


HAWAII SOLAR INTEGRATION STUDY:

Executive Summary

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U.S. Department of Energy
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Hawaiian Electric Co.

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Introduction

The Hawaii Solar Integration Study is a detailed technical examination of the effects of high penetrations of solar and wind energy on the operations of the electric grids of two Hawaiian Islands: Maui and Oahu. Carried out under the auspices of the Hawaii Clean Energy Initiative (see below), the study was jointly sponsored by the Hawaii Natural Energy Institute, the U.S. Department of Energy, and the Hawaiian Electric Co. (HECO).

Unlike mainland power grids, island power grids are self-contained and isolated, so they have no neighboring grids to turn to for support if they are pushed beyond their normal operating limits. The Hawaiian Islands also rely heavily on oil and oil products to fuel their power plants, which results in high electricity costs that help make renewable energy economically competitive.

Maui and Oahu already have significant wind and solar power feeding their electric grids, but the utilities on each island wanted to know how their grids will operate with more renewable energy. Some of this is will be under utility control in the form of centralized, utility-owned solar power plants, but much of the solar power will be distributed throughout the island on homes and businesses—outside of the utility's control.

The study included detailed computer modeling and simulations of the generation and transmission systems on each island to examine how future scenarios of high penetrations of solar and wind power will affect generator operations under normal system configurations. The distribution-level impacts were not assessed in this study. For cases in which the generator deviated from its preferred operating parameters, potential mitigation strategies were proposed and modeled.

About the Hawaii Clean Energy Initiative

The Hawaii Clean Energy Initiative is an unprecedented collaboration between the State of Hawaii and the U.S. Department of Energy that was initiated in January 2008. The purpose of the Hawaii Clean Energy Initiative is to transform Hawaii into a world model for energy independence and sustainability. The state's goal is to meet 70% of its energy needs with energy efficiency and renewable energy by 2030 (meeting 40% with renewable energy while eliminating 30% through energy efficiency). In October 2008, with the Hawaii Clean Energy Initiative as a foundation, the State of Hawaii, the Hawaiian Electric companies, and the State Consumer Advocate signed an energy agreement—the first of its kind in the United States—that set specific commitments and timetables to accomplish this transformation.

The Department of Energy and its national laboratories have been working with its partners in Hawaii to provide technical expertise and support across key energy segments, including renewable electricity generation and transmission, end-use energy efficiency, transportation, and renewable fuels. An important aspect of the Department of Energy's technical contribution has been in the area of grid integration of renewables, including the Hawaii Solar Integration Study and a prior study, the Oahu Wind Integration and Transmission Study.

Key Insights

The Hawaii Solar Integration Study found that adding large amounts of new solar power to the electric grids on Maui and Oahu—enough to achieve roughly 20% renewable energy penetration—will create operational challenges that could affect grid reliability, but it also recommended a variety of mitigation strategies that could address those challenges while optimizing the use of renewable energy. The study recommends specific mitigation strategies for further study and details the reduction in renewable energy curtailment for those strategies.

The Maui and Oahu power grids present contrasting examples of small power grids, although they also have similarities. At the time of the Hawaii Solar Integration Study in 2012, the Oahu grid was much larger, with firm generation sources at nearly seven times the capacity of the Maui grid (1,822 MW versus 264 MW). Both islands featured wind power plants and distributed solar power, but Oahu included a 1-MW central-station photovoltaic (PV) facility, while Maui had a much higher percentage of wind and solar power. Maui also featured a 10-MW battery energy storage system (BESS).

The scenarios examined for both islands involved increases of both centralized and distributed PV capacity, while an additional wind plant was included in one of the Oahu scenarios. Key insights from the study included the following:

- There is less variability with distributed PV systems than with central-station PV plants because one dark cloud can affect an entire central-station facility quickly, while only a large storm system can affect all distributed PV generators—and this takes place over a longer time.
- Variability is lower for a mix of wind and solar power rather than all-solar power because wind and solar resources generally don’t move in lockstep and are sometimes complementary. An example is a cold front that brings cloudy and windy conditions, which decreases solar power production but boosts wind power production.
- Distributed PV contributes less variability to the grid, but it presents a challenge in high-penetration scenarios (in the absence of a smart grid) because of the inability of the utility to curtail its power production, which results in less flexibility for grid operators.
- Centralized PV plants and wind plants can be controlled and curtailed. In addition, both centralized PV systems and wind plants can potentially serve a grid-support function. For example, the study found that adding governor controls to the wind and central-station PV plants on Oahu would allow them to respond to loss-of-load events.

Key Terms

Ancillary services: Services that assist the grid operator in maintaining system balance.

Curtailment: A reduction in the scheduled capacity or energy delivery of a generator.

Frequency response: The ability of a generator (or responsive load) to increase output (or reduce consumption) in response to a decline in system frequency and decrease output (or increase consumption) in response to an increase in system frequency. For generators, this requires governor response.

Minimum power: The minimum output that can be provided from a generator. Different generators have different minimum levels based on fuel source, plant design, and common use.

Operating reserves: That capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages, and local area protection. Up reserves can inject additional power into the grid when needed; down reserves can reduce the power fed into the grid.

The study also looked at the value of several mitigation strategies that consisted of changes to the operational practices of conventional generators.

- HECO identified several units that could potentially reduce their minimum power levels by about half by investing in unit modifications (the cost of which was not determined in this study), thereby significantly reducing wind and solar power curtailment and creating more operational flexibility for handling challenges to the grid.
- Other potential Oahu mitigation measures include relaxing the operating schedule for certain baseload units and providing reserves from alternate resources, such as demand response or a BESS.
- The top Maui mitigation measure is to upgrade the utility's combined-cycle units to enable them to switch between single- and dual-train operation as needed to reduce renewable energy curtailment.
- Other Maui potential mitigation strategies include relaxed operating schedules for the utility's four oil-fired units and a change in the commitment process to increase the priority of operating reserves.

Maui has an additional tool for responding to grid events: a 10-MW BESS, which is capable of delivering 10 MW of up reserve continuously for 45 minutes, after which it will ramp down linearly for 45 minutes until it reaches zero. The BESS can also reduce down reserves by charging at its full capacity following loss-of-load events. The study found that the BESS helped the Maui grid restrict frequency excursions to a band of ±0.1 Hz.

In evaluating the potential benefits of adding another 10-MW BESS with 20 MWh of storage, two operating strategies were considered: using the BESS to provide an additional 10 MW of operating reserves or using it to "time-shift" energy—storing the wind and solar power that would otherwise be curtailed and delivering it to the grid at the first opportunity. The study found that using the BESS to provide operating reserves resulted in greater benefits by reducing curtailment and thereby reducing operating costs. Using a larger, 100-MWh BESS for time-shifting energy yielded results similar to using the 10-MW BESS for reserves but at a higher capital cost.

In summary, the Hawaii Solar Integration Study provided valuable insights into the integration of solar and wind power into two very different utility grids. The results provide a deeper understanding of the differences between distributed PV systems, centralized PV power plants, and wind power in terms of variability, ability to curtail power output, grid support function, and characteristics relative to the load. Although reliability challenges increase with increasing levels of variable renewable generation, this study found those challenges are manageable from the standpoint of the bulk power system for the scenarios studied with the mitigation approaches recommended. Note that this study did not look at the capital costs for the higher renewable energy scenarios or the mitigation strategies. It also did not assess the integration issues at the distribution level of the power systems.

Ultimately, the Hawaii Solar Integration Study found that higher levels of variable renewables can be reliably accommodated by the bulk power system in a collaborative fashion (i.e., by changes made to both utility equipment and operating practices and variable generation equipment capabilities) and noted the importance of asking for the right capabilities (e.g., inertial and frequency response, voltage and frequency ridethrough, and provision of ancillary services) from variable generating plants in grid codes. The study did not look at incentives, and they may not be necessary for the mitigation measures that were considered. The importance and value of reviewing existing operating practices and adjusting certain assumptions (e.g., minimum power generation levels, certain must-run generator rules) was modeled and the impact on solar and wind curtailment shown. Finally, the use and value of storage in a high-penetration system was modeled and discussed. The insights from the Hawaii Solar Integration Study form a large body of knowledge for future grid integration studies, and the results can be used to further our understanding of grid integration in other island systems as well as in mainland U.S. systems with high regional solar and wind penetrations.

How Power Grids Work

Like all complex machines, electric grids have a special nomenclature and operate in a unique way. Knowing the ins and outs of electric grids is critical to understanding the Hawaii Solar Integration Study.

An essential task of system operators is to match the amount of electricity being generated with the amount being consumed. In grid parlance, that means matching generation with load, where the load is the amount of power being drawn from the system. Most grids, including the Hawaii grids, deliver alternating current, so grid operators also need to keep the frequency of the current at a constant level. In the United States, that level is 60 cycles per second, or 60 Hz. Electrical devices are often designed to operate at 60 Hz, and deviations from this standard can damage equipment.

Electric grids are branching networks, with the main branches being feeder lines, which feed electricity to smaller distribution lines that run house-to-house and business-to-business. Circuit breakers protect the lines from short circuits or "ground faults"—unintentional connections of power lines to ground—by opening, or "tripping," thereby taking the power lines out of service.

If a grid is balanced so generation equals load, a loss of load, perhaps caused by a feeder line tripping offline, will cause generation to exceed load. The excess generation in the system will increase the frequency in what is called an "over-frequency event." Likewise, a power plant tripping offline can cause load to exceed generation, causing an "under-frequency event."

To avoid such excursions from normal operating parameters, grid operators maintain power reserves that can be drawn on during emergencies. Contingency reserves (often called "spinning reserves") are idled but operating plants, or plants operating at less than full power that can quickly be brought up to full power. A BESS can also serve as spinning reserve. Contingency reserves are meant to cover the single largest generation outage that could occur on a system, such as the largest power plant tripping offline. Because wind and solar units are not large, they do not typically affect the contingency reserve needed.

Operating reserves are meant to cover the net variability of the power system. Wind resources, solar resources, and continuously changing loads all contribute to net system variability. Operating reserves can be a mixture of spinning reserves and non-spinning reserves, such as quick-start diesel generators and combustion turbines. Total reserves are the sum of contingency and operating reserves.

There are also two types of operating reserves. "Down reserves" are used when solar and wind generation suddenly increase and are often power plants that can quickly ramp down power production to balance the system. Likewise, "up reserves" are used when solar and wind power suddenly drop and are often power plants that are either idled or operating at less than full power and have the ability to ramp up power production rapidly.

Up reserves can also include demand response, which typically involves a large industrial user that agrees to reduce its power use when needed in exchange for favorable electricity rates. More sophisticated demand-response technologies use the Internet or smart grid technologies to control user devices. In the summer, for instance, demand response could involve delaying the on-and-off cycling of a large number of customer air conditioners or domestic water heaters, which can effectively remove a large load from the power system.

Electric utilities rely on a variety of power generation sources. On Maui and Oahu, large, centrally located coal- and oil-fired power plants often run 24 hours a day to provide a steady source of power throughout the day. These types of plants are called “baseload” units because they provide a base that can be added to with other types of power. Other plants can be “cycling” units that ramp up and down quickly to match the variation in system load, or they can be “peaking” units that are normally idled but can ramp up quickly to help meet peak power demands. The efficiency and operating characteristics of each power plant contribute to the determination of how it is used by the utility.

All power plants have limits on how quickly they can ramp up and down—called a “ramp rate”—and a minimum power level below which they cannot operate reliably. Operating units below their minimum power levels can result in unstable operating conditions and unanticipated unit outages that lead to system instabilities and even blackouts. But as we’ll see, in some cases, minimum power levels can be relaxed with additional support from batteries and renewable resources.

Study Methodology

Modeling the behavior of an electric grid with significant solar and wind power required an excellent weather model to allow researchers to examine how solar and wind power behave over time in real-world situations. For the Hawaii Solar Integration Study, AWS Truepower generated solar power production profiles using a numerical weather prediction model coupled with a stochastic-kinematic cloud model. The weather prediction model drove the cloud movements, while the cloud model determined when and where clouds were generated and how they dissipated over time.

The weather model was run for a historical year, and the weather was “re-created” so historical weather inputs could drive the model and continually update it. Re-creating weather is more accurate than predicting weather, and it allows the weather to be correlated to the actual loads of the historical year. The loads can then be adjusted for load growth for the future study year. Capturing the synchronization between the weather and loads is important because the loads, the solar output, and the wind output are all driven by the weather and interconnected.

The weather model yielded a set of solar power production profiles that showed the power produced over time, at 2-second intervals, for both distributed and central-station solar power facilities. These profiles provided critical information about how quickly the solar power was likely to ramp up and down with changing weather—providing realistic “worst case” scenarios that were used to test the robustness of each island’s power grid for an entire year of data. The weather predictions and power profiles were also compared with real-world data to verify their accuracy.

The weather prediction model was also used to create solar power forecasts, which simulated actual forecasts that grid operators use to plan each day’s operations. These modeled forecasts were used to schedule resources for each day, as is done with actual load forecasts, and then the grid simulation model was used to see how the system performed. But just like real weather forecasts, the modeled forecasts would occasionally miss significant weather events that adversely affected the power grid. Performing these simulations allowed the researchers to determine realistic operating parameters for each of the island power grids and single out the worst-case operating conditions of the year.

This study examined the behavior of each grid with increasing amounts of solar and wind power. For each scenario examined, the required contingency and operating reserves were calculated, and, once these parameters were set, the operation of the grid was simulated at hourly intervals for a full year using the Multi-Area Production Simulation Software (MAPS) developed by General Electric Co. (GE). This simulation quantified how the conventional (thermal) power plants would be dispatched over the course of a year and showed if wind and solar energy resources would be curtailed, allowing an hourly calculation of the variable operating costs and the resultant power-plant emissions.

The variable operating costs are dominated by fuel costs but also include operating costs for the plants. They do not include the capital costs of wind or solar plants, so the study is an annual operational impact study that details production costs, including those from the additional operating reserves needed, and not a life-cycle cost study that includes capital costs.

The hourly operation results from the simulation were then analyzed to quantify the impact of wind and solar variability. This analysis examined wind and solar power production at subhourly intervals to determine how well the conventional power plants kept up with variations in renewable power production, within the constraints of each power plant's ramp rate and power limits. Worst-case conditions were examined to evaluate dynamic effects, such as a power plant's control system overshooting the desired power level, using GE's Positive Sequence Load Flow software. As a result, the study identified the most challenging events that each grid was likely to face and then examined potential mitigations to improve grid performance.

Oahu

The Oahu Electric Grid

Oahu's power supply includes one baseload coal plant, one baseload waste-to-energy plant, three baseload oil-fired plants, two cycling oil-fired plants, and one peaking oil-fired plant. Together, these plants provide 1,822 MW of "firm" generation resources—power plants that the utility can count on to produce power when they are in service. In addition, the island draws on two wind farms with a total capacity of 99 MW, a 1-MW solar PV power facility, and about 80 MW of distributed, grid-connected PV systems located at homes and businesses throughout the island.

For the Oahu grid, the operating criterion is to always carry sufficient contingency reserves to completely make up for the loss of the largest single generating unit on line (usually the 185-MW coal plant).

Table 1. Oahu Generation Resources as of August 2012

Firm Generation Resources	Capacity (Gross MW)
Honolulu (steam, cycling, oil) - HECO	108
Waiau (steam, baseload, oil) - HECO	169
Waiau (steam, cycling, oil) - HECO	201
Waiau (combustion turbine, peaking, oil) - HECO	103
Kahe (steam, baseload, oil) - HECO	604
CIP (combustion turbine, peaking, biodiesel) - HECO	113
HPower (steam, baseload, waste-to-energy) - IPP	46
Kalaeloa (combined-cycle, baseload, oil) - IPP	208
AES (steam, baseload, coal) - IPP	185
Total firm generating capability	**1,737**

Non-Firm Generation	Capacity (Net MW)
Kahuku wind farm	30
Distributed PV	80
Utility-scale PV	1
Total non-firm generation	**111**

The Oahu study looked at increasing penetrations of wind and solar power on the island, with different distributions of central PV power plants versus distributed PV systems. Starting with a baseline of 60 MW of distributed PV power, scenarios 3A and 3B examined the impact of adding another 300 MW of PV power and 100 MW of wind (30 MW existing plus 70 MW scheduled to be in service at year-end 2012). Scenario 3A added a 100-MW central PV plant and 200 MW of distributed PV systems, while 3B added a 200-MW central PV plant and 100 MW of distributed PV systems.

Scenarios 4A and 4B examined the impact of adding 500–700 MW of renewable power; 4A added a 400-MW central PV plant and 300 MW of distributed PV systems, while 4B added a 200-MW central PV plant, 100 MW of distributed PV systems, and 200 MW of wind capacity from a proposed wind plant on a neighboring island, sent by submarine cable (see Table 2). Although scenarios 4A and 4B differ by 200 MW of renewable generating capacity, the annual power generation of the solar and wind resources results in essentially the same level of renewable energy. (Scenarios 1 and 2, meant to examine lower PV penetrations, were dropped because the results were expected to result in small operating impacts to the system and, hence, less information on mitigation options.)

Table 2. Study Scenarios for the Oahu Power Grid

Scenario	Distributed PV	Central Plant PV	On-Island Wind	Off-Island Wind	Total	
Baseline	60 MW	–	100 MW	–	**160 MW**	
3A	260 MW	100 MW	100 MW	–	**460 MW**	Same Solar MW
3B	160 MW	200 MW	100 MW	–	**460 MW**	
4A	360 MW	400 MW	100 MW	–	**860 MW**	Same Wind + Solar Energy
4B	160 MW	200 MW	100 MW	200 MW	**660 MW**	

Each of these scenarios was then modeled to determine the worst-case drop in power from the aggregate wind and solar resources, as shown in Table 3. A noteworthy fact is that a central PV power plant can experience larger power drops than the same capacity of PV systems distributed across the island. This is because a single dark cloud can cause a power drop at the centralized plants, while even a massive storm takes some time to sweep over the island and affect the power production of all distributed PV systems. Likewise, wind and solar resources are geographically dispersed and rarely change in lockstep, so Scenario 4B, with a mix of wind and solar power, has lower variability than Scenario 4A, which relies entirely on solar power.

Table 3. Worst-Case Variability for Oahu Scenarios

	Scenario 3A	Scenario 3B	Scenario 4A	Scenario 4B
Worst 5-minute drop (MW)	-64	-129	-186	-132
Worst 10-minute drop (MW)	-88	-136	-183	-143
Worst 30-minute drop (MW)	-151	-168	-308	-219
Worst 60-minute drop (MW)	-201	-217	-399	-324

The study set a criterion that the grid must have sufficient operating reserves to cover wind and solar variability 99.99% of the time without dipping into contingency reserves. Contingency reserves assure that the grid continues to function normally if a major power plant shuts down, so this criterion effectively means that it is an acceptable risk to expose the grid to that threat 0.01% of the time, or slightly less than 1 hour per year. This is similar to accepting the threat of other low-probability events such as multiple plants shutting down simultaneously or multiple feeders tripping off line at the same time.

Required Reserves for Oahu

Figure 1 shows the minimum operating reserves required for each of the scenarios under existing utility operating practices. During daytime hours, operating reserves need to cover the variability from both wind and solar energy resources, so the reserve requirements are significantly different for each scenario. During nighttime hours, operating reserves need to cover only the variability of wind power resources, so only Scenario 4B, which draws on an off-island wind plant, has greater operating reserve requirements at night.

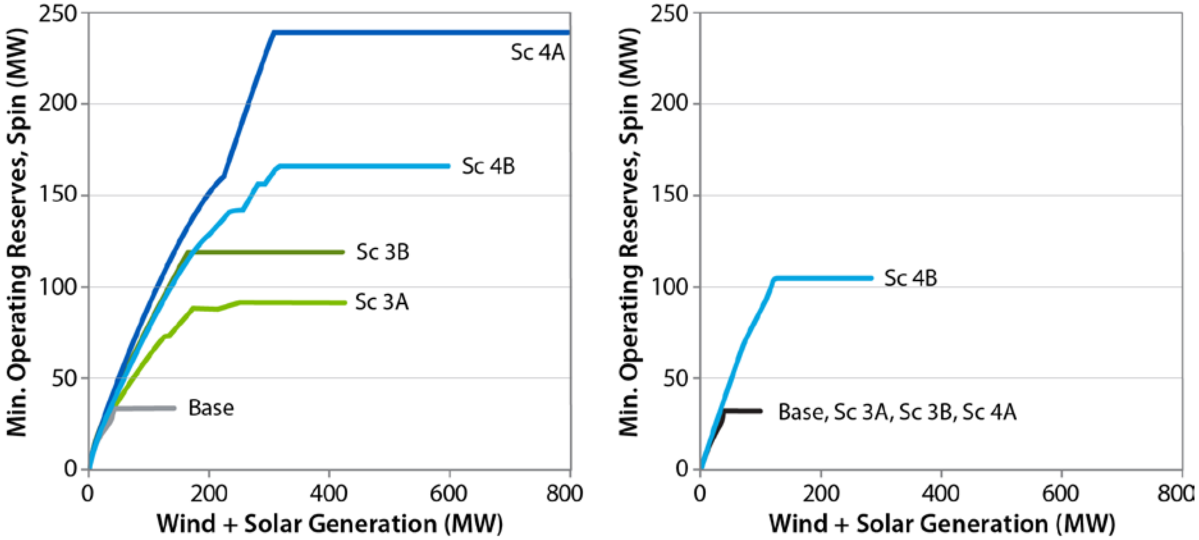


Figure 1. Oahu spinning operating reserve requirements for day (left) and night (right)

The Oahu grid also needs to carry sufficient down reserves to accommodate a sudden loss-of-load event. HECO has historically allocated a minimum of 40 MW of down reserves for this purpose, but a recent HECO analysis found that 140 MW of load could be lost during the daytime, while 90 MW of load could be lost during the night. These levels of down reserves were assumed for scenarios 4A and 4B, while scenarios 3A and 3B used the 40-MW target. However, the available down reserves for scenarios 3A and 3B met the more stringent requirements for almost all hours of the year.

Oahu Grid Operating Characteristics

The MAPS simulations were used to examine how often the solar and wind resources would be curtailed—required to reduce their power production—to maintain grid control parameters. Curtailment is to be avoided as much as possible because it wastes renewable energy that carries no fuel charge and thereby hurts the economics of the generation source and increases the utility's emissions.

For this study, simulations assumed curtailment is prioritized on a "last installed, first curtailed" basis, which is consistent with HECO's power purchase agreements. This prioritization results in curtailment of the central-station PV system first, then the off-island wind plant, then the 70-MW on-island wind plant, and finally the 30-MW on-island wind plant. The distributed PV systems cannot be curtailed by the utility.

The study found that the Oahu bulk power grid is able to absorb all the wind and solar energy in scenarios 3A and 3B and variable operating costs for both scenarios are the same, at 90.8% of the baseline cost (see figures 2 and 3). The lower costs reflect the fuel savings from the displaced fossil-fueled generators. Renewable energy penetration for these two scenarios is 11.8% and 12.2%, respectively. See Figure 4.

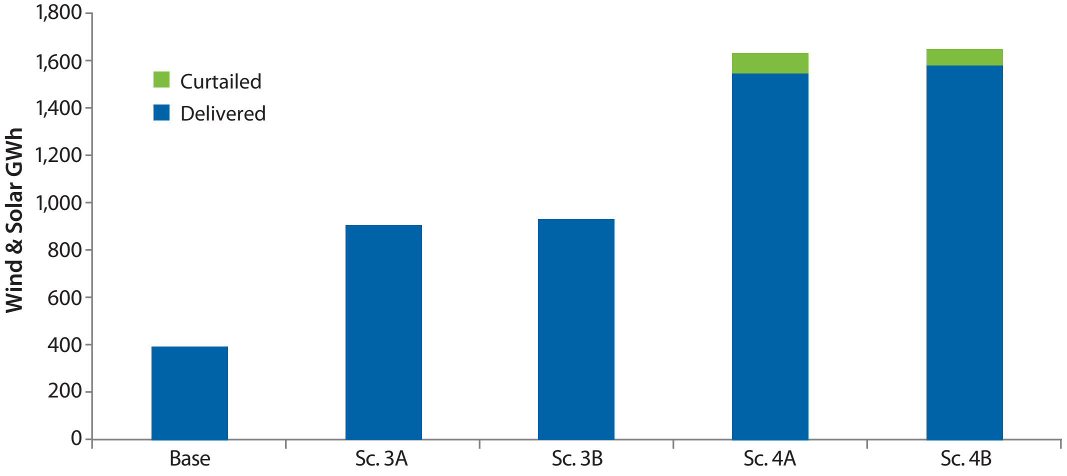
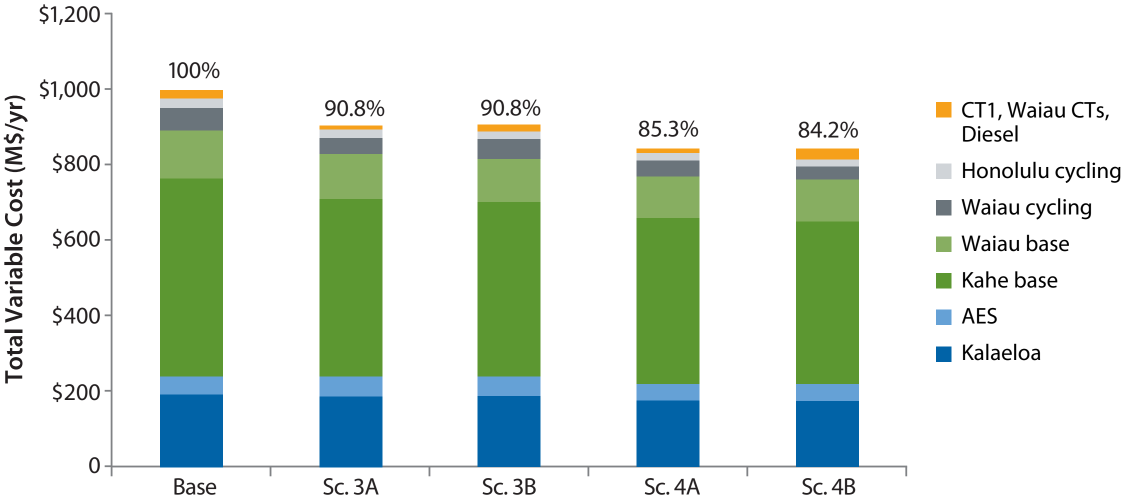


Figure 2. Annual wind and solar energy delivered and curtailed for study scenarios



Note: Does not include capital costs of wind or solar plants

Figure 3. Annual variable operating costs for study scenarios

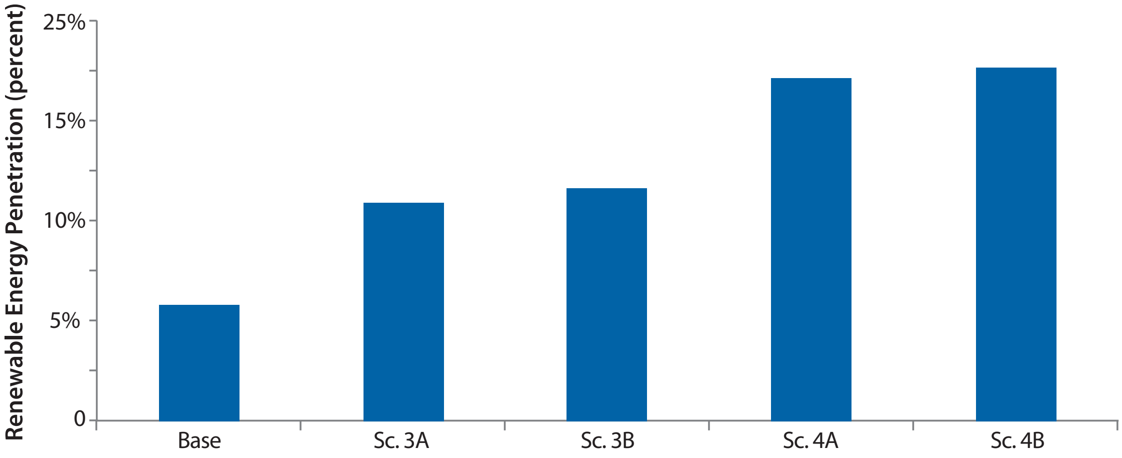


Figure 4. Renewable energy penetration for study scenarios

For Scenario 4B, curtailment is 4.3% of the available wind and solar energy, resulting in a variable cost that is 84.2% of the baseline, with a renewable energy penetration of 20.2%. For Scenario 4A, however, curtailment is much higher, at 8.6% of the available wind and solar energy, resulting in a slightly higher variable cost, at 85.3% of baseline, as well as a slightly lower renewable energy penetration of 19.1%. Scenario 4B employs more wind power, which has a different generation profile from solar power, so it acts to complement the solar resource. In contrast, Scenario 4A relies entirely on solar power. Those resources tend to reach peak power generation at the same time, which results in more curtailment. Average daily curtailment patterns for the two scenarios are shown in Figure 5.

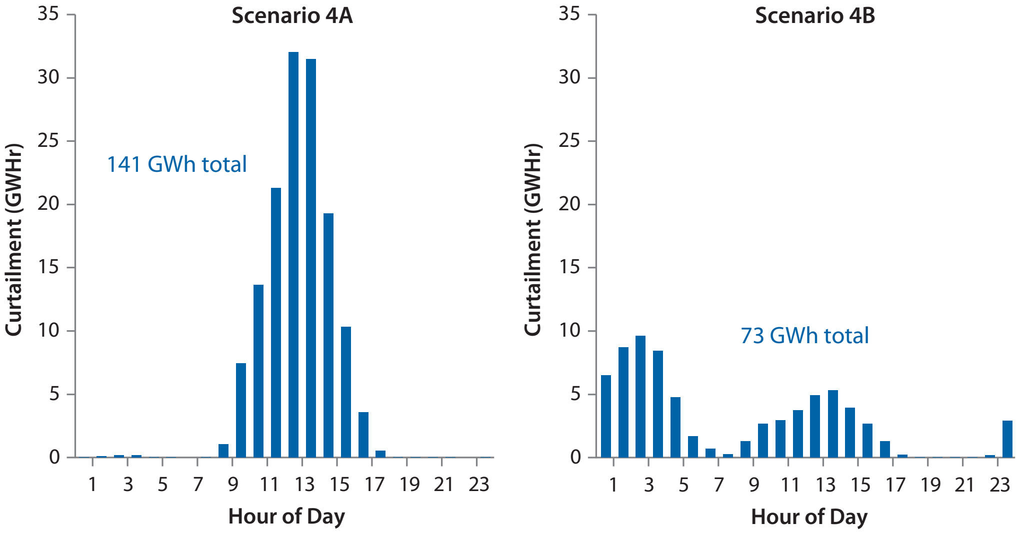


Figure 5. Average daily wind and solar curtailment patterns for scenarios 4A and 4B

When wind and solar power production is high, grid operators need to reduce power production from fossil-fueled generating stations. In many cases, the baseload fossil-fueled power plants will need to run at their minimum rated power. As shown in Table 4, the hours the baseload power plants run at minimum power increases dramatically as wind and solar penetration increases. In scenarios 4A and 4B, several units operate at minimum load for more than 6,000 hours per year, and some units operate more than 90% of the time at minimum load. The operations and maintenance impact of operating baseload generation at this low level for the hours shown needs to be assessed, but doing so was outside the scope of the study.

Table 4. Annual Hours at or Near Minimum Load for Oahu Baseload Generating Units

Facility Name	Unit Name	Scenario				
		Baseline	3A	3B	4A	4B
AES Coal	AES	442	446	448	2,089	1,806
Kalaeloa Combined Cycle	KALAELOA	291	292	291	1,514	2,305
Kahe Base	KAHK1	4,108	5,934	6,091	7,308	7,675
	KAHK2	3,648	5,539	5,874	7,075	7,467
	KAHK3	1,108	1,649	1,764	3,733	3,821
	KAHK4	1,414	2,134	2,323	4,927	5,148
	KAHK5	585	846	906	2,668	2,690
	KAHK6	2,625	4,593	4,911	4,898	6,031
Waiau Base	WAIW7	2,648	3,591	3,856	7,686	7,913
	WAIW8	789	976	1,052	3,981	4,622

Another concern with high penetrations of renewable energy is that a large percentage of the island's power comes from so-called "nonsynchronous" generation. Conventional steam-driven power plants use a synchronous generator that literally spins in synchronicity with the frequency of the power supply; the generator's rotation period is exactly equal to an integral number of alternating current cycles. This helps the grid maintain its normal operating parameters, including controlling voltage. Nonsynchronous generators, such as wind turbines and PV systems, do not typically provide this grid support. The fraction of the island's power supply that comes from synchronous generators is an indication of the relative strength and stability of the grid.

The study found that the percentage of synchronous generation is lowest in Scenario 4A, dropping below 50% for a few hours each year. Scenario 4A falls short of reaching unstable levels of nonsynchronous generation, but much higher levels of renewable energy than reflected in Scenario 4A could cause grid control challenges.

Operational Challenges for the Oahu Grid

Challenges to the Oahu grid with increasing penetrations of wind and solar energy are mainly related to rapid drops or rises in wind and solar power production. Wind and solar power drops of a sustained fashion over the course of 5–10 minutes can challenge the ability of the conventional (thermal) power plants to compensate by ramping up in power; dropping in a sustained fashion for 30–60 minutes consumes up-reserve resources and requires quick-start units. Wind and solar power can also rise when thermal power plants are near their minimum power level, consuming down reserves, and renewable power can vary rapidly within an hour, challenging the ramp rate and maneuvering ability of thermal power plants. Other concerns are the transient responses to a loss of load or the trip of a large thermal power plant.

Impacts of Wind and Solar Variability

The screening analysis showed there were adequate reserves to cover sustained drops of wind and solar power in periods of 5–60 minutes in all hours for all scenarios. In all cases, the thermal generation was able to compensate for the change in wind and solar power output without excessive deviation from nominal system frequency. There were, however, some instances in which 20–60 MW of contingency reserves were used to compensate for large reductions in wind and solar power output, and Scenario 4B experienced one event in which 128 MW of contingency reserves were consumed by a wind and solar power reduction. However, these were infrequent events, and all scenarios met the criterion for operating reserves to cover 99.99% of wind and solar variability.

Transient analysis of the grid's response to the worst-case hourly variability of wind and solar power found it was able to maintain proper frequency levels under all scenarios. The worst-case variability was under Scenario 4A, and the worst-case frequency excursion in this scenario was within ±0.2 Hz, which was deemed acceptable. However, this scenario resulted in considerable maneuvering of thermal units. It should be noted that the HECO units were assumed to be more responsive to system events than they are today and not all aspects of the generator systems are modeled. The ability of the HECO units to achieve this level of performance will need to be verified.

The situation is trickier when wind and solar power output is high and the thermal power plants are operating at or near minimum load to maximize the use of wind and solar power. If the wind and solar power output experiences a sustained increase for 5–30 minutes, the thermal power plants cannot reduce their power levels further to compensate. As a result, down reserves are consumed, and the study found that down reserves fall below their minimum levels for the high-penetration scenarios. Specifically, the analysis found about 2,000 hours of down-reserve violations for Scenario 4A and 950 hours for Scenario 4B, meaning grid reliability is at risk during these periods.

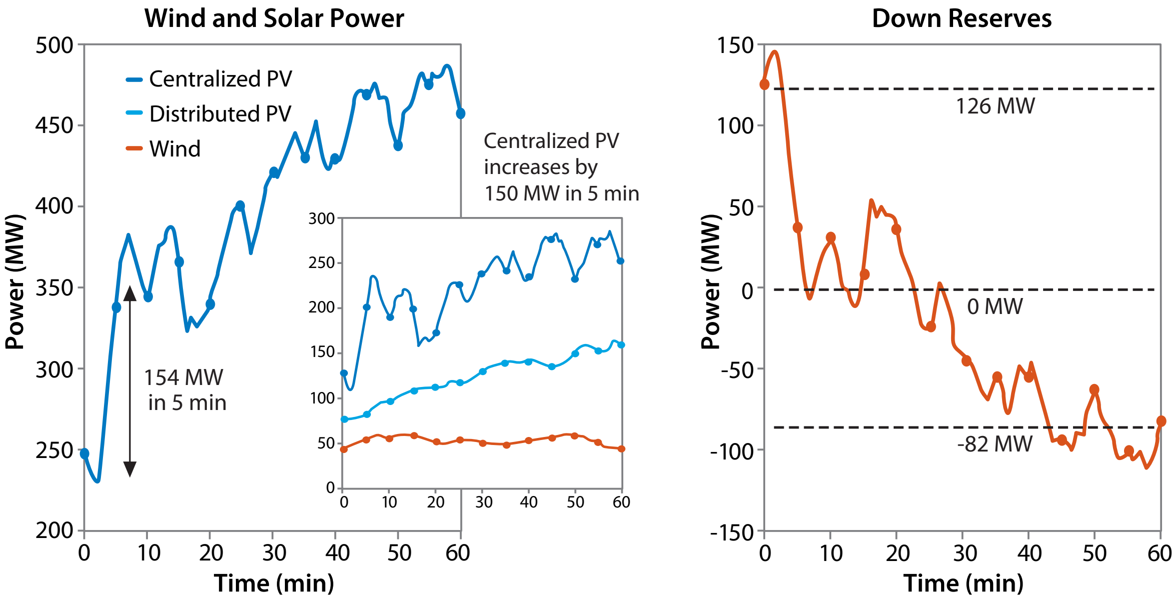
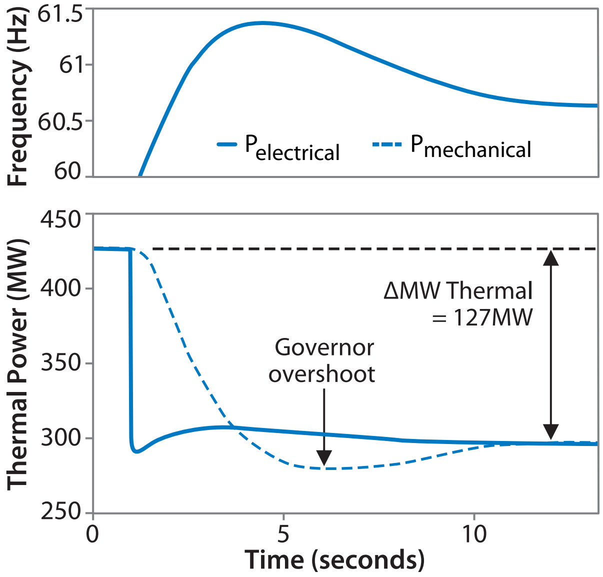


Figure 6. Down reserves consumed by an increase in wind and solar power under Scenario 4A during the worst-case 5-minute increase in wind and solar power

Figure 6 shows the down-reserve violation for the worst-case 5-minute increase in wind and solar power under Scenario 4A, caused by a rapid power increase at the central PV power plant. These results demonstrate the need to continuously manage down reserves with high penetrations of wind and solar power. One practical solution is to automatically curtail wind and central PV power plant resources when the down reserves fall below the minimum level required for loss-of-load contingencies.

Worst-Case Loss-of-Load Event

Transient simulations of the worst-case loss-of-load event on the Oahu grid showed that even though adequate down reserves were allocated to the thermal power plants, transient overshoot caused some thermal units to momentarily fall below their minimum power limits. As shown in Figure 7, under Scenario 4A, a 140-MW loss-of-load event caused two thermal units to experience transient power swings 16%–17% below their minimum power limits. Further analysis is required to quantify the risk of unit trips due to such transient events. However, if the wind and central-station PV resources were equipped with governor functions, they could participate in the response to loss-of-load events and reduce the reliability risk for thermal plants.



Units	Transient Minimum Mechanical Power (MW)	Unit Minimum Rating (MW)	Turn Down Below the Rating
KAHE-1	31.4	34.7	-10%
KAHE-3	34.7	35.0	-1%
KAHE-4	33.0	35.2	-6%
KAHE-6	46.3	55.1	-16%
WAI-7	24.2	25.7	-6%
WAI-8	20.9	25.1	-17%
AES	70.2	76.0	-8%

Figure 7. Transient response to a 140-MW loss-of-load event under Scenario 4A

Worst-Case Generating Plant Trips With Low System Reserves

The worst-case trip of a generating plant on Oahu is the loss of the 185-MW coal plant when system reserves are low. Figure 8 shows the system response to that event for the baseline case and Scenario 4A. In the baseline case, the frequency nadir (a direct measure of how close a system has come to interrupting the delivery of electricity to customers) is 58.65 Hz, and 95 MW of load is shed in two stages. Under Scenario 4A, the frequency nadir is 58.8 Hz, and 47 MW of load is shed in one stage. This indicates the Oahu grid handles the plant trip better with a high penetration of wind and solar energy, apparently because of the greater diversity of generating sources.

In 2012, HECO began requiring its distributed PV systems to ride through frequency excursions down to 57 Hz without tripping. Without that requirement, PV systems operating to conventional standards would trip offline at 59.3 Hz, exacerbating the frequency excursion. In that case, the frequency nadir would be 58.2 Hz under Scenario 4A, and the system would have to shed 190 MW of load. However, about 40 MW of distributed PV currently interconnected with the Oahu system were installed (prior to 2012) without ridethrough capability. Thus, the worst-case loss of generation for Oahu would be 225 MW, corresponding to the combined loss of the 185-MW plant and 40 MW of distributed PV. Further analysis will better establish the worst-case loss-of-generation events and the system reserves needed to deal with those events.

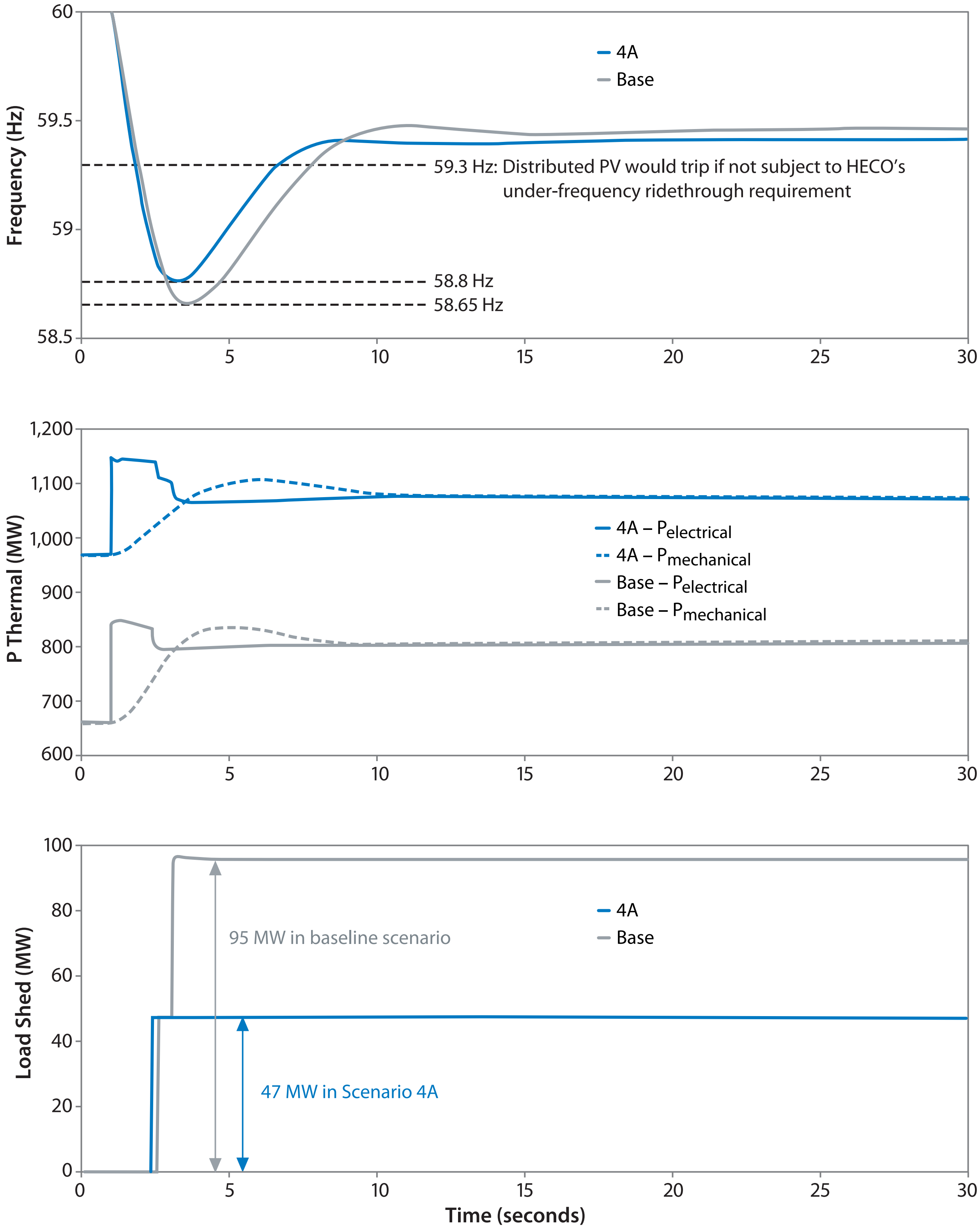


Figure 8. Response to a trip of the 185-MW coal plant under the baseline scenario and Scenario 4A

Mitigation Measures

A summary of operational challenges and potential mitigation measures associated with increased wind and solar energy penetration on the Oahu grid is presented in Table 5.

Table 5. Summary of Oahu Operational Challenges and Possible Mitigation Measures

Operational Challenges of Increased Wind and Solar Penetration	Mitigation Measures
Significant curtailment of wind and solar energy	Lower the minimum power level of thermal generation resources. This reduces curtailment from 8.6% to 2.7% in Scenario 4A and from 4.4% to 0.5% in Scenario 4B. This is by far the most effective mitigation measure. Relax fixed operating schedules for Oahu baseload generation. This reduces curtailment from 8.6% to 6.4% in Scenario 4A and from 4.4% to 1.2% in Scenario 4B. Provide a portion of spinning reserves from demand response or a BESS. Providing 50 MW of reserves from nonthermal resources reduces curtailment from 8.6% to 7.1% in Scenario 4A and from 4.4% to 3.9% in Scenario 4B. Provide a portion of down reserves from wind or central solar PV plants. This reduces curtailment from 8.6% to 5.5% in Scenario 4A and from 4.4% to 2.5% in Scenario 4B.
Frequency response of thermal unit operation during loss-of-load events	Equip wind and solar plants with governor controls that reduce power output in response to over-frequency events. This reduces the governing duty on thermal plants and prevents them from transiently falling below their minimum power limits.
Frequency response of thermal fleet during generator trip events	Provide a portion of spinning reserves from a BESS with a governor or from frequency-responsive demand response. This increases the system's overall governing response and shares the governing duty over more resources. It also helps avoid protective load-shedding actions. Apply synthetic inertia control functions on wind plants.
Wind and solar generation consumption of down reserves intended for loss-of-load events	Automate curtailment of wind and central PV plants to continuously maintain required levels of down reserves on thermal plants.
Increased variability in system frequency and regulation duty on thermal generation caused by wind and solar power variation	Study results show this is not expected to be a significant problem, but if better performance is desired: • Limit ramp rates on individual central solar PV plants (requires a BESS to limit down-ramps) • Apply a BESS as a grid-level frequency-regulating resource (would need to be about one-third the total rating of BESS applied to limit ramp rates on individual PV plants).

Curtailment Reduction

The study found the best way to reduce the curtailment of wind and solar power was to lower the minimum power limit on select thermal power units. HECO has identified several units that could potentially reduce minimum power levels by about 50%. Other mitigating measures include relaxing the operating schedules of certain baseload units, procuring additional spinning reserves through demand response or a BESS, and procuring additional down reserves from wind and solar energy resources. Combining all these mitigation measures yields significant improvements. Under Scenario 4A, curtailments can be lowered from 8.6% to only 0.9%. These mitigation measures will require investment in utility-owned generation or collaboration from the wind and solar power producers.

Improving Grid Performance Under Loss-of-Load Events

Under high penetrations of solar and wind power, thermal generators can fall below their minimum power levels during transient responses to severe loss-of-load events. The solution to this problem is to include the wind and central-station PV plants in the response by equipping them with governor controls. The responsiveness of governor controls is indicated by the "droop," which is the percentage difference in speed with no load on the generator and with full load on the generator. A governor with a lower-percentage droop results in a more responsive system.

North American power plants use governors with a droop of 5%. A standard droop helps ensure that the synchronous generating sources share the load equally in proportion to their generating capacity. To evaluate the benefit of adding governors to wind and central-station PV plants, the study examined adding governors with 5% droop—as responsive as the synchronous generators—and with 2% droop, which makes them more responsive.

The study found the response of the thermal units was reduced from 127 MW with no wind and solar governors to 80 MW using governors with 5% droop and to 50 MW using governors with 2% droop. As shown in Table 6, with no wind and solar governors, all five thermal units have transient power excursions that fall below their minimum power limit by 20%–30%. With 5% droop governors on wind and solar plants, four units remain above their minimum power levels, and one unit falls below by only 1%. With 2% droop governors on wind and solar plants, all the thermal units stay well above their minimum power levels for the loss-of-load event. In this case, it might be possible to reduce the minimum dispatch limits of some thermal units, thereby further reducing the curtailment of wind and solar energy.

Table 6. Thermal Power Plant Excursions Following a 140-MW Loss-of-Load Event

		No Governors on Wind + Solar Plants		Governors With 5% Droop on Wind + Solar Plants		Governors With 2% Droop on Wind + Solar Plants	
Units	Unit Pmin Limit (MW)	Transient Min Mech Power (MW)	Turn Down Relative to Pmin Limit	Transient Min Mech Power (MW)	Turn Down Relative to Pmin Limit	Transient Min Mech Power (MW)	Turn Down Relative to Pmin Limit
KAHE-1	17.0	12.4	-27%	18.5	9%	21.2	25%
KAHE-2	17.2	12.9	-25%	18.4	7%	21.2	23%
KAHE-6	55.1	38.5	-30%	54.8	-1%	61.0	11%
WAIAU-8	17.0	12.0	-29%	18.4	8%	21.0	23%
AES	76.0	59.8	-21%	80.5	6%	89.2	17%

Improving Grid Performance During Thermal Plant Trips

The loss of the 185-MW coal plant requires the Oahu grid to shed 95 MW of load with a frequency nadir of 58.65 Hz under the baseline case and 47 MW of load with a frequency nadir of 58.8 Hz under Scenario 4A. Although the Oahu grid performs better with high penetrations of wind and solar power and higher generation reserves on the system, it would be preferable to reduce the load shed and minimize the deviation from standard operating frequency.

Proposed mitigation measures include using demand response to shed 75 MW of load when system frequency falls below 59.5 Hz and using "synthetic inertia control functions" on the wind plants to momentarily boost wind power output when system frequency falls below 59.85 Hz. These synthetic inertia control functions draw on the kinetic energy of the spinning blades to generate extra power, thereby slowing the blades. After a power boost of a few seconds, the wind plant takes about 30 seconds to return to speed, so its power output dips during that period.

The study found that under Scenario 4B, drawing on 75 MW of frequency-responsive demand response would raise the frequency nadir from 58.6 Hz to 58.9 Hz and reduce load shedding to 30 MW. Using synthetic inertia controls on the wind plants would boost wind plant output by 35 MW but have little impact on the system, improving the frequency nadir by only 0.1 Hz without changing the amount of load shed. However, combining both mitigation measures would limit the frequency nadir to 59 Hz and eliminate the need to shed load.

Conclusions for the Oahu Electric Grid

The Oahu electric grid can accommodate 360 MW of solar PV generation and 100 MW of wind generation with additional spinning reserves, investments in generating units to reduce their minimums, and improved ramp rates. This mix of wind and solar generation supplies 11% of Oahu's annual electric load. If the solar PV resources are concentrated into larger plants with single-axis tracking rather than geographically dispersed with no tracking, the system will require more operating reserves to respond to the additional short-term variability in power output.

The Oahu electric grid with system modifications and additional reserves can accommodate additional wind and solar resources that result in renewable energy providing roughly 20% of the island's annual electricity needs. Additional operating reserves are required under the 20% renewable energy scenarios. Daytime operating reserves are higher for the PV-dominated scenario, and nighttime operating reserves are required for scenarios with wind. Centralized PV plants have more variability and, hence, need more operating reserves than distributed PV.

These high-penetration scenarios resulted in some curtailment of wind and solar power. Under current operating practices, the wind and solar mix resulted in curtailment of 4.3% of the renewable energy, while the solar-dominant mix resulted in curtailment of 8.6%. Reducing the minimum power level of the thermal power plants is the most effective method of reducing curtailment. Other effective methods include:

- Allocating down reserves to wind and solar plants
- Relaxing fixed operating schedules for a few thermal units
- Providing reserves from alternate resources such as a BESS or demand response.

Combining these mitigation measures can reduce curtailment to less than 1%, which is very acceptable.

The study also found that, under the scenarios with high renewable energy penetration, the modified grid controls are capable of maintaining adequate frequency control for subhourly variations of wind and solar power. However, certain operating conditions and grid stresses could degrade the safety margins of the grid and make it less reliable. For example, when thermal generation is backed down to minimum dispatch limits, increased wind and solar generation will consume down reserves intended for loss-of-load contingencies. This can be resolved with an automated scheme to curtail wind and solar plant output and maintain required down reserves on the thermal units.

Likewise, system over-frequency responses for loss-of-load events can be improved if wind and solar plants are equipped with over-frequency governor controls. This reduces the risk of thermal unit trips because of transient excursions below minimum power levels. In addition, system under-frequency responses to generator trip events can be improved by a combination of synthetic inertia on wind plants and frequency-sensitive demand response.

Maui

The Maui Power Grid

Maui's power supply includes four oil-fired power plants, a number of small diesel-fueled generators, two large diesel-fueled units, and a biomass-fueled power plant. Together, these power plants provide 264 MW of "firm" generation resources—power plants that the utility can count on to produce power when they are in service. For this study, the 16-MW biomass plant, which uses coal as a secondary fuel, is assumed to provide 13 MW of power during daylight hours and 9 MW at night. In addition, Maui has three wind farms that provide a total of 72 MW of power and 20 MW of grid-connected PV systems distributed around the island at homes and businesses. Finally, the Maui grid has a 10-MW BESS installed at one of the wind power plants. It provides up to 10 MW of up reserves for the Maui grid. A detailed listing of Maui generation resources is presented in Table 7.

Table 7. Maui Generation Resources as of November 2012

Firm Generation Resources	Capacity (MW)
Maalaea, combined cycle, distilate, 2×58 MW	116
Maalaea, diesels, distilate	96
Kahului, oil steam, four units	34
Hana, diesels, distilate	2
HC&S Sugar Mill, IPP, biomass	16
Total firm generating capability	**264**

Non-Firm Generation	Capacity (MW)
KWP1 wind farm	30
Auwahi wind farm	21
KWP2 wind farm	21
Distributed PV	20
Utility-scale PV	0
Total non-firm generation	**92**

The Maui study examined only two scenarios: a baseline scenario that reflects the system as it is today and Scenario 3, which adds 15 MW of centralized PV and 15 MW of distributed PV. (Scenario 2, meant to examine lower PV penetrations, was dropped because the results were expected to be trivial.) See Table 8.

Table 8. Study Scenarios for the Maui Power Grid

Scenario	Distributed PV (MW)	Centralized PV (MW)	Wind (MW)	Total (MW)
Baseline	15	0	72	**87**
Scenario 3	30	15	72	**117**

Each of these scenarios was modeled to determine the worst-case drop and rise in power from the aggregate wind and solar resources. The results are shown in Table 9. The study found renewable resource variability on Maui is dominated by the wind power plants, and, as a result, there is little difference in variability between the baseline scenario and Scenario 3.

Table 9. Worst-Case Variability for Maui Scenarios

	Baseline Scenario 72 MW Wind + 15 MW Solar		Scenario 3 72 MW Wind + 45 MW Solar	
Time Interval	Max ΔP Drop (MW)	Max ΔP Rise (MW)	Max ΔP Drop (MW)	Max ΔP Rise (MW)
30 seconds	7.0	6.8	8.1	7.1
1 minute	10.4	9.9	10.7	11.2
5 minutes	18.2	17.7	19.1	19.7
10 minutes	29.9	26.7	30.0	28.2
20 minutes	38.3	45.8	38.3	45.8
60 minutes	50.8	56.5	52.3	56.5

Required Reserves for Maui

On Maui, contingency and operating reserves are pooled together, with a minimum reserve level of 6 MW. This study focused on integrating more solar resources into the Maui grid. The technical analysis assumed that operating reserves would be allocated to cover variability of both wind and solar resources. A new method for calculating reserve requirements was developed, and that method produced reserve requirement curves (see Figure 9) that are significantly different from those presently used for Maui grid operations.

The reserve requirement developed for this study would generally require more reserves for lower levels of wind and solar contributions and less reserves for higher levels of wind and solar contributions, as compared with the existing reserve requirements for the system. However, it is difficult to compare the two methods because the new reserve requirement also adds reserves for solar power in addition to the wind power, where the existing reserve method only carries reserves for the wind power added to the system.

Further technical analysis is recommended to quantify curtailment impacts to the existing wind plants and to explore if and how the existing reserve practices should be changed to cover both wind and solar variability.

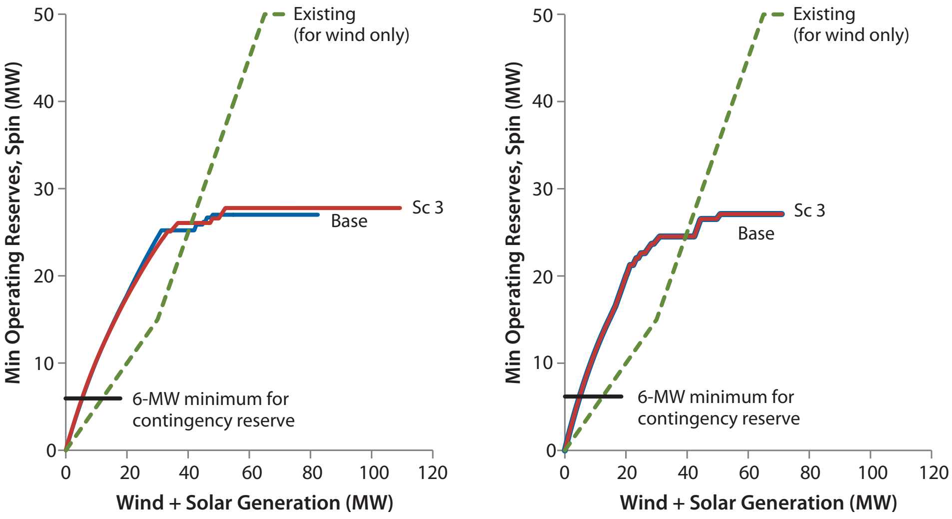


Figure 9. Maui operating reserve requirements, including BESS contribution, for day (left) and night (right)

The existing reserve requirements include the contributions of the BESS, which is capable of delivering 10 MW of up reserve continuously for 45 minutes, after which it will ramp down linearly for 45 minutes until it reaches zero. The BESS can also contribute 10 MW to down reserves by charging at its full capacity.

Maui Grid Operating Characteristics

In a similar fashion to the Oahu analysis, MAPS simulations examined how often solar and wind resources would be curtailed to maintain grid control parameters. On Maui, the central PV power plant was curtailed first, followed by the wind plants. The results, shown in Table 10, are that wind and solar penetration increases from 21% in the baseline scenario to 23.5% under Scenario 3, while wind and solar curtailment increases from 19.9% to 23.1%.

So although Scenario 3 features 34.5% more wind and solar capacity than the baseline scenario, it delivers only 11.7% more renewable energy to the grid because only 57% of the additional renewable power is delivered to the grid. Nearly half of the central PV resource is curtailed (the additional distributed PV cannot be curtailed); curtailment of one of the wind plants also increases. This happens because Maui has a high wind penetration in the baseline scenario and already has significant wind curtailment, so the bulk of the additional renewable energy contributions in Scenario 3 are curtailed.

Table 10. Annual Wind and Solar Energy Use, Curtailment, and Penetration

		Maui Wind + Solar Resources						Renewable Utilization		Comparison to Baseline		
		30 MW KWP1	21 MW Auwahi	21 MW KWP2	Central PV	Dist PV	Total (GWh)	Wind + Solar Curtailment	Wind + Solar Penetration	Add'l RE Available (MWh)	Add'l RE Delivered (MWh)	% Add'l RE Delivered
Baseline	Available GWh	129	88	90	0	25	332	19.9%	21.0%			
	Curtailed GWh	3	18	46	0	0	66					
	Delivered GWh	126	70	45	0	25	266					
	CF (Delivered)	48%	38%	24%		19%						
Scenario 3	Available GWh	129	88	90	30	49	386	23.1%	23.5%	54	31	57%
	Curtailed GWh	2	18	54	14	0	89					
	Delivered GWh	126	69	36	15	49	297					
	CF (Delivered)	48%	38%	20%	12%	19%						

Like Oahu, Maui draws on nonsynchronous power sources for a large percentage of its power supply. Under the baseline scenario, the grid approaches 50% nonsynchronous generation for a few hours of the year, while under Scenario 3, that percentage approaches 60%. Scenario 3 exceeds 50% nonsynchronous generation for about 100 hours per year.

Operational Challenges for the Maui Grid

As on Oahu, the challenges of increasing penetrations of wind and solar energy to the operation of the Maui grid are primarily related to rapid drops or rises in wind and solar power production. There is also a potential vulnerability to loss-of-load events.

Impacts of Wind and Solar Variability

The screening analysis confirmed there are adequate reserves in all hours to cover sustained drops of wind and solar power in periods of 5–60 minutes. The analysis exhausted the thermal reserves first and then drew on the BESS, and, in most cases, the thermal reserves were sufficient to compensate for the drop. Under the baseline scenario, there are 10 hours per year when the reserve margin falls below 5 MW, and during the worst-case event, the reserve margin falls to 1 MW. Under Scenario 3, there are only 7 hours per year when the reserve margin falls to 5 MW, which is the lower limit on the reserve margins during the worst-case event.

Transient analysis of the grid's response to the worst-case hourly variability of wind and solar power found the grid was able to maintain proper frequency under all scenarios. In the simulations, the thermal units handled most of the regulation duty, but the BESS contributed briefly when the frequency excursion exceeded ±0.1 Hz. As a result, all the frequency excursions were held within that ±0.1-Hz band.

Worst-Case Loss-of-Load Event

The largest anticipated loss-of-load event on the Maui grid is 20 MW. Per Maui Electric Co. operating practices, the system carries 5 MW of down reserves on its thermal resources during the day and 3 MW at night, and the BESS contributes another 10 MW to down reserves. Analysis shows there are 3,530 hours per year when the thermal units and BESS could not cover a 20-MW loss-of-load event. Transient analysis shows that four diesel-fueled combustion turbines at Maalaea fall below their minimum power limits during the worst-case loss-of-load event, and two of these units settle at a final power level that is 1.5 MW below their minimum power level.

However, the wind plants and the central PV plant can contribute to down reserves by curtailing output. The study determined these three sources of down reserves are sufficient to compensate for the largest loss-of-load event. Another alternative is to automatically curtail wind and solar power to preserve down reserves on thermal plants. During the 3,530 hours when the thermal units and BESS have inadequate reserves, the wind and central solar plants could be automatically curtailed to maintain a thermal plant down reserve of at least 10 MW, but doing so would significantly increase wind and solar curtailment.

Table 11. Annual Wind and Solar Energy Use, Curtailment, and Penetration

Operational Problems With Increased Wind/Solar Penetration	Mitigation Measures
Significant curtailment of wind and solar energy	Combined-cycle units switch between single- and dual-train operation as needed. Relax or eliminate fixed operating schedules for Kahului 1-4. Increase the priority of reserves in the commitment process. Install an additional 10-MW BESS for reserves. Install an additional 10-MW BESS for time-shifting energy.
Wind and solar generation consumption of down reserves intended for loss-of-load events	Automate curtailment of wind and central PV plants to continuously maintain required levels of down reserves on thermal plants.
Thermal unit operation during loss-of-load events	Equip wind and solar plants with governor controls that will reduce power output in response to over-frequency events. This reduces the governing duty on thermal plants and prevents them from transiently falling below their minimum power limits. Install an additional 10-MW BESS with a frequency-responsive governor.
Wind and solar generation consumption of down reserves because of rapid and/or sustained decreases of wind and solar power	Analytical results demonstrate the assumed criteria for operating reserves (both spinning and non-spinning) was sufficient to cover all subhourly down-ramps in wind and solar. No additional mitigations are required.
Increased variability in system frequency and regulation duty on thermal generation caused by wind and solar power variation	Study results show that frequency regulation during the most volatile hour is within 0.1 Hz, as the BESS responds rapidly for excursions beyond its 0.1-Hz governor deadband. Ramping duty on thermal units and frequency variations can be reduced by reducing or eliminating the 0.1-Hz deadband on the BESS.

Mitigation Measures

A summary of operational challenges and potential mitigation measures associated with increased wind and solar energy penetration on the Maui grid is presented in Table 11. Note that the reductions in variable cost discussed below do not account for the cost of implementing the mitigation action assumed or any cost of the additional renewable energy accepted by the system.

Curtailment Reduction

A screening analysis assessed the ideas for reducing curtailment. The analysis found that enabling the combined-cycle units to switch between single-and dual-train operation increased wind and solar penetration from 23.5% to 25.1%, reduced curtailment from 23.1% to 17.9%, and increased the percentage of additional renewable energy that was actually delivered to 94%.

However, adding in relaxed operating schedules for the four oil-fired units and a change in the commitment process to increase the priority of reserves improved grid performance, raised wind and solar penetration to 25.7%, lowered curtailment to 15.8%, and actually delivered more renewable energy than the additional renewable energy that was added. This reflects a more efficient use of the existing wind and solar resources.

The study also evaluated the benefits of adding another 10-MW, 20-MWh BESS, similar to the existing one, to the Maui grid. Two BESS operating strategies were considered: using the second BESS to provide an additional 10 MW of operating reserves or using it to "time-shift" energy—storing the wind and solar energy that would otherwise be curtailed and delivering it to the grid at the first opportunity. These two strategies were examined independent of the other proposed mitigation methods.

When providing reserves, the BESS raised wind and solar penetration to 17.6%, reduced curtailment to 25.2%, and delivered 96% of the available added renewable energy to the grid. It also reduced variable operating costs by $5 million per year. When used to time-shift energy, the BESS reduced curtailment to 19% and dropped operating costs by $1.8 million per year, so it is clearly preferable to use the BESS to provide operating reserves.

However, the study also examined time-shifting energy with a BESS that has more hours of storage. Using a 100-MWh BESS instead of a 20-MWh BESS produced a result similar to using a 20-MWh BESS to provide operating reserves, with curtailment lowered to 17.6%. However, the 20-MWh BESS used for operating reserves results in lower operating costs than the 100-MWh BESS used for time-shifting energy, so it is still preferable to employ the smaller BESS to provide reserves. Note that the cost reductions stated show the relative benefits provided by an additional BESS but do not include the cost of the BESS or the additional renewable energy accepted by the system.

Improving Grid Performance for Loss-of-Load Events

A loss-of-load event could cause four combustion turbines at Maalaea to drop below their minimum power levels. To mitigate this problem, the study examined the use of over-frequency governor controls on the central-station PV plant and two of the three wind farms, representing 42 MW of capacity. (The third wind farm is under a power purchase agreement that does not allow a governor function. However, the BESS does have an aggressive fequency response.) This resulted in a modest reduction in the thermal plant response. Only three of the four combustion turbines went below their minimum power levels because of overshoot on their transient responses, and two of the four ended up operating below their minimum power levels after the event.

Other possible mitigation approaches include modifying the Maalaea combined-cycle units to reduce their minimum power levels and installing over-frequency relays with low settings on selected wind-plant feeders to trip a portion of the wind generation during loss-of-load events. These approaches were not investigated in the study.

Improving Grid Frequency Regulation for High-Variability Periods

Maui's thermal units can adjust their output for most periods of high variability of solar and wind resources, but, occasionally, the BESS kicks in to keep the frequency range within a ±0.1-Hz band around the nominal 60-Hz frequency. To see if the BESS could provide even better frequency regulation, the study examined whether system performance under high-variability periods could be improved by removing the 0.1-Hz deadband in the BESS control scheme. The analysis found that operating the BESS with no deadband resulted in greater cycling of the BESS but decreased the power maneuvering of the thermal plants and improved frequency control. The results are shown in Figure 10.

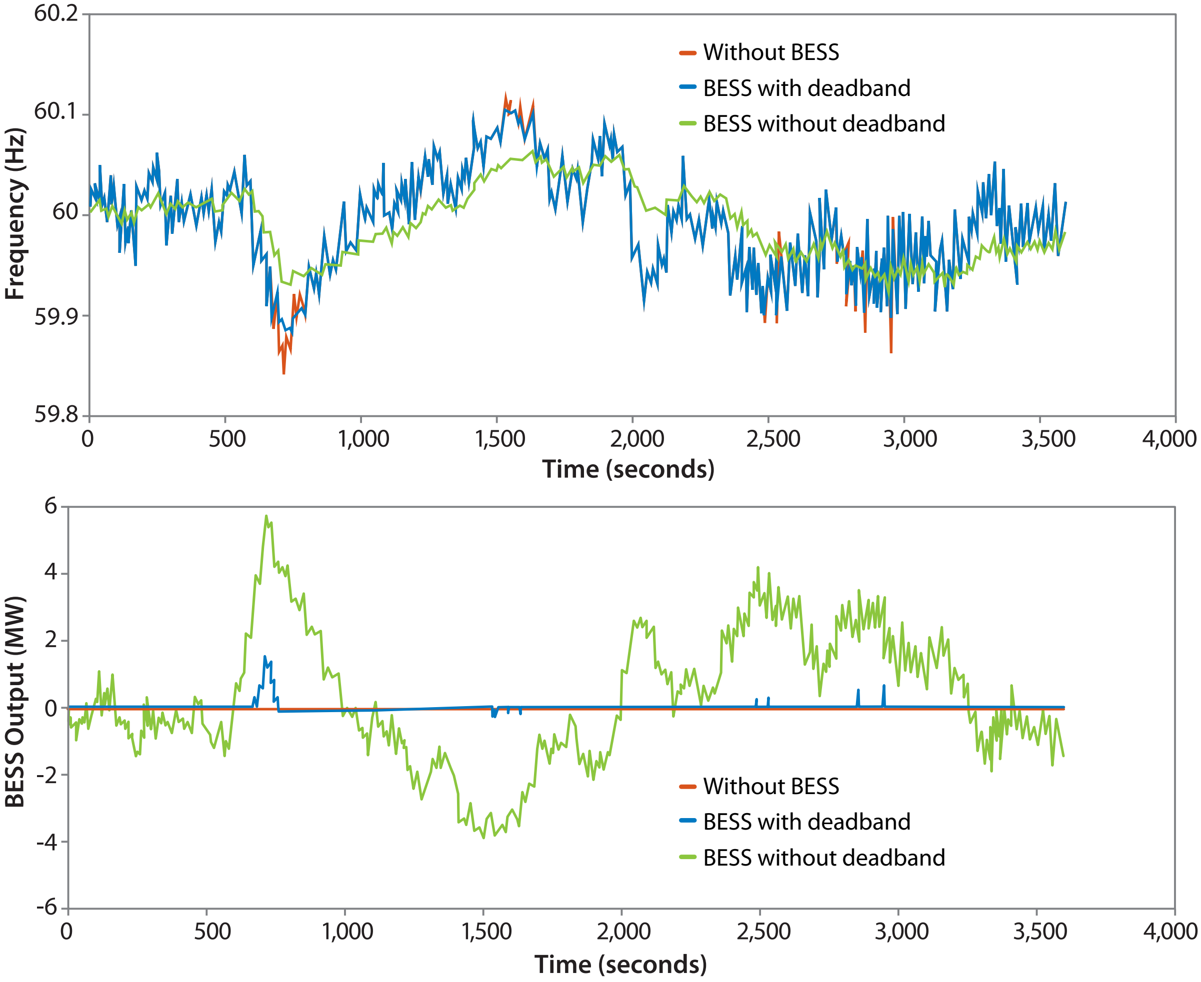


Figure 10. Regulation performance for the most volatile hour under Scenario 3, with and without the 0.1-Hz deadband in the BESS control scheme

Conclusions for the Maui Electric Grid

Compared with the baseline scenario, Scenario 3 has 54 MWh of additional solar energy available from 30 MW of new solar PV resources. However, under existing operating practices, only 57% of this solar energy can be used to serve load; the rest must be curtailed. Despite the curtailment, wind and solar resources provide 23.5% of Maui's power needs under Scenario 3. The reserves required for the 72 MW of wind resources in the baseline scenario were found to be sufficient to cover the additional 30 MW of PV resources in Scenario 3.

Several methods for reducing curtailment were explored. The two mitigation methods that performed well were enabling the single- or dual-train operation of the combined-cycle units and adding a 10-MW, 20-MWh BESS. The flexible operation of the combined-cycle units enabled 94% of the additional renewable energy in Scenario 3 to be delivered to the grid, with only 6% curtailed, while the BESS enabled 96% of the additional renewable energy to be delivered to the grid, with only 4% curtailed. Using the BESS to time-shift energy was not as effective for reducing curtailment as using the BESS to provide reserves.

The study also found that some thermal units fell below their minimum operating power levels during the worst-case loss-of-load event with high wind and solar power production. The addition of frequency droop response in the new wind power plants resulted in a modest improvement, but the study recommended that the utility review the modeled power excursions at the thermal units to evaluate the risk of them tripping offline under these conditions.

However, the system has enough maneuvering capability in the thermal plants and the BESS to counteract the most volatile periods of wind and solar power production. With the existing BESS deadband, the thermal units do most of the maneuvering in response to short-term variations, but with the deadband removed, the BESS shares in the system frequency regulation and significantly reduces maneuvering duty on the thermal units.

Conclusions

In summary, the Hawaii Solar Integration Study provided valuable insights into the integration of solar and wind power into two very different utility grids. The results provide a deeper understanding of the differences among distributed PV systems, centralized PV power plants, and wind power plants in terms of variability, ability to curtail power output, grid support, and characteristics relative to the load. Although reliability challenges increase with increasing variable renewable generation, this study found that those challenges are manageable for the scenarios studied with the mitigation approaches recommended.

This study found that higher levels of variable renewables can be reliably accommodated in a collaborative fashion (i.e., by changes to both utility equipment and operating practices and variable generation equipment) and noted the importance of asking for the right capabilities (e.g., inertial and frequency response, voltage and frequency ridethrough, and ancillary services) from variable generating plants. The importance and value of reviewing existing operating practices and adjusting certain assumptions (e.g., minimum power generation levels and must-run generator rules) was modeled and the impact on solar and wind curtailment shown. Finally, the use and value of storage in a high-penetration system was modeled and discussed. The insights from the Hawaii Solar Integration Study form a large body of knowledge for future grid integration studies, and the results can be used to further our understanding of grid integration in other island systems as well as mainland U.S. systems with high regional solar and wind penetrations.

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