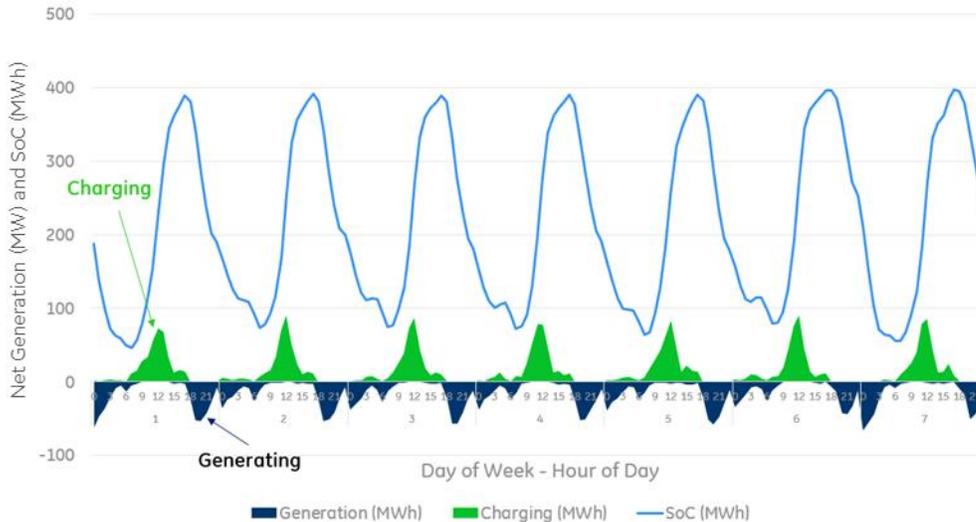


Figure 5: Charge-Discharge profile and State of Charge of BESS (one week)

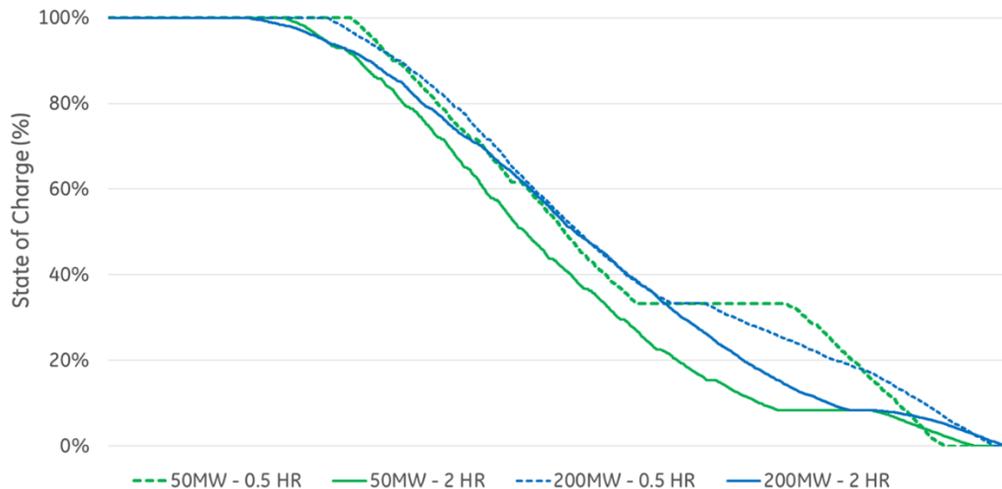
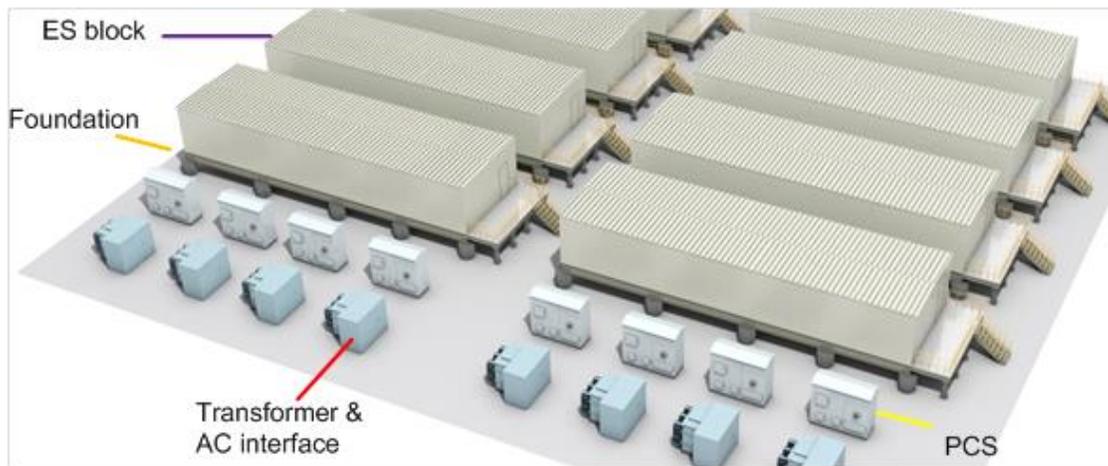


Figure 6: State of charge duration curves for various capacities of BESS

3 IMPACT OF BESS ON SYSTEM ECONOMICS

3.1 BESS Description

There are several components and sub-systems in a BESS. An example BESS is shown in Figure 7. The example BESS is 10MW/40MWh (4-hour) system which is based upon 1.25MW/5MWh sub-systems. In this figure, a building is utilized for each 5MWh of energy storage (ES), and outdoor rated Power Conditioning System (PCS) and transformers. Vendors of BESS may package the components differently or use fully outdoor rated components, resulting in slightly different cost structures.



Example 10MW/40MWh (4-hour) BESS unit on a 50m x 50m square of land, showing several of the key components (GE-Energy Storage),
Not shown: fence & security perimeter, HVAC for the ES blocks, controls and communication equipment.

Figure 7: Example 10MW/40MWh (4-hour) BESS Unit

3.1.1 Energy Storage Block

The energy storage block includes the cells, modules, and racks that store the electrostatic or electrochemical energy. The Energy Storage Block may also include mechanical racking, thermal management components, and some DC distribution and Battery Management Functions. The energy storage block may come from the battery vendor or in conjunction with a third party packaging and integration vendor.

3.1.2 Battery Management System

The management of the energy storage cells, modules, strings, and banks is performed through controllers situated in the enclosure. This subsystem informs plant and/or inverter level controllers about the state of charge of energy storage modules, the recharge or discharge rate limits, temperature, or other physical measurements.

3.1.3 Power Conditioning System

The Power Conditioning System (PCS) has a primary function of controlling and converting the DC power between the ES device and the AC electrical network. Below is a listing of

Battery Energy Storage System Analysis

typical PCS functions, with an example of a 1.25 MW PCS from a BESS application shown in Figure 8.

Low-level PCS functions

- coordination of pre-charge and interface with the DC storage block
- synchronization to the AC electrical network
- over current protection of the DC and AC connections

Mid-level PCS functions

- control of the real and reactive power to the AC network (as dispatched)
- control of the DC current and voltage limits

High-level PCS functions

- system level ground fault detection and protection
- PCS status monitoring and reporting

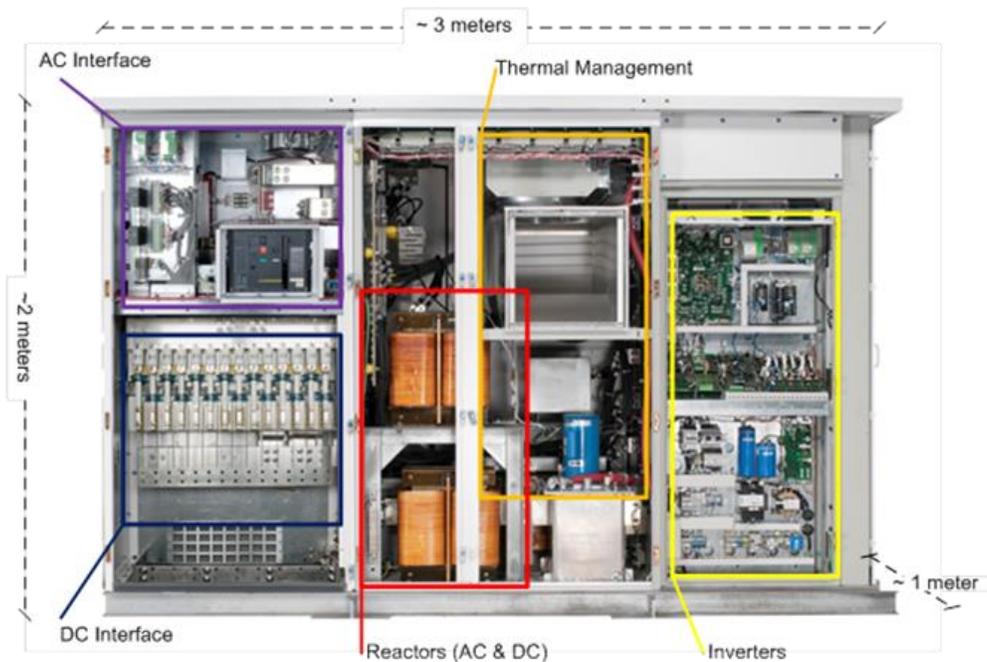


Figure 8: Example BESS Power Conversion System

3.1.4 Controls and Communications Equipment

Typical energy storage control architecture is shown in Figure 9, including the devices and software applications in different control layers (shown in blue). These sub systems are explained in more detail below (in the figure, from right to left).

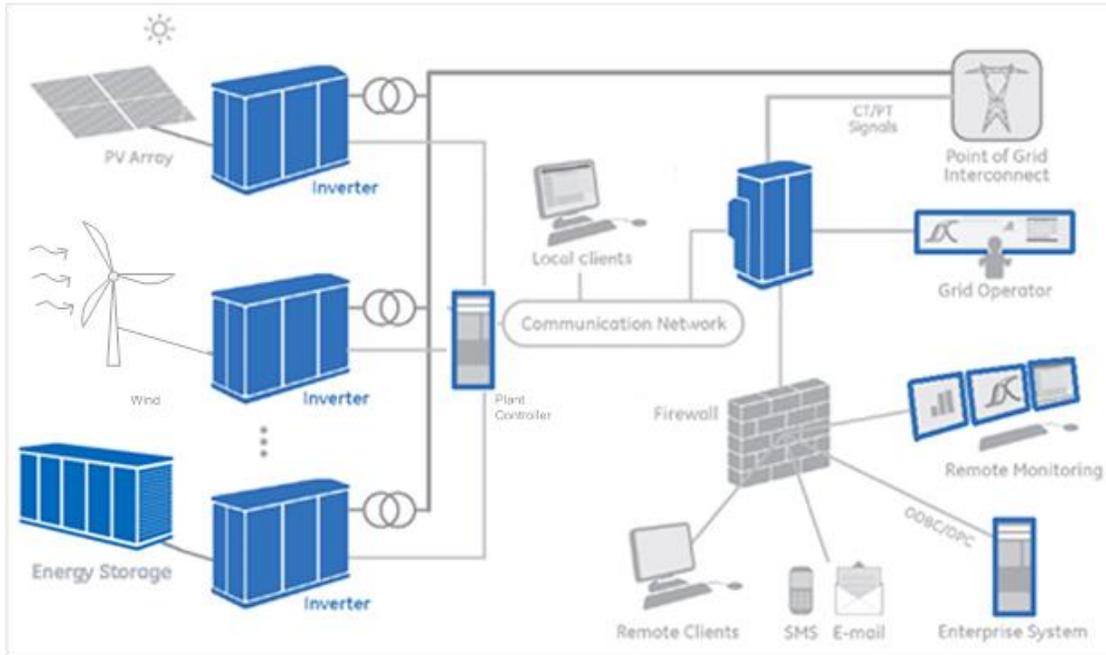


Figure 9: Controls and Communications Diagram for a Renewables + Storage Plant

3.2 BESS Cost components

This section describes the components of the capital expenditure (CapEx) for a battery energy storage system along with general capital cost assumptions used in this analysis. The dominant capital cost is the energy storage block (particularly the battery cells), even in a short duration application. Both elements are discussed below.

3.2.1 CapEx for DC Subsystem

The dominant CapEx component in most BESS installations is the DC subsystem or the energy storage block. This is a collection of cells or modules and possibly mechanical racking and electrical distribution and collector buses. The CapEx cost for this sub-system is often expressed in units of expense per energy purchased [\$/kWh]. The DC subsystem typically includes the following:

- Cells
- Battery Trays
- Battery String Controllers
- Battery Zone Controllers

- DC Bus & Cables
- Battery Racks
- Battery Interface Cabinets

3.2.2 CapEx for balance of system

Besides the energy storage block, the BESS includes many other components and sub-systems referred to as the Balance of System (BOS). These include the following:

- AC Subsystem (Low Voltage)
 - Inverter
 - Inverter Transformers
- AC Subsystem (High Voltage)
 - Medium Voltage Disconnects & Switchgear
 - Step-up Transformer
 - Main Breaker
- Mechanical Systems
 - Concrete pads
 - Enclosure Units
 - HVAC System
 - Fire Suppression System
- Plant Control
 - Plant Controller
 - SCADA System

3.2.3 Project development and EPC costs

In the design phase of a project, there are several costs, due to planning, permitting and commissioning phases of a BESS project. These elements may include:

- Interconnection studies (battery to electrical network compatibility study)
- Land use agreements
- Permitting and application submissions
- Commissioning costs for the major equipment

These design integration costs are highly dependent upon the location of the proposed BESS and the nature of the regulations and rules governing the local utilities and the deployment of distributed energy resources. This study did not evaluate the EPC costs associated with a specific project on Oahu, but instead used a generic, yet representative, 20% EPC cost multiplier to account for these costs.

3.2.4 BESS degradation and replacement costs

BESS technology experiences degradation over the lifetime of the project, which decreases the efficiency and ability for the lithium-ion cells to store energy and the power levels at which the units can respond. The amount of degradation depends on a variety of factors and depends on the how the BESS is configured and utilized over multiple years. In addition, many

Battery Energy Storage System Analysis

of the degradation drivers interact with one another, making the net impact on degradation difficult to discern. In general, the four largest drivers of degradation are as follows:

- **Charge and discharge rate:** Faster charging and discharging rates, relative to the BESS energy capacity, increase degradation. The charge or discharge rate is measured as a C-rate, where the number indicates the portion of the total energy capacity that would be transferred if the rate was sustained for one hour. For example, a BESS configuration that is rated for 2C (i.e. 10MW:5MWh 30 minute BESS) can charge or discharge in less time than a configuration rated for only 0.25C (i.e. 10MW:40MWh 4 hour BESS). Typically, this is the most significant driver of degradation and is most apparent in high power, low energy applications such as frequency regulation and load following. As a result, it is important that the BESS is designed properly for the application.
- **Number of Cycles:** Charge/discharge cycles lead to degradation. The number of cycles is measured as the amount of energy exchanged by the BESS (throughput) divided by the energy capacity of the BESS. For example, a low power, high energy BESS that shifts solar from mid-day hours to peak load hours may only have one full cycle per day. In contrast, a BESS used for regulation or ramp-rate control may have multiple cycles per day and more degradation. Similar to the charge and discharge rate, this tends to affect the high power, lower energy configurations more than the multiple hour systems.
- **State of Charge:** A higher average state of charge will result in increased degradation. This is especially true when a BESS is charged to max energy rating and left at a high state of charge for a long period of time. This could be done to serve as a FFR asset for large, but rare, contingency events or for an energy shifting asset during periods of sustained high renewable penetration. In general, state of charge degradation impacts the low energy configuration more as they spend more time at higher states of charge.
- **Temperature:** While temperature is a significant driver of lithium-ion degradation, it is usually managed by onsite HVAC temperature control and thus not considered for this analysis.

Understanding how each factor translates to impact on technical life of the BESS project is difficult and largely out of scope for this comparative analysis. However, given that the battery cells constitute the largest cost component for the BESS plant, an estimate of degradation was included in the cost estimates. To overcome this limitation, the study assumed *relative* degradation assumptions across the different configurations. It was assumed that the 30-minute configurations had a DC subsystem replacement (or addition) at 8-years, the 1-hour systems had a replacement at 12 years, the 2-hour systems had a replacement at 16 years, and the 4-hour systems were assumed to last, without replacement, for the full 20-year project life. While this may be a simplistic assumption for a detailed cost quote for an actual BESS proposal, it is a useful exercise to estimate the relative capital cost impacts across the various BESS configurations analyzed and provide a directional assessment of the degradation costs relative to other components of the capital costs.



Battery Energy Storage System Analysis

To limit degradation, it was also assumed that the original installation included a 1.2x “useful cell multiplier” on the DC subsystem, which increased the total battery cells by 20%. For example, a 100 MWh system referred to in this analysis was assumed to have a useable range, able to hold a state of charge of up to 100 MWh, but was actually sized to 120 MWh for the capital cost assumptions, leaving 20 MWh of surplus capacity to mitigate degradation and serve as replacement capacity later.

Because the degradation is on the battery cells, only the DC subsystem was assumed to be replaced. When the replacement occurred, it was assumed that 50% of the DC subsystem was replaced (or simply added) to the BESS (i.e. a 100 MWh BESS required at 50 MWh CapEx addition at a future year). This replacement cost was discounted back to a net present value and the DC subsystem technology was assumed to have a learning curve that lower costs over time, thus decreasing the \$/kWh cost of the DC subsystem by 50% within 8 years. As a result of these assumptions, degradation is a relatively small (~4-7%) cost component of the cost of the initial capital expenditure (CapEx) requirements for a BESS, as illustrated in Figure 10.

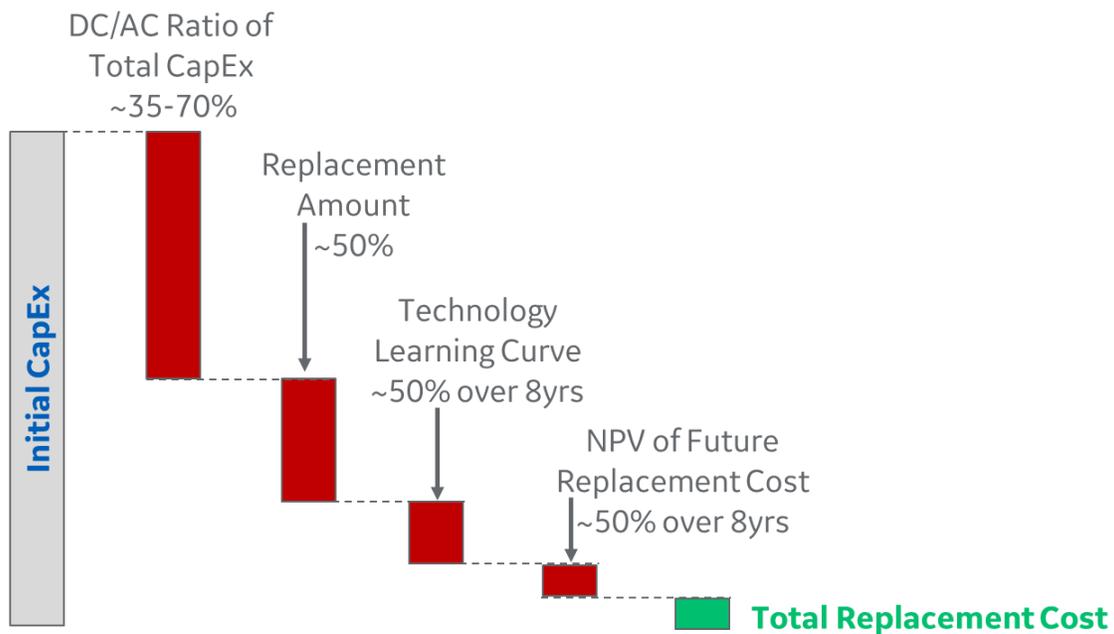


Figure 10: Degradation Assumptions Effect on Total Replacement Costs

3.2.5 Capital Cost Assumptions used in this Analysis

Table 3 shows the capital cost of a lithium BESS broken down by the DC system cost and the balance of system costs. The cost of the BESS, particularly the DC system, has been decreasing steadily due to scaling up of manufacturing driven by the growth in electric vehicles. The table shows how some BESS cost components (i.e. DC subsystem) are priced based on the amount of *energy* (\$/kWh), whereas other components (i.e. AC subsystem, and mechanical systems) are often based on the *power* rating (\$/kW) of the system. This is important when comparing across different configurations where a simple cost assumption in total \$/kWh, typically used in industry press, may not be sufficient.

Battery Energy Storage System Analysis

Table 3: Assumed Capital Cost Estimates for BESS

250	\$/kWh DC Subsystem
150	\$/kW AC Subsystem
70	\$/kW Mechanical Systems & Plant Control
20%	EPC Cost Multiplier
20%	Useful Battery Cell Multiplier
10%	Discount Rate
15	\$/kW-y Annual Fixed O&M
50%	DC Subsystem Replaced due to Degradation
50%	Future BESS DC Subsystem Cost (learning curve)

It is important to note that the assumptions for capital costs used in this analysis are not for a specific BESS application or configuration. Instead they are intended to be relative, general cost estimates compiled from a variety of publicly available sources. While this is sufficient for the relative comparison analysis conducted for this report, a more detailed cost breakdown is required to analyze an actual proposed project. In addition, BESS technology and manufacturing techniques are rapidly advancing. While the numbers included in this report are sufficiently accurate for analysis conducted at time of writing (2nd half of 2017) they may not be accurate at a later date.

Figure 11 shows the total capital cost components for four BESS configurations in millions of dollars. The following chart, Figure 12, illustrates the same capital cost components, but on a \$/kWh basis, which is commonly used in industry press when referencing BESS costs. Both perspectives are important when determining the correct BESS configuration for a given application. The four configurations are sorted by increasing energy (MWh) from left to right, with the two middle configurations both having 100 MWh of energy, but varying power (MW) ratings to allow for a direct comparison between the two configurations.

From the figures it can be seen that the balance of system costs, including the AC subsystem and mechanical systems, constitutes a significant part of the total capital cost for the power (i.e., lower energy rating) battery when compared with the high-energy battery. For the high-energy battery, the DC subsystem price constitutes a significant portion of the overall capital cost. The total CapEX for all the configurations considered in this analysis are shown in Figure 13.

Battery Energy Storage System Analysis

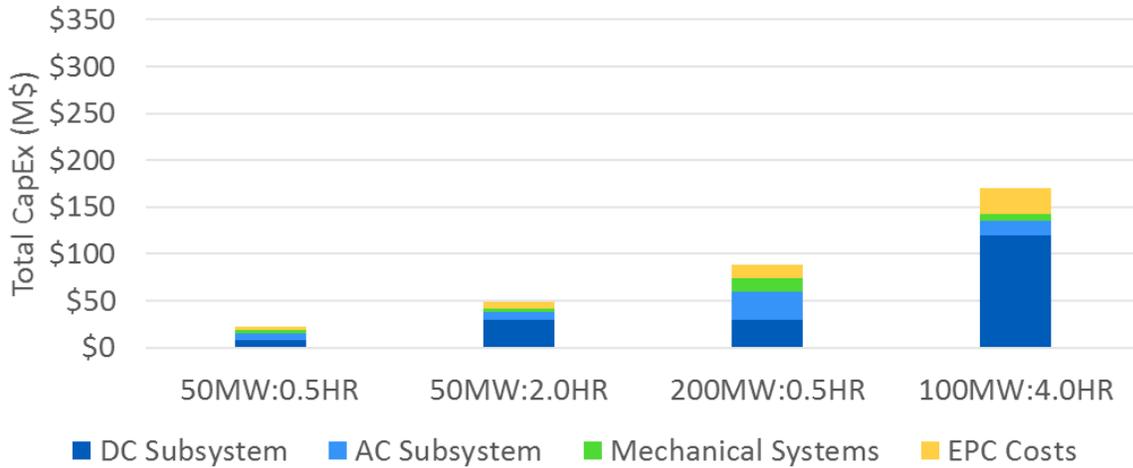


Figure 11: Total CapEx (M\$) Estimate for Four BESS Configurations

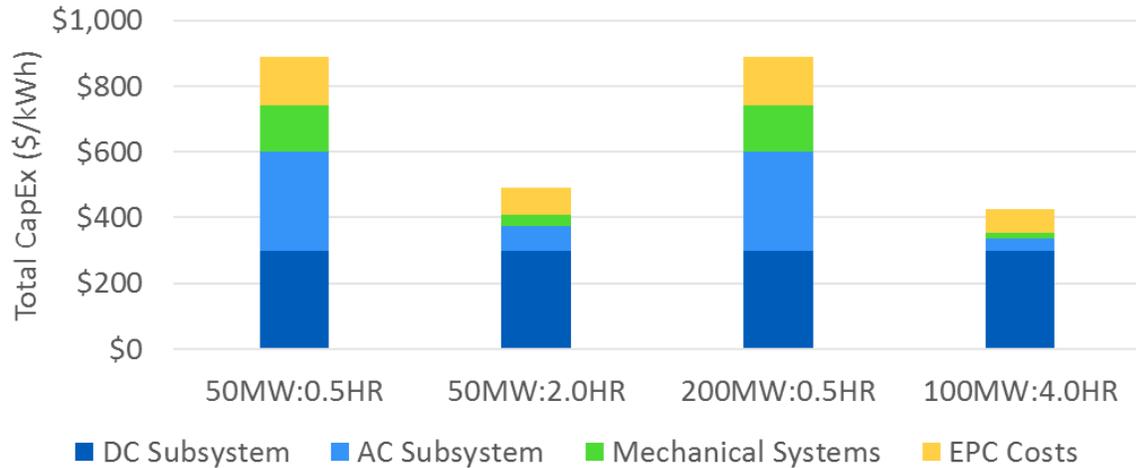
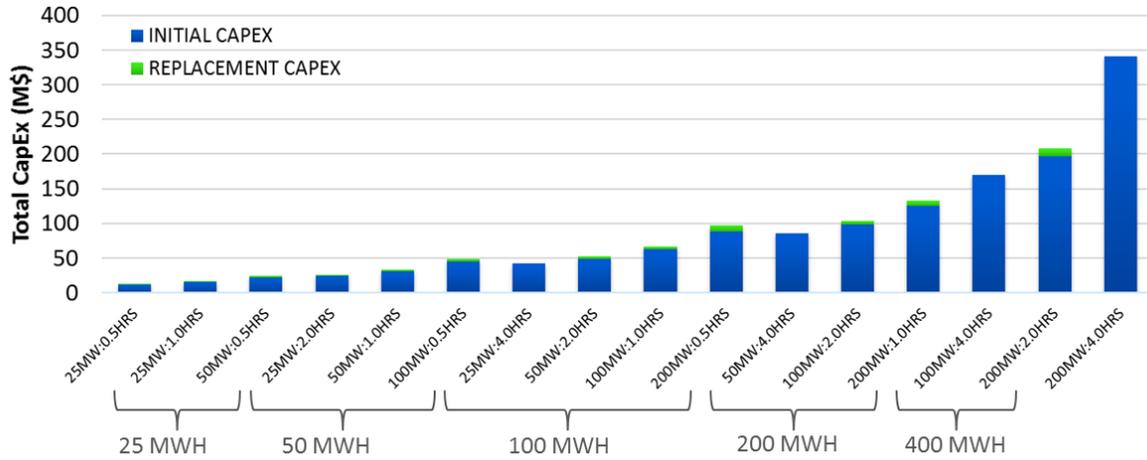


Figure 12: Total CapEx (\$/kWh) Estimate for Four BESS Configurations

Battery Energy Storage System Analysis



Total CapEx (k\$)		Power (MW)				CapEx (\$/kWh)		Power (MW)			
		25	50	100	200			25	50	100	200
Storage (Hrs)	0.50	11,100	22,200	44,400	88,800	Storage (Hrs)	0.50	888	888	888	888
	1.00	15,600	31,200	62,400	124,800		1.00	624	624	624	624
	2.00	24,600	49,200	98,400	196,800		2.00	492	492	492	492
	4.00	42,600	85,200	170,400	340,800		4.00	426	426	426	426

Figure 13: CapEx for all BESS Configurations Analyzed

3.3 Benefit Cost Analysis

3.3.1 Economics of BESS with High Renewables

As discussed in Section 2, the operation of the BESS is optimized to shift generation from hours of excess solar and wind generation to peak load hours, meet the ramping requirements of the system particularly during the morning ramps, and provide ancillary services such as regulation and contingency reserves. The production cost (also referred to as total generation cost) of operating the system for the base case, as well as the cases with different BESS configurations, is shown in Figure 14. The savings in production cost for each BESS configuration is also shown in this figure. It should be noted that the production cost of operating the system is primarily the fuel cost. This cost also includes other variable operations and maintenance costs associated with operating the system, as well as any emissions costs (not applicable).

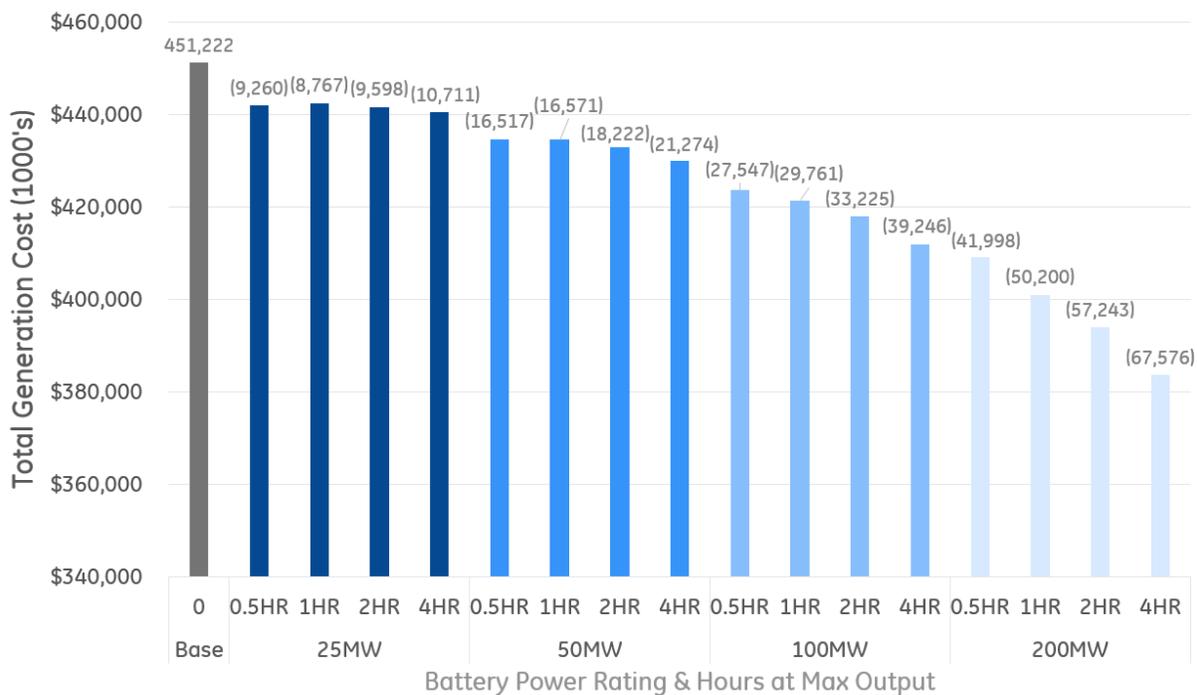


Figure 14: Total Production Cost by BESS Configuration in a 50% Renewable Scenario

It can be observed that, in general, there is a reduction in production cost due to the addition of BESS. As discussed before, this is due to the reduction in energy supplied from peaking units during on-peak hours, a reduction in the commitment of thermal units during off peak hours to provide ancillary services (regulation down), as well as a reduction in the provision of ancillary services (regulation up and contingency reserves) from thermal units. It can be observed from the figure that the savings increase with larger power rating of the BESS and to a lesser extent with its energy rating.

Battery Energy Storage System Analysis

The annual benefits, i.e., the annual production cost savings is compared with annualized cost of the BESS to determine its overall benefit. The annualized cost of the BESS is made up of two components: the annual fixed charge recovery and the annual fixed operations and maintenance (O&M) cost of the BESS. The annual fixed cost is obtained from the BESS CapEX costs shown in Figure 11 using a Fixed Charge Ratio (FCR) of 12%. The annual fixed O&M cost is assumed to be \$15/kW-yr.

Using the annual cost of the BESS discussed above and the production cost savings discussed in Section 3.3.1, the benefit-cost ratios are calculated for various configurations of BESS. This is shown in Figure 15. A benefit-cost ratio of 1 or greater indicates that the addition of the BESS will result in sufficient production cost savings to cover all the fixed costs associated with the installation of operation of the BESS.

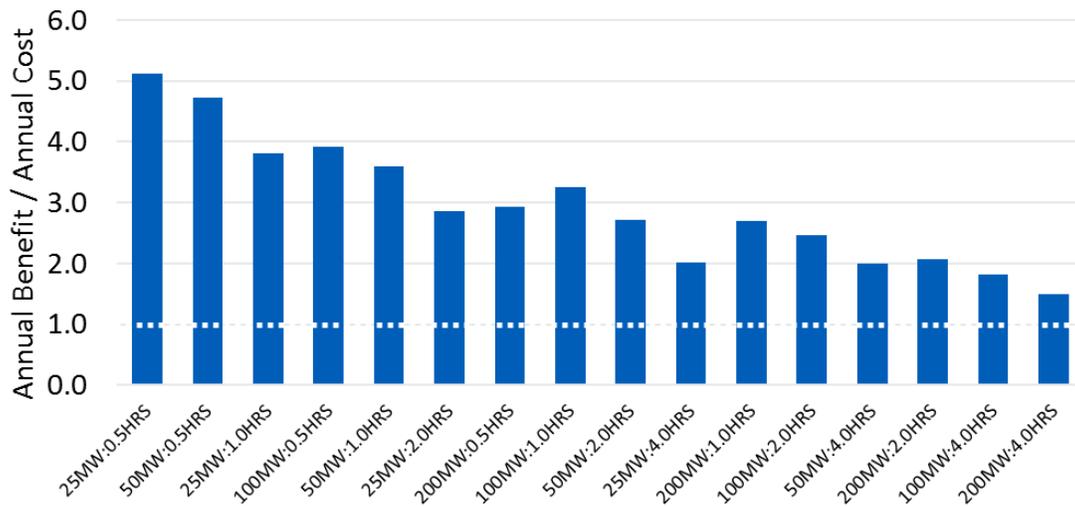


Figure 15: Benefit-Cost ratio of BESS configurations in a 50% Renewable Scenario

Figure 16 shows the annual production cost savings versus the annual capital cost for various BESS configurations. In this figure, the capability (in hours) of discharging at rated power (0.5hrs, 1hrs, 2hrs and 4hrs) are shown in different colors (blue, green, cyan and magenta). The size of the circle indicates the storage capacity of the BESS. A larger circle indicates a higher energy capability (MWh) of the BESS. In this figure, the dotted line represents a cost benefit ratio of 1. Any point above the line indicates that the benefit outweighs the cost. The further the point from the dotted line, the higher the benefits when compared with costs. It can be observed from the figure that the configurations that result in the highest benefit-cost ratio, as well as higher absolute benefits (M\$), are the high power, low energy configurations.

Battery Energy Storage System Analysis

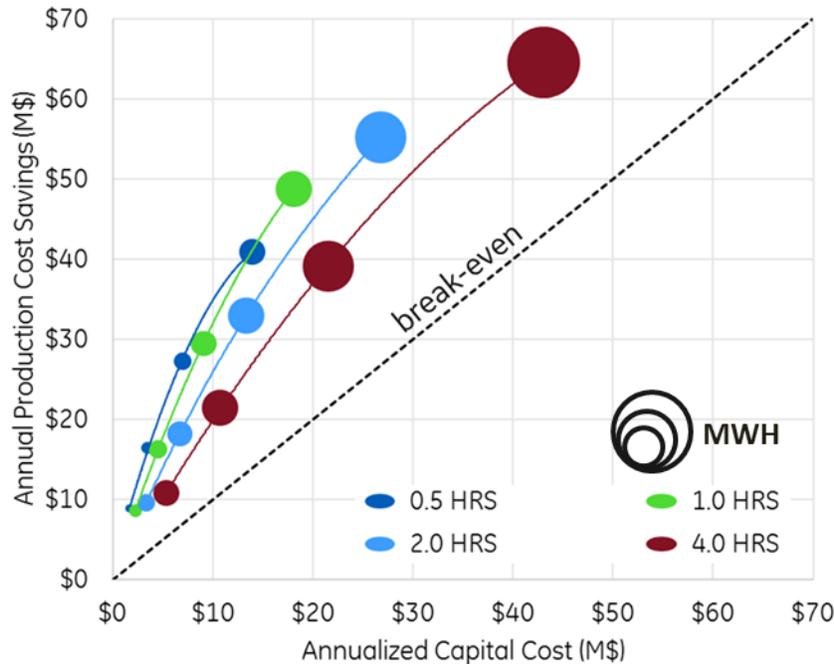


Figure 16: Production Cost Savings vs Annual Capital Cost by Configuration

3.3.2 Comparing Economics of BESS by Scenario

While much of the analysis presented thus far in the report has covered the operations and economics of storage in a high wind and solar scenario (50% W&S), the analysis was also conducted on a lower wind and solar scenario (Current W&S), representing the near-term wind and solar resource mix on Oahu, serving approximately 20% of annual load energy. This section compares the economic results between the two scenarios. In general, a grid with higher wind and solar penetration will increase the economic benefits of a BESS addition. This is due to the following reasons:

- Increased wind and solar generation increases net load variability requiring additional regulation reserves. For example, average mid-day regulation requirements increase from approximately 150 MW in the Current W&S Scenario to 350 MW in the 50% W&S Scenario. The increased reserve requirement can be served by BESS, among other resources, thus increasing the economic value.
- Increased curtailment in a high wind and solar scenario creates an opportunity for energy arbitrage, shifting curtailed solar from mid-day hours to evening peak. In addition, a BESS adds value by shifting reserve provision from conventional thermal resources and freeing up additional load on the system to be served by wind and solar and reducing curtailment.
- Fewer thermal units online during high wind and solar periods decreases the amount of ramping capability on the system. The value of a BESS system providing ramping capability will also increase in a higher wind and solar scenario.
- There are several other benefits that will likely increase in a higher wind and solar scenario, as outlined in Figure 1, but these were not evaluated in this analysis.

Battery Energy Storage System Analysis

Figure 17 provides a comparison of the economic value of five BESS configurations between the two scenarios evaluated. The middle three configurations each represent 100 MWh energy systems, with varying power ratings. This allows for a better understanding of how BESS economics change with an increasing penetration of wind and solar in the resource mix. It can be seen from the figure that net benefits increase for all configurations with increasing wind and solar. It can also be observed that all configurations analyzed were economic (benefit-cost ratio greater than 1.0) in both scenarios with the exception of the 200 MW:400 MWh BESS in the current wind and solar configuration. In general, the system favors higher power, lower energy systems due to the high value of reserves on Oahu.

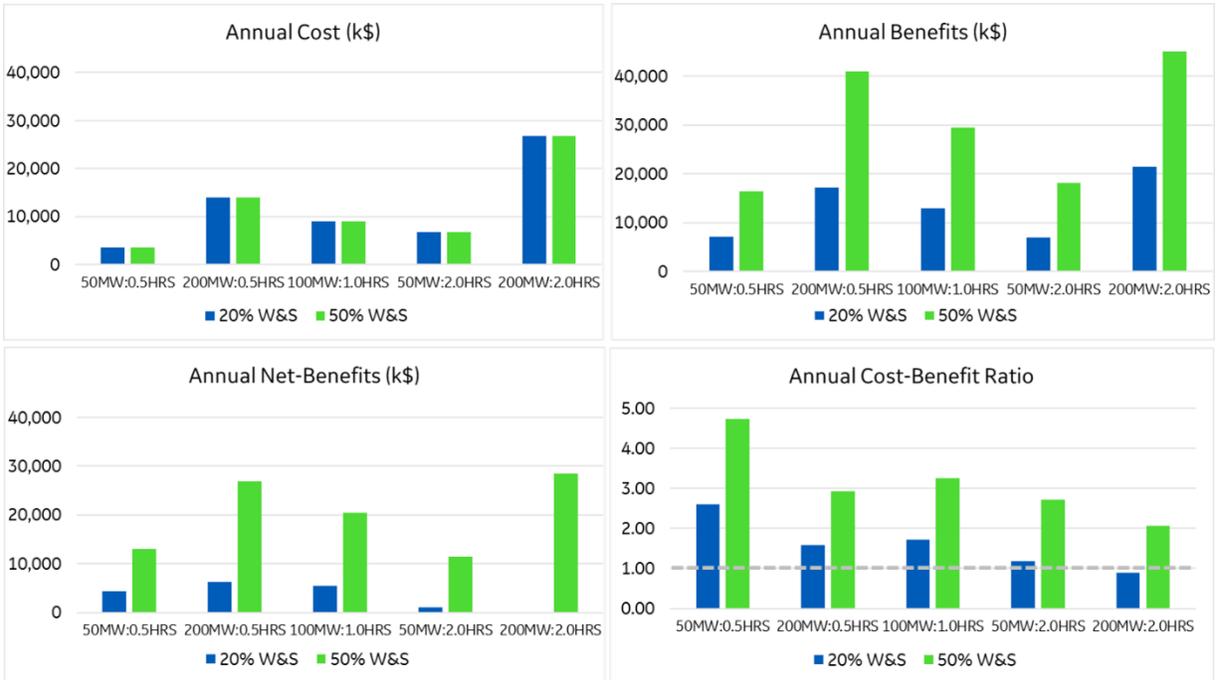


Figure 17: Benefit Cost Analysis by BESS Configuration and Scenario

3.3.3 Sensitivity Analysis

A sensitivity analysis was performed to determine the effect of various factors such as the DC and AC subsystem costs, discount rate, and the degradation of the battery on the overall benefit-cost ratio of various configurations of BESS.

The top left chart of Figure 18 shows the impact of the DC subsystem price on the benefit-cost ratio of the project for various configurations. With the base price assumption of \$250/KWh for the battery subsystem, all of the configurations except the high power and energy BESS have a benefit-cost ratio of greater than 1. When the DC subsystem cost drops to \$200/KWh, all of the BESS configurations have a benefit-cost ratio of 1 or greater.

The top right chart of Figure 18 shows the impact of the AC subsystem price on the benefit-cost ratio of the project for various configurations. The AC subsystem has less of an impact on the benefit-cost ratio than the DC subsystem price. With the base price assumption of \$150/KW for the AC subsystem, all of the configurations except the high power and energy BESS have a benefit-cost ratio of greater than 1. When the AC subsystem cost drops to

Battery Energy Storage System Analysis

approximately \$100/KW, all of the BESS configurations have a benefit-cost ratio of 1 or greater.

The bottom left chart of Figure 18 shows the impact of the projects' discount rate price on the benefit-cost ratio of the project for various configurations. With the base discount rate assumption of 10%, all of the configurations except the high power and energy BESS have a benefit-cost ratio of greater than 1. When the discount rate drops to 8%, all of the BESS configurations have a benefit-cost ratio of 1 or greater.

The bottom right chart of Figure 18 shows the impact of degradation of battery life on the benefit-cost ratio of the project for various configurations. As discussed earlier, degradation does not have a significant impact on the benefit-cost ratio of the BESS.

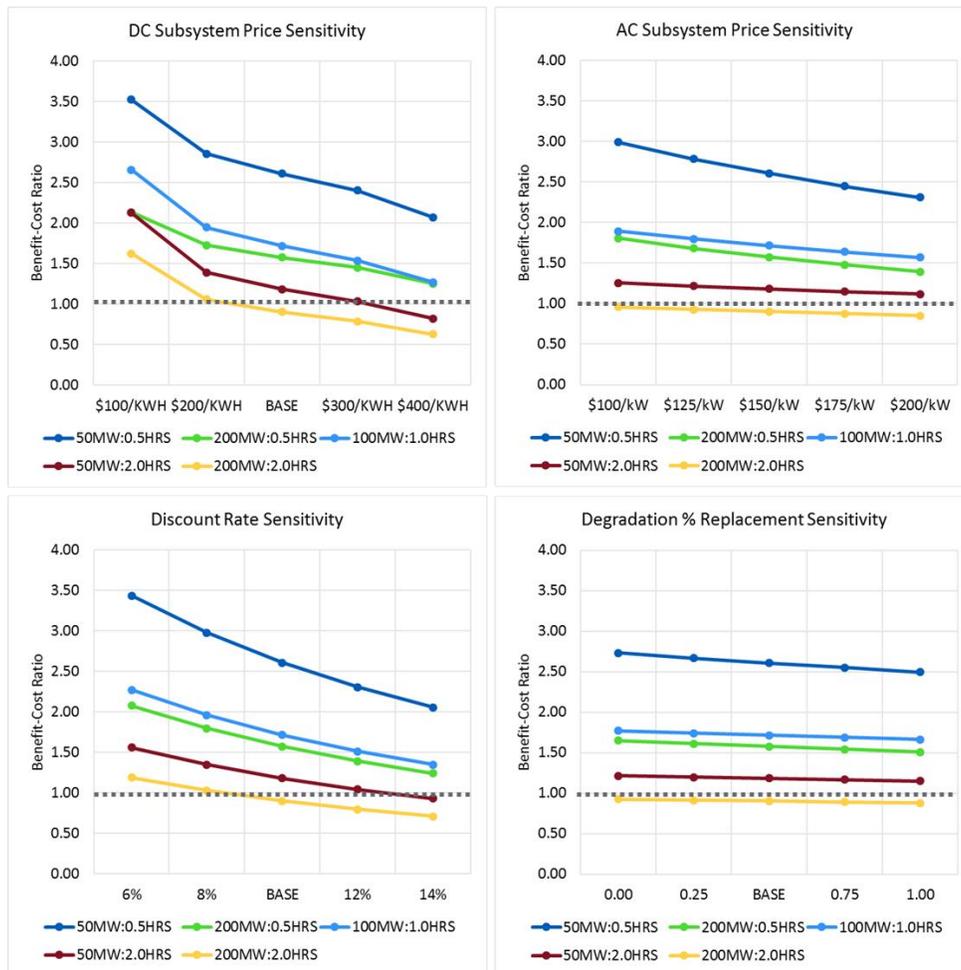


Figure 18: Sensitivity of Key Assumptions on Benefit-Cost Ratio

3.3.4 Comparing Value from Reserves versus Energy Arbitrage

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 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.

- A. **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),
- B. **Reserves:** 0.5 HR BESS, which represents a 'reserve only' storage system (previously presented results),
- C. **Combined:** 4.0 HR BESS, assumed able to provide reserves. This represents the combined reserve and energy arbitrage storage system (previously presented results).

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 are presented in Figure 19, along with the corresponding savings provided in Table 4, and the reduction in annual curtailment provided in Figure 20.

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 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. This finding is even more applicable to the current Oahu system, which has limited (if any) wind and solar curtailment, and thus limited value for energy shifting. 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.

Battery Energy Storage System Analysis

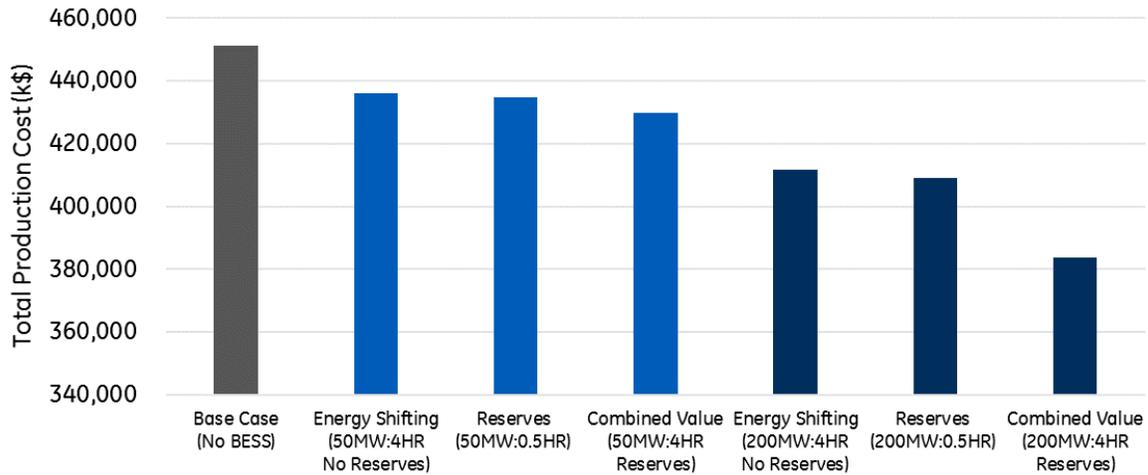


Figure 19: Total Generation Cost by BESS Use Case

Table 4: Production Cost Savings by BESS Use Case

BESS Power Rating (MW)	BESS Energy (MWh)	BESS Use Case	Total Annual Generation Cost (k\$)	Annual Savings Relative to Base Case (k\$)
Base Case (No BESS)		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

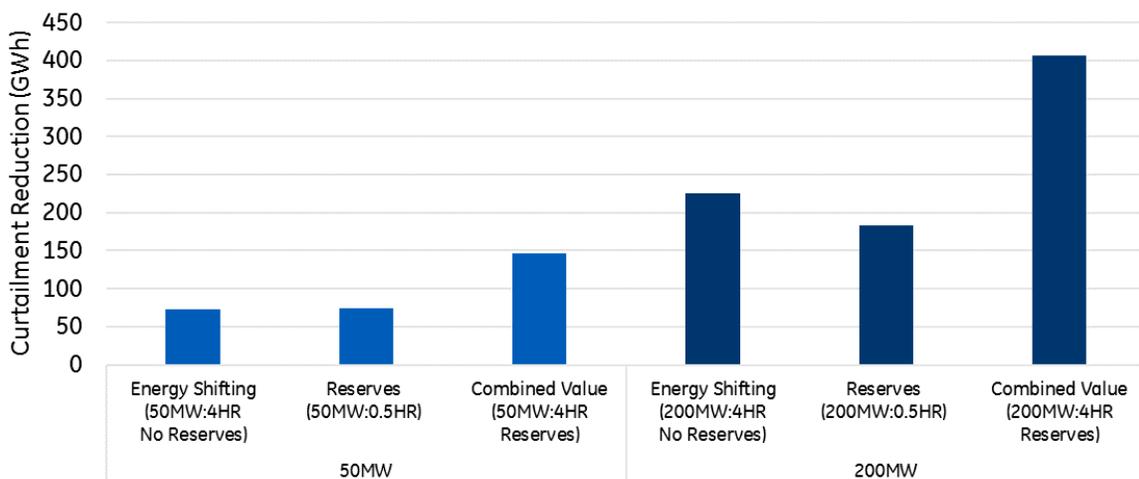


Figure 20: Annual Curtailment Reduction by BESS Use Case



4 KEY FINDINGS

As Hawaii transitions further towards renewable energy, the penetration of wind and solar generation will increase significantly. This transition will require a significant change to grid operations and a new framework to ensure the system is operated efficiently, reliably, and securely. It may be necessary for new emerging technologies, including distributed energy resources (PV, demand response, energy storage, etc.) to provide grid support and other essential reliability services in a way they are not currently utilized. This analysis, which provided an in-depth review of BESS applications in the Oahu grid, resulted in the following key findings:

- BESS technology and costs are advancing quickly. As a result, storage may play an increasingly important role in Hawaii’s renewable energy future.
- Understanding the tradeoffs (economic and operational), between different power and energy configurations is grid specific. There is no “one size fits all” storage application so robust economic and engineering analysis is required.
- Operation and control of storage can be co-optimized to provide both reserves (regulation and FFR) and energy arbitrage. The costs and benefits of each service depend on the configuration.
- Energy storage will increase generation from wind and solar (decreased curtailment) along with more efficient operation of thermal resources. The decreased curtailment is due to two reasons:
 - The BESS charges using otherwise curtailed wind and solar energy and effectively increases the system’s load during hours of surplus wind and solar. This replaces energy provided by expensive oil-fired generation with previously curtailed wind and solar, and
 - The BESS provides 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 served by the required MWs necessary for the reserve generator to operate. 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 have a significant ability to decrease curtailment.
- 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
- Energy storage can be economic in some (but not all) configurations with Current W&S Scenario. Economic benefits increase as wind and solar penetration increases.
- While this analysis shows that BESS can be an economic addition to Oahu’s resource mix, it is not necessarily the most economic. Other options to analyze and compare include demand response and increased flexibility in thermal fleet.
- BESS technologies can provide additional services and benefits not explored in this analysis, namely by deferring additional capital expenditures in transmission, distribution, and generation capacity upgrades. This should be explored in future analysis.