Oahu Distributed PV Grid Stability Study
Part 3: Grid Strength

Prepared for the

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Task 2: Energy Modeling and Scenario Analysis

Prepared by

GE Energy Consulting

Submitted by

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

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HNEI
Hawai‘i Natural Energy Institute
School of Ocean and Earth Science and Technology
University of Hawai‘i at Mānoa

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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 3: Grid Strength." It follows a similar approach as the previous two parts by combining production cost modeling, grid stability simulations, and statistical analysis. The underlying production cost simulations and challenging hour selection are consistent between all three study parts. The results and charts in this report are intended to complement the first two parts, while some material is repeated to allow the reports to be read and understood in isolation of one-another.

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. ("GEII"); 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 Stenclik

Manager, Power Systems Strategy

GE Energy Consulting

General Electric International, Inc.

One River Road

Building 53

Schenectady, New York 12345

Phone: 518-385-7438

Fax: (518) 385-5703

E-Mail: derek.stenclik@ge.com

Project Team

GE Energy Consulting

Derek Stenclik

Matthew Richwine

Richard Piwko

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.

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1 INTRODUCTION

1.1 Introduction to Weak Grids and Short Circuit Analysis

What is it?

As power electronic sources of generation (such as wind, solar, and battery energy storage) increase on a grid, the amount of generation from conventional synchronous generators (gas turbines, steam turbines, etc.) is reduced. While the real power (MW) produced by the power electronic sources may be the same as that produced by conventional synchronous generators, there are inherent characteristics of synchronous generators that contribute to the stability of the power system that are not inherently shared by power electronic sources. Specifically, the conventional synchronous machines (rotating electromagnetic devices) contribute what is commonly referred to as "strength" of a grid.

Strong grids are those with many synchronous machines, where each synchronous machine acts as an "anchor" to fix the grid voltage at a selected value and oppose sudden changes in the voltage of the grid at locations close to the synchronous machine. Conversely, "weak grids" are those in which there are relatively few synchronous machines online. These weak grids have fewer "voltage anchors," which leaves them susceptible to larger fluctuations in voltage during disturbances and poses challenges to stable operations of the grid and sustaining power transfer. Typically, weak grid regions were areas where large utility-scale wind generation was sited far from load or other conventional generators (i.e. ERCOT Panhandle). However, given that the Hawaii grids are isolated and the amount of wind and solar generation is quickly increasing and displacing conventional generation, it may be one of the first locations to experience weak grid conditions across the entire grid.

For an analogy, visualize the grid as a trampoline and the springs connecting the trampoline to the frame as conventional synchronous generators. If one jumps on the trampoline (the equivalent of an electrical disturbance like a generator trip or a line fault), the trampoline is relatively stiff and pushes back. If some springs are disconnected from the frame (turning off a conventional generator), the relative strength of the trampoline erodes. While the trampoline still appears flat (and the grid will continue to operate normally in steady state), if one jumps on the trampoline it may no longer push back and could fail. The same is true for the weak grid analogy.

To use another analogy, grid strength can be thought of as a measure of the "electrical stiffness" of the voltage at a particular bus in an electrical grid. An infinitely strong bus would have an ideal voltage source connected to it with zero impedance (low resistance to the flow of electricity), such that any attempt to change the voltage at that bus would be met with an infinite supply of current that would keep the voltage the same. Conversely, a weak bus would be one where it is relatively easy to change the voltage at the bus by drawing or sourcing current, whether the source or sink of current is an air-conditioning motor or a distributed photovoltaic (DPV) solar inverter. A weak bus could be considered a bus connected to an ideal voltage source by a relatively large impedance such that devices that sink or source current would result in a significant voltage drop across the impedance between the weak bus and the ideal voltage source, thus making for an "electrically flimsy" bus voltage, to return to the mechanical analogy.

The primary advantage of a strong grid, where the buses in the grid are considered "stiff", is that the bus voltages respond less to changing currents in the network, which reduces the potential for unintended interaction among connected equipment, thus making the entire grid more stable.

Why is it a risk?

At its simplest interpretation, a weak grid can facilitate power transfer from generators to loads under normal operating conditions. However, under abnormal conditions there is a risk to grid stability if a disturbance occurs. As the amount of renewable generation increases, specifically wind and solar, conventional generators are no longer required to serve load and operate less frequently. With the loss of the synchronous generation, grid strength erodes. The reduction of grid strength impacts:

1. the severity of voltage excursions and distortion,
2. protective relaying accuracy, and
3. system stability.

With respect to voltage excursions and distortion, routine grid events like switching shunt capacitors and energizing transformers will produce greater voltage excursions and distortion on weaker grids. Protective relaying refers to the devices that continuously monitor transmission and distribution lines for faults and to disconnect lines quickly when a fault is detected. These relays are designed to operate correctly over a range of grid strength. If the grid strength falls outside of the range, then the protection scheme and relay settings may need to be reevaluated. Regarding system stability, if a grid becomes too weak, then a disturbance like a fault may cause the grid to collapse, resulting in a blackout for part or potentially all of the system.

What helps, and what doesn't?

Grid strength is generally increased by the connection of synchronous machines to the system. This includes thermal resources such as oil, gas, coal, biofuel and waste-fired generation, as well as conventional hydro and pumped hydro storage. These machines, whether they are part of turbo-generator drivetrains, hydro-electric plants, synchronous condensers, or synchronous motor loads have a magnetic flux in the core that is resistant to sudden changes, helping to maintain a stable terminal voltage. The short-circuit current contribution of a synchronous machine is not a function of the operating power of the machine – it is present as long as the machine is magnetized and connected to the network. Generally, larger machines (higher MVA rating) provide more short-circuit strength than smaller machines.

The vast majority of today's power-electronic devices do not contribute to system strength. This includes distributed and utility-scale PV, type 3 (doubly-fed) and type 4 (full conversion) wind turbines, HVDC links, and energy storage devices with a power-electronic interface (commonly used in battery energy storage systems), electric vehicles, flywheel systems, etc. Instead, most power electronic devices depend on the AC power grid to maintain voltages and waveshapes and a certain level of "grid strength" that assures stability of their internal control functions.

How is grid strength measured?

There are a variety of measures for quantifying grid strength, most of which are variations of the short-circuit ratio (SCR). The nomenclature "short-circuit" may be misleading because this analysis does not pertain to the response of equipment to a fault, but rather it is a historical term used in the industry to determine the grid strength, in which the "short-circuit" function of power flow program is used. SCR in its most basic form is quantified at a particular bus in the network and is calculated as the ratio of short-circuit current (measured in MVA) from only the synchronous machines in the network to the MW rating of the power electronic equipment connected locally at the bus. Often, a bus will have many power electronic devices connected to it, or in the local vicinity. If the different power electronic equipment is operating with the same control algorithm (identical inverter model and identical inverter settings), then it tends to act together as one large device and must be evaluated in aggregate. The form of SCR in which two or more local, identical devices are aggregated is called the composite short-circuit ratio (CSCR), which is computed as the ratio of the short-circuit current from only the synchronous machines in the network at a common bus to the aggregate rating of the power electronic devices. The advantage of these measures is that they are a simple, single measure that is generally indicative of risk. However, the trade-off for the simplicity is accuracy, especially as grids become very weak. CSCR values do not convey the complex realities of power systems in deciding how "electrically close" two or more devices must be and "how similar" must their controls be in order to aggregate them. While these questions may be rigorously answered through the use of high-fidelity models using electro-magnetic transients programs (EMTP), the data requirements and complexity of a single feeder with DPV, let alone the entire network, make this approach intractable. A healthy dose of engineering judgment is prescribed, where a conservative approach is to aggregate multiple devices knowing that in reality, not all devices will be "pulling together" on an unstable feedback path.

Another similar measure of grid strength developed and applied by the Electric Reliability Council of Texas (ERCOT) in Western Texas is the weighted short-circuit ratio (WSCR).[1] This approach aggregates a region of a power system network assuming that all power electronic equipment is closely connected and operates with identical controls. This approach has been adapted in this study to Oahu where a single WSCR is calculated for the entire island for a given dispatch condition.

Why is it becoming more of a concern?

With little or no power electronic equipment connected on a network, the control stability concerns described are minimal because the network is dominated by synchronous machines where high values of SCR and all its variants would be found. As power electronic equipment penetration increases and the number of synchronous machines remains constant or

[1] Panhandle Renewable Energy Zone Study Report, Prepared by ERCOT System Planning, April 2014

http://www.ercot.com/content/news/presentations/2014/Panhandle%20Renewable%20Energy%20Zone%20Study%20Report.pdf

decreases due to displacement by power-electronic sources, the grid strength decreases. There may be pockets of the grid where the effect is exaggerated, for instance where a lot of power electronic devices are clustered together and connected to the grid by long transmission lines that separate the power electronics from most of the large synchronous machines on the network. For example, this is the case in the Texas Panhandle, and with the increasing number of power electronic sources of generation from both distributed and utility-scale solar and utility-scale wind projects, there is a risk that weak grid pockets will arise on Oahu that could become unstable.

1.2 Industry Experience

The growth of wind power in the United States over the last 15 years has been dramatic. In the years of early growth, project sites were selected in places that had the best wind resources and close to power transmission corridors. In such environments, the grid strength at the point of interconnection remained high and grid strength was not a concern in the industry. As these sites became saturated, developers pursued sites that had excellent wind conditions, but were farther from existing transmission corridors, load, and other synchronous generators, resulting in projects having a weak grid at the point of interconnection. Some sites experienced unstable behavior and the inability to ride-through disturbances. This attracted attention and prompted equipment manufacturers to enhance their power electronic controls for weak grid applications, which required significant investment and was accompanied by some lessons learned in the field. While the major equipment manufacturers are aware of the challenges, variations in equipment capability for weak grid applications still persist as making advancements in weak grid capability without compromising the performance in other operating conditions is a challenging and complex task.

The solar industry of 2016 resembles aspects of the wind industry from 2006 where growth is advancing rapidly, installation sites are being pursued in locations with weak grids, and the concern for stability of the equipment in weak grid locations is understated or non-existent. However, unlike in 2006, many of the hard lessons about operating power electronic equipment on weak systems have been learned, screening methods for identifying risk have been developed, and strategies for enhancing controls exist.

This study serves to highlight the risk and propose approaches for managing the risk based on the experience of the wind industry. There has been very little attention to date on grids where a large amount of power electronic equipment is distributed across the system and causing significant displacement of conventional generation. It is expected that Oahu (and other islands), given the recent rapid growth in distributed solar adoption, may be one of the first power grids to experience a systemic weak grid concern.

1.3 What does this mean for Hawaii?

The grid in western Texas shares some similarities with the not-too-distant future Oahu grid. Both have high amounts of power-electronic based generation relative to synchronous generation in a relatively concentrated area. This is the reason for applying the WSCR method originally implemented in ERCOT to the Oahu network. However, there are many significant differences between the two systems that limit the utility of WSCR on Oahu. These include:

- **Equipment Variety:** The Texas Panhandle is characterized by large, utility-scale wind plants that were provided from only a few vendors. On the other hand, Oahu has many thousands of individual inverter-based devices including wind plants, central solar plants, and distributed rooftop PV, all from a much wider range of vendors. The large variety of equipment on Oahu impacts study work as the high-fidelity EMT models critical for evaluating controls stability may be difficult to obtain from so many different vendors with varied levels of experience with this issue.

- **Equipment Distribution:** Western Texas can be considered a pocket of the grid where the connected equipment is dominated by wind turbines, where load and synchronous machines are relatively small. This pocket of the grid is connected by long transmission lines to a more conventional power system dominated by synchronous machines and loads. However, in Oahu, the connected equipment tends to be a mix of power-electronic equipment, synchronous machines, and load. Oahu resembles the reciprocal of Texas, where a pocket of synchronous machines is connected through transmission lines to a grid dominated by power electronics (DPV) and loads.

- **Network Complexity:** In Western Texas, the power electronic generation is primarily connected to the transmission system. This transmission system appears simple in contrast with the Oahu system where the power electronic generation is connected not only to the transmission system (for utility-scale plants) but to the distribution system, where the topology of the system is much more complicated. The distribution system can be configured in many more ways by various switches and sectionalizers, the equipment is often single-phase, generation and loads are comingled, and the protection systems are more varied.

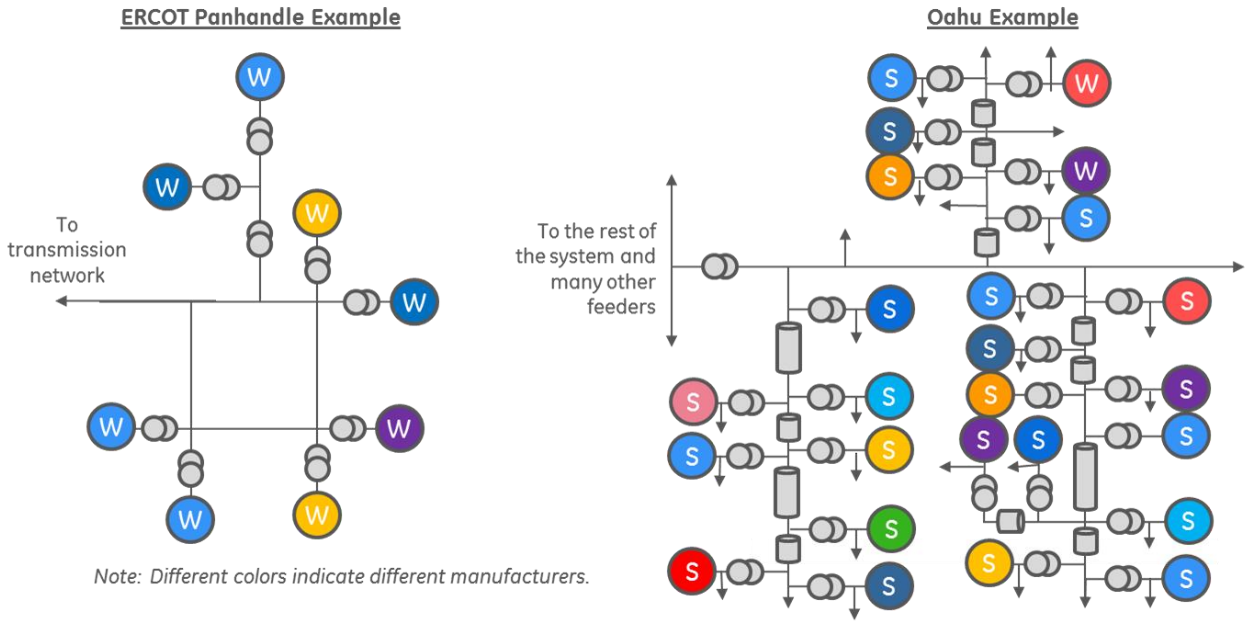

Figure 1: An Illustrative Example of Oahu versus ERCOT Panhandle Network Complexity

An illustrative example of the increased network complexity and equipment variety of Oahu relative to the ERCOT Panhandle is provided in Figure 1, where the circles represent wind and solar generators and the coloring represents different inverter vendors.

In Texas, it was possible for the grid operator (ERCOT) to obtain models from vendors and conduct detailed studies of weak grid stability issues. For Oahu, the much larger number of individual devices and the greater variety of vendors makes a similar analysis an order of magnitude more difficult. In addition, dynamic models for DPV inverters are not presently available within the industry.

1.4 Study Scope & Limitations

The objective of this study is to evaluate the trends in grid strength across the Oahu power system as additional distributed PV is added. It is intended to be an exploratory analysis only. Quantifying the WSCR across an entire power system is a relatively new endeavor and more information on the performance of DPV inverters is required before full conclusions can be made, minimum thresholds can be drawn, and requirements can be codified. Instead, this study is intended to increase awareness around weak grid issues on Oahu, illustrate the trends with increased DPV additions, and to outline a series of next steps to investigate further.

While this study significantly expands the technical analysis into areas not examined in previous studies, it is not exhaustive in covering all possible risks and mitigations for grid strength. In particular 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.
- While many parallels to the ERCOT Panhandle experience are drawn, the Oahu power grid is unique. Although lessons from ERCOT are valuable to the Oahu grid, specific requirements and minimum thresholds used in ERCOT are not directly applicable to Oahu due to differences in the transmission network and power electronic equipment.
- This study does not answer the question of when weak grid system stability becomes a realistic concern, nor does it propose a minimum threshold to WSCR for Oahu. While simulations and experience in ERCOT indicates a stability concern at WSCRs below 1.5, this measure is highly system specific and should not be extrapolated to Hawaii. One critical factor here is that weak grid operational capabilities of DPV inverters are not yet understood by the industry at large. Although some vendors may have performed some internal investigations of this emerging issues, they have not shared their findings publicly.

2 METHODOLOGY

2.1 Analytical Process & Modeling Tools

To analyze the impact of increasing DPV penetration on grid strength, a variety of models and statistical techniques were employed in this analysis to simulate both system operations and short circuit strength of the grid. While these models are not duplicating actual system conditions, they have been routinely benchmarked and validated against historical operations and are consistent with engineering and operating practices utilized by HECO and other industry stakeholders. The methodology employed in this analysis included seven steps outlined below. Please note that the production cost simulations and the selected dispatch conditions passed to the short-circuit strength simulations are identical to those evaluated in Part 1 System Frequency Response to Generator Contingency Events and Part 2 System Frequency Response to Load Rejection Events. This allows for a direct comparison of dispatch and system conditions between these three parts of the study.

Step 1 - Production Cost Simulations (GE MAPS):

The first step in the analysis was to conduct detailed hourly production cost simulations. The GE-MAPS production cost model simulates the power system operation on an hourly, chronological basis over the course of the year. The model simulates the system operator's unit commitment (on or offline) and dispatch (MW output) decisions necessary to supply the electricity load in a least cost manner, while appropriately reflecting transmission flows across the grid and simultaneously preparing the system for unexpected contingency events and variability. The chronological modeling is crucial to understanding renewable integration because it simulates temporal changes to electrical load and the underlying variability and forecast uncertainty associated with wind and solar resources.

This modeling was performed for two scenarios, along with intermediate steps (described in Section 2.2), with increasing levels of DPV penetration. This step is an essential part of the analysis because as solar penetration increases, the model provides accurate changes in hourly unit commitment, dispatch, spinning reserves and potential curtailment. An overview of the 8,760 hourly results from the production cost modeling are provided separately in Parts 1 and 2 of this report, with the outputs of specific dispatch conditions (selected hours) passed to Step 2 for further analysis.

Step 2 – Selecting System Dispatch Conditions for Grid Strength Simulations:

The production cost analysis (Step 1) generated 8,760 hourly dispatch conditions over the course a year of simulation, of which 21 were selected for further, more detailed, evaluation in the Grid Strength Simulations evaluated in Step 3. Unlike previous analyses conducted on short circuit strength, the selected dispatch conditions were not isolated to the most extreme operating conditions over the course of a year. Instead, a broad range of system dispatches were evaluated to ensure that conclusions could be drawn holistically across a full spectrum operating conditions. In general, however, the focus of the analysis was on DPV integration, and therefore all but three hours selected were during daytime periods when solar is online and grid strength is expected to be relatively low.

Step 3 – Grid Strength Calculations (GE PSLF):

The grid strength of the system due to the connected synchronous machines was calculated at every 138kV bus on Oahu for each of the dispatch conditions. This was done in GE's Positive Sequence Load Flow (PSLF) program by first disconnecting all of the power-electronic-based generation and then by applying a three-phase short-circuit at each HV bus using PSLF. The resulting short-circuit MVA from PSLF at each bus is fed into the WSCR calculations.

Step 4 – Weighted Short Circuit Ratio Calculation:

With the short-circuit MVA from synchronous machines calculated and the MW rating of power-electronic-based generation connected to each HV bus known, the WSCR value is calculated according to a recent paper produced by ERCOT.[2] The result is a single WSCR value for the entire Oahu system for the given dispatch condition and represents one metric quantifying grid strength across an entire system.

Step 5 – Analyze Relative Grid Strength Within the Network:

Unlike the frequency stability which is system-wide, grid strength is partly dependent on location. However, the WSCR method treats the system in aggregate, producing a single number for the entire Oahu system for a given dispatch condition and offering no insight to variation in grid strength across the system from bus to bus.

The WSCR method for Oahu is augmented by another approach in order to provide insight within the Oahu network to understand the variation of grid strength across the different buses of the network. This method is called the impedance-weighted SCR or "ZSCR" and is calculated as the ratio of the short-circuit current at a bus from contributions of synchronous machines only (as previously done for SCR, CSCR, WSCR) and dividing by the impedance-weighted rating of the power electronic equipment. The impedance-weighted rating of the power electronic equipment is determined using the short-circuit function in a load-flow program to apply a 3-phase fault at a given bus after disconnecting all synchronous machines and leaving connected all power electronic equipment. The power-electronic devices are represented by Thevenin-equivalent sources where the generator rating is the rating of the power electronic equipment and the subtransient reactance is set to 1.0. This method results in values with only relative meaning and little absolute meaning. In this way, they are used to compare buses to each other.

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[2] Panhandle Renewable Energy Zone Study Report, Prepared by ERCOT System Planning, April 2014

http://www.ercot.com/content/news/presentations/2014/Panhandle%20Renewable%20Energy%20Zone%20Study%20Report.pdf

Step 6 – Estimating Weighted Short Circuit Ratio for all Dispatch Conditions:

After the short circuit strength and WSCR was quantified for each of the 21 selected dispatch conditions the results were used to estimate the WSCR across an entire year of operation. This was completed by evaluating a curve fit relationship between amount of power electronic equipment online and the resulting WSCR (which was quantified in the detailed short circuit strength analysis). The resulting trend line was then applied to each of the 8,760 hourly production cost results to develop an estimated WSCR across each dispatch condition. More information on this step is provided in Section 3.3.

Step 7 – Analyze Potential Mitigations to Low Grid Strength:

The final step of the analysis evaluated one possible mitigation to improve grid strength. Honolulu units 8 and 9 have been decommissioned, though it is understood that the generators are still installed. It is possible that these units may be converted to synchronous condensers to provide additional grid strength to the system. A synchronous condenser is a synchronous generator with an excitation system that is not connected to a prime mover like a gas or steam turbine. It consumes a relatively small amount of power to overcome windage, friction, and electrical losses and can sink or source reactive power to help regulate voltage. Additionally, it contributes to system inertia and grid strength, providing a positive impact on frequency stability evaluated in previous reports as well as on controls stability evaluated in this report.

To quantify the impact of the Honolulu units as synchronous condensers on grid strength, steps 3 and 4 were repeated for the 21 dispatch conditions with the addition of both Honolulu units. The WSCR for each dispatch condition was recalculated and the impact for all hours of year was determined according to the method described in Step 5.

2.2 Scenario Overview

To evaluate the impact of DPV on grid strength, two scenarios were evaluated. Scenario 1 included 400 MW of installed DPV capacity and Scenario 2 had 700 MW of DPV installed. Note that intermediate scenarios were evaluated with incremental 100 MW DPV capacity additions, but only the scenarios with the lowest and highest installed DPV are discussed in this report. Scenario 1 represents the likely installed DPV capacity online by 2017, assuming a continuation of recent trends. Scenario 2 was analyzed to show the impact of increased DPV penetration and was identified as a system hosting capacity limit in a recent PUC docket filing.[3] The hourly chronological solar output profiles were scaled linearly between the two scenarios, and the spinning reserve requirements were adjusted accordingly (see section 2.3 for more information). All other inputs and assumptions were held constant across the scenarios, isolating any changes due to increased DPV penetration.

Figure 2 provides an overview of the installed renewable capacity and available energy (prior to potential curtailment) for each of the scenarios evaluated. In the absence of curtailment, annual wind and solar energy penetration would be between 16% in Scenario 1 to 22% in Scenario 2. It is important to note that while production cost simulations and hourly screening were performed on all four scenarios, only Scenario 1 and Scenario 2 were evaluated in the dynamic simulations to provide a bookend analysis and to limit the number of dynamic simulations required. In addition, the 700 MW of DPV selected in Scenario 2 is not intended to show a maximum amount of DPV on the Oahu grid, but rather to reflect potential near-term growth.

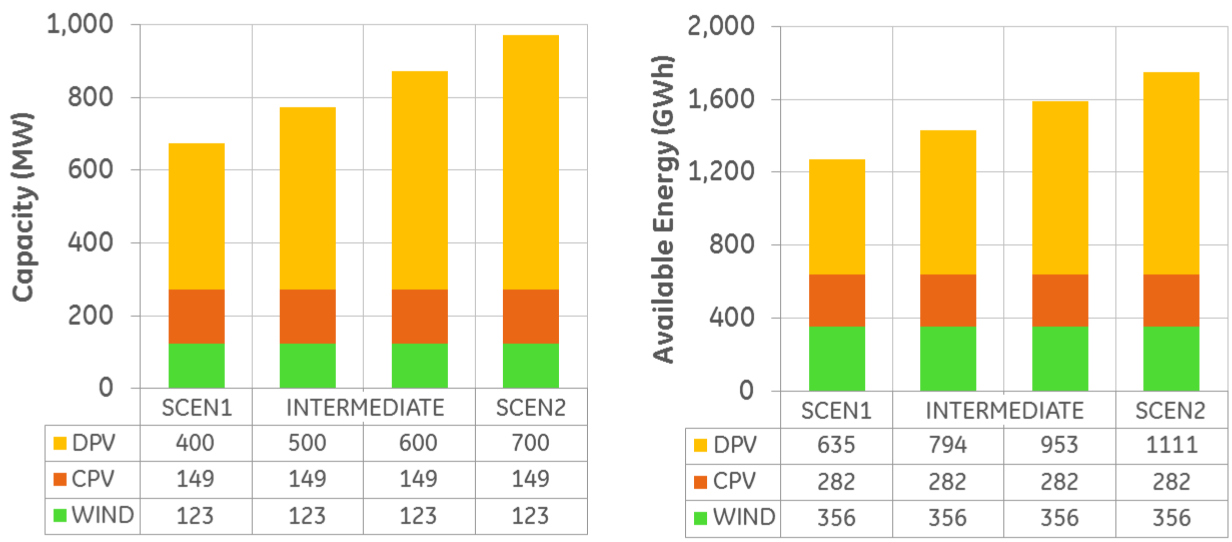

Figure 2: Installed Wind & Solar Capacity & Available Energy by Scenario

[3] Hawaiian Electric Company, "System Level Hosting Capacity," HPUC Docket 2014-0192, Commission Order No. 33258, December 11, 2015.

2.3 Inputs & Assumptions

Each 138kV bus on Oahu is evaluated in the WSCR calculation where the power electronic equipment associated with each HV bus is assumed to be the equipment most closely connected to that high voltage bus. In reality, the system is not completely radial, but has many loops where the power-electronic equipment may be considered “shared” among two or more high-voltage buses. Attributing all of a utility-scale plant to a single bus is one simplification of the WSCR method. The same approach is applied for DPV, but since the DPV is represented as 31 aggregate generators, it may be considered that the proportionate contribution to each high-voltage bus is factored in to the aggregation of the DPV.

The WSCR method assumes that there is complete interaction among power-electronic sources such that many power-electronic sources connected at different point on the network behave as a single, large power electronic source with a rating equal to the sum of the individual ratings. In practice, complete interaction does not happen. This is because there is always some impedance between different sources. Also, different makes, models, and controls on different power electronic equipment will behave differently, so it is unlikely that they will all behave as one device. This is especially true of DPV equipment because for a given MW of power electronic equipment, there is more variety of equipment and more dispersion across the network, including across individual phases.

The assumption that power electronic equipment interacts completely and behaves as one large device with the sum of all the individual ratings is conservative. Any incomplete (non-additive) interaction reduces the “effective” MW rating of the equipment. Carrying this through the WSCR and ZSCR calculations, this assumption causes those numbers to be at the low end of what is theoretically possible, or put another way, portrays the grid as being weaker than it than it most likely would be.

3 ANALYTICAL RESULTS

3.1 Selected Hours for Analysis

In order to adequately quantify the impact of increasing DPV on grid strength a production cost analysis is required to accurately reflect expected changes to unit commitment and dispatch as solar generation increases. The key drivers determining the grid strength of the system are the amount (MVA) of synchronous machines online at a given time and the amount (MVA) of power electronic equipment online at a given time. Both of these values change over the course of the day, and seasonally, to follow changes in system load and wind and solar resource availability. The production cost modeling simulates the changing generation mix and number of units online at different periods to serve load while providing reserves for variability in wind and solar resources and emergency events.

The grid operator is continually balancing the system load and generation, determining the commitment and dispatch of each generator in a least cost manner. This process is simulated by the production cost analysis and is critical to selecting feasible and appropriate dispatch conditions for further short circuit strength analysis. By using the production cost analysis, a wide range of realistic dispatch conditions can be evaluated. The alternative approach, using a static thermal unit commitment for further short circuit strength analysis, may result in infeasible or inappropriate dispatch conditions that may not be an accurate reflection of system operations, especially when used to forecast a future grid with additional renewables.

This study also assumed that all contingency and regulation reserves are provided by thermal units. Thus, reserve requirements also affect unit commitment. If reserves are partially shifted from the thermal unit to other resources, then commitment of thermal units could be lower as wind and solar penetration increases.

Figure 3 shows the results of the production cost analysis for unit commitment. The left chart shows duration curve of the total synchronous commitment (MVA) across the entire year of operation between Scenario 1 and Scenario 2 while the right chart shows the duration curve of the total number of thermal units online at different time periods. Both charts show significant changes in unit commitment over the course of a year, but also that there is relatively little change in unit commitment between the two scenarios as 300 MW of additional DPV is added to the system. In general, Scenario 2 has less thermal units online and lower synchronous commitment due to the increased solar. Note that this is expected to be a non-linear phenomenon, so the results of this study should not be linearly extrapolated to higher renewable penetration scenarios.

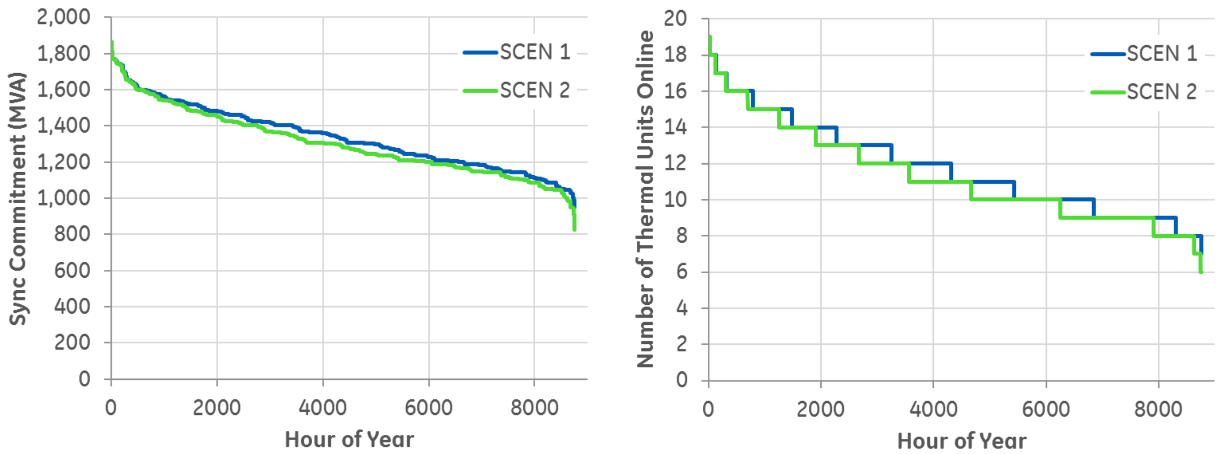

Figure 3: Synchronous Commitment and Number of Thermal Units Online by Scenario

As discussed earlier, grid strength is determined by two main factors:

- The total amount of synchronous generation online, and
- The total amount of power electronic equipment online.

These two factors tend to be inversely related. As the amount of power electronic equipment online increases, the synchronous thermal commitment will generally decrease as fewer thermal units are required to serve load. For this analysis, these two drivers were combined into a single metric, the Power Electronic Ratio (PER), which quantifies the relative amounts of synchronous thermal commitment and power electronic equipment online at any given time. Using the results of the production cost analysis, the PER can be calculated for each dispatch condition across an entire year of operation.

$$Power\ Electronic\ Ratio = \frac{Online\ Power\ Electronic\ MVA\ Capacity}{Total\ Online\ MVA\ Capacity}$$

where the numerator is the sum of the online (generating) MVA rating of the power electronic capacity (including wind, solar, BESS, etc.), and the denominator is the sum of the online MVA rating of synchronous generators and the online MVA rating of power electronic equipment.[4] The Power Electronic Ratio is thus independent of the actual power output (MW) of either the power electronic equipment or the synchronous generators. If the unit is online and generating, the entire MVA rating of the equipment is used for this calculation. As a result, the PER experiences large swings from nighttime hours to daytime hours as the PV flips from offline to online.

Figure 4 illustrates the differences in annual duration curves of the Power Electronic Ratio between Scenario 1 and Scenario 2, as 300 MW of DPV is added to the system. The figure illustrates a clear distinction between daytime hours (PER greater than 30% when both wind

[4] The Power Electronic Ratio (%), which is based on the MVA rating of committed capacity, should not be confused with renewable penetration, which is typically conveyed as a percentage of total load. In general, the PER is typically lower than renewable penetration values.

and solar are online) and nighttime hours (PER less than 10% when PV is offline and only wind is online). The curves also highlight a clear trend of a higher PER in Scenario 2 as more DPV is added to the system. The yellow validation points indicate the 21 dispatch conditions in each scenario that were selected from the production cost results and used in the short circuit analysis. While this selection process was completed in Part 1 of the study, System Frequency Response to Generator Contingency Events, the large range in values analyzed verifies that the selection of 21 operating conditions covers the full range of PER from min to max, with more emphasis on daytime periods when PER is higher.

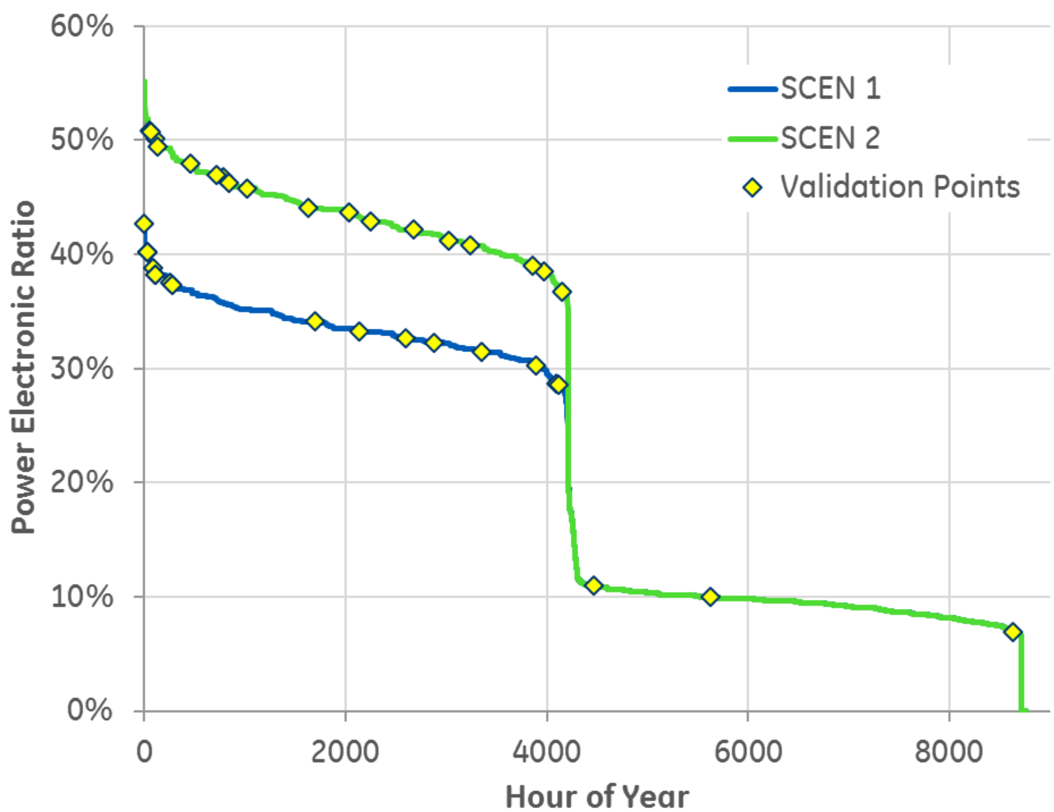

Figure 4: Power Electronic Ratio & Selected Dispatch Conditions

3.2 Grid Strength Results

Using the 21 dispatch conditions selected from the production cost analysis, the short circuit strength and weighted short circuit ratio was calculated to quantify the relative grid strength across different hours and scenarios. To do this, the grid strength of the system due to the connected synchronous machines was calculated at every 138kV bus on Oahu for each of the dispatch conditions. This was done using the GE PSLF software by first disconnecting all of the power-electronic-based generation and then by applying a three-phase short-circuit at each high voltage bus. The resulting short-circuit MVA from PSLF at each bus is fed into the WSCR calculations.

With the short-circuit current from synchronous machines calculated and the MW rating of power-electronic-based generation connected to each high voltage bus is known, the WSCR value is calculated according to a paper produced by ERCOT.[5]

$$WSCR = \frac{Weighted\ \ S_{SCMVA}}{\sum_i^N P_{RMWi}} \quad = \quad \frac{\sum_i^N S_{SCMVAi} * P_{RMWi}}{\left(\sum_i^N P_{RMWi}\right)^2}$$

Where:
S_{SCMVA} is the short circuit capacity at bus i before the connection of power electronic plant I,
P_{RMWi} is MW rating of power electronic plant i to be connected,
N is the number of power electronic plants fulling interacting with each other, and
i is the power electronic plant index.

The result is a single WSCR value for the entire Oahu system for the given dispatch condition. The WSCR is therefore a weighted measure of the overall grid strength and can be used to quantify the risk to the power system from a power electronic controls stability perspective during a disturbance or contingency event (generator trip, transmission line fault, etc). Higher WSCR values are indicative of a stronger grid and lower WSCR values are indicative of a weaker grid, which is at a higher risk of controls instability. While there are many possible ways to quantify grid strength, the WSCR has gained traction across the industry over the past several years as a valuable quantitative measure for power system analysis.

Figure 5 provides the WSCR for each day-time dispatch condition evaluated in Scenario 1 and Scenario 2. The figure shows that WSCR is consistently lower in Scenario 2, which has 300 MW more DPV on the system. The two exceptions to that relationship occur in hours 2197 and 2534, where the WSCR is slightly higher in Scenario 2 compared to Scenario 1. Upon further inspection, this is a result of significant curtailment in those hours. The additional DPV generation forced the curtailment of all available utility-scale wind and solar that was online in Scenario 1. If a plant is curtailed to zero output, the analysis considers the plant to be offline. As a result, there is less power electronic equipment online in those hours, and thus a higher WSCR.

While Figure 5 effectively demonstrates the changes to the system's WSCR, and thus grid strength, as more DPV is added to the system, it does not answer the question of where system stability becomes a realistic concern. Simulations and experience in ERCOT indicates a stability concern at WSCRs below 1.5. However, this measure is highly system specific for wind plants in ERCOT and should not be extrapolated to Hawaii. Differences in the transmission network and types of power electronic inverters will yield very different results with grid disturbances. Instead of quantifying a minimum reliable WSCR, this analysis shows the trend of decreasing WSCR as additional DPV is added to the system and quantifies the extent of the WSCR erosion with a higher level of renewable integration as compared to the existing grid.

[5] Panhandle Renewable Energy Zone Study Report, Prepared by ERCOT System Planning, April 2014
http://www.ercot.com/content/news/presentations/2014/Panhandle%20Renewable%20Energy%20Zone%20Study%20Report.pdf

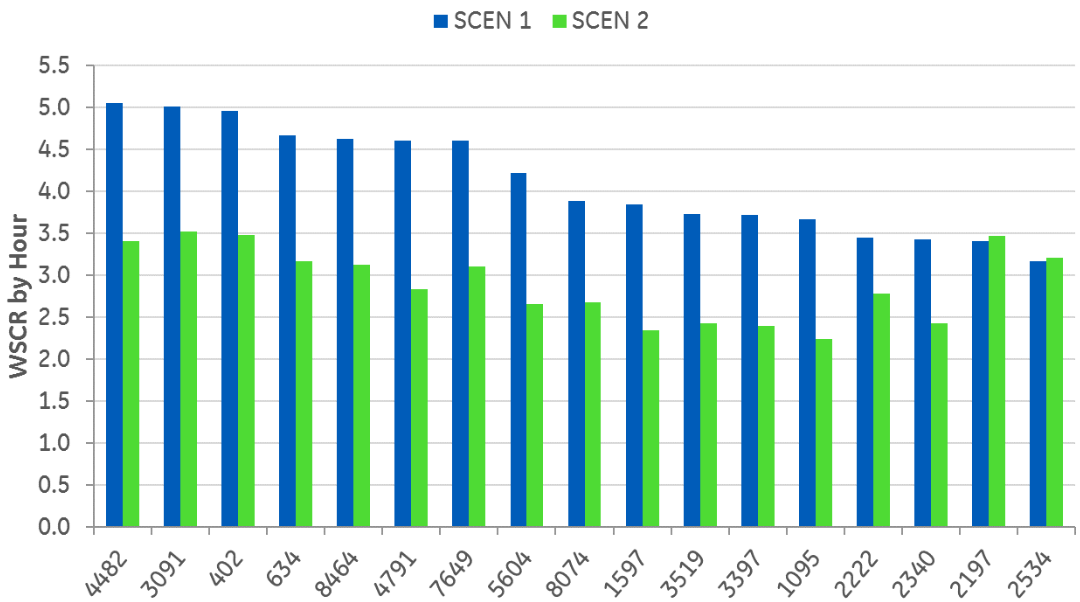

Figure 5: Weighted Short Circuit Ratio by Hour (day-time only)

The WSCR presented in Figure 5 is a system value, representing a weighted average of all high voltage busses on the system. Unlike the frequency stability which does not vary across the system, grid strength varies by location. It can be higher than average at some locations and lower than average at other locations. However, the WSCR method treat the system in aggregate, producing a single number for the entire Oahu system for a given dispatch condition and offering no insight to variation in grid strength across the system from bus to bus. Relative grid strength will vary across the system due to proximity to synchronous generation, amount of power electronic equipment, and overall transmission network connectivity. Therefore, a better understanding of the locational impacts of grid strength is beneficial to planning for future renewable energy development on Oahu.

To provide a better understanding of location specific grid strength, the WSCR method for Oahu is augmented by another approach. This method is called the impedance-weighted SCR or "ZSCR" and is calculated as the ratio of the short-circuit current at a bus from contributions of synchronous machines only (as previously done in for SCR, CSCR, WSCR) divided by the impedance-weighted rating of the power electronic equipment.[6] While this method results in values with only relative meaning and little absolute meaning, it is a useful methodology to compare relative grid strength across different buses.

The results of this calculation are provided in Figure 6, which provides the median daytime ZSCR of each high voltage transmission bus on the system evaluated across the 21 dispatch conditions in Scenario 1 and Scenario 2. Higher values represent higher than average grid

[6] The impedance-weighted rating of the power electronic equipment is determined using the short-circuit function in a load-flow program to apply a 3-phase fault at a given bus after disconnecting all synchronous machines and leaving connected all power electronic equipment. The power-electronic devices are represented by Thevenin-equivalent sources where the generator rating is the rating of the power electronic equipment and the subtransient reactance is set to 1.0.

strength in that region of the grid. While the buses in the chart are sorted from highest grid strength to lowest, the order of the busses also generally follows a geographic trend (measured by electrical distance) going from west to east across the island. Higher grid strength is generally indicated in the western region of Oahu (KAHE, CEIP, AES, HRRP) where most of the large, utility-scale synchronous thermal generation is found. The lower grid strength is found in the eastern region of Oahu (IWILEI, SCHOOL, ARCHER, KEWALO, KOOLAU, KOMOKO, PUKELE) where most of the load and distributed PV is located. In general, the further the distance from the western region's generating plants, the lower the grid strength. The north region (AKU, WAHIAWA) experiences the lowest measures of ZSCR as it is the location of the large-scale utility-scale wind and solar development and electrically distant from the thermal plants.

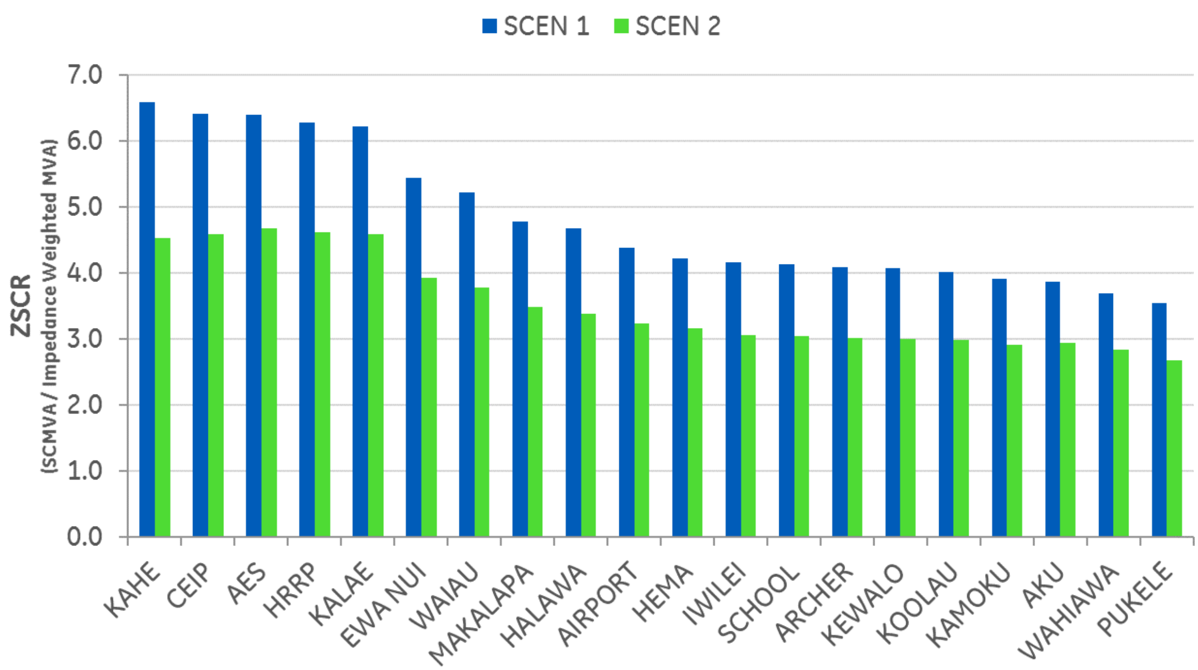

Figure 6: Grid Strength Contribution by Bus (day-time only)

These results raise important considerations for the decision on where to site new distributed or utility-scale renewable generators, the scheduling of synchronous generator retirements, and the location of potential new synchronous condensers. Figure 7 provides a geographic map of the relative ZSCRs evaluated with the location of each high-voltage bus represented. Cooler colors (blues) represent areas with higher grid strength whereas brighter colors (reds) represent areas with lower grid strength. Table 1 provides the raw data underlying the figures throughout this section. In both the map and Table 1 the busses are grouped based on location and thus relative grid strength and characterized by four regions:

- West: location of synchronous generation (High grid strength)
- Central: transition zone between west and east
- East: load center and high distributed PV (Low grid strength)
- North: utility-scale renewable interconnections (Low grid strength)

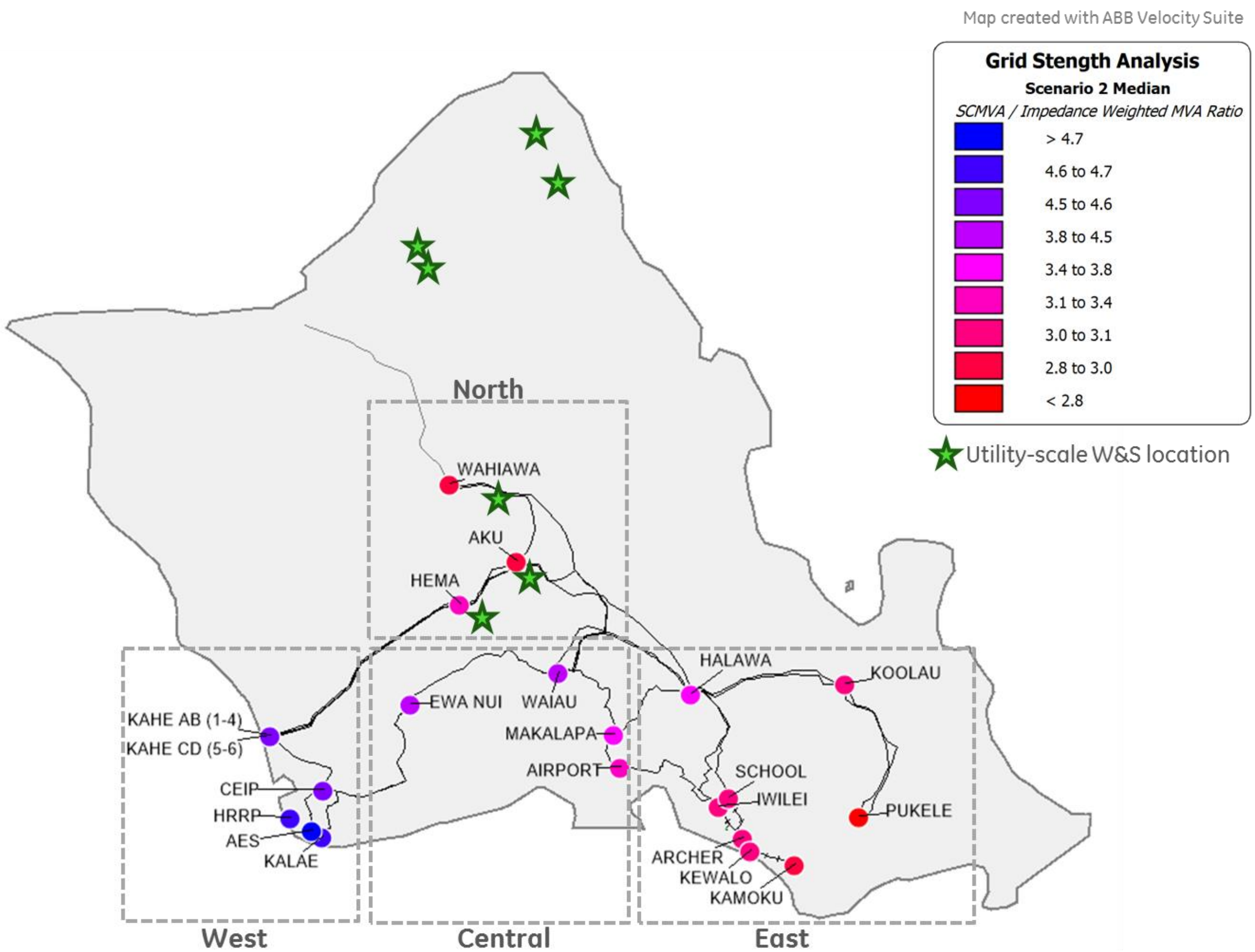

Figure 7: Map of Grid Strength Contribution by Bus

Table 1: WSCR by Hour and Grid Strength Contribution by Bus

West ——— Central ———> East North

Day-Time Scenario 1 Hours

Hour	AES	CEIP	HRRP	KALAE	KAHE	EWANUI	WAIAU	MAKALAPA	AIRPORT	HALAWA	SCHOOL	IWILEI	ARCHER	KEWALO	KAMOKU	KOOLAU	PUKELE	HEMA	AKU	WAHIAWA	WSCR
4482	9.5	9.3	9.2	9.2	9.1	7.8	8.1	6.9	6.2	6.5	5.6	5.7	5.5	5.5	5.2	5.5	4.7	5.4	5.0	4.8	5.0
3091	9.8	9.6	9.6	9.5	9.3	8.0	8.2	7.1	6.3	6.6	5.7	5.8	5.6	5.6	5.4	5.6	4.8	5.5	5.1	5.0	5.0
402	8.7	8.8	8.5	8.6	8.9	7.5	7.9	6.8	6.1	6.4	5.6	5.6	5.5	5.4	5.2	5.5	4.7	5.3	4.9	4.8	4.9
634	7.6	7.8	7.5	7.5	8.1	6.8	7.2	6.3	5.6	5.9	5.2	5.2	5.1	5.1	4.9	5.1	4.4	5.0	4.6	4.5	4.6
8464	7.8	7.9	7.7	7.6	8.1	6.8	7.1	6.2	5.5	5.8	5.1	5.2	5.0	5.0	4.8	5.0	4.3	5.0	4.6	4.5	4.6
4791	7.6	7.5	7.4	7.5	7.5	6.4	6.6	5.7	5.2	5.4	4.8	4.8	4.7	4.7	4.5	4.7	4.1	4.6	4.3	4.2	4.6
7649	8.5	8.5	8.3	8.3	8.6	6.9	6.7	6.0	5.4	5.8	5.1	5.1	5.0	5.0	4.8	4.9	4.3	5.0	4.6	4.5	4.5
5604	7.1	7.0	6.9	6.9	7.0	5.6	5.2	4.8	4.4	4.7	4.1	4.2	4.1	4.1	3.9	4.0	3.5	4.2	3.9	3.7	4.2
1597	5.8	5.7	5.7	5.7	5.7	4.8	4.6	4.2	3.9	4.1	3.7	3.7	3.6	3.6	3.5	3.6	3.2	3.7	3.4	3.3	3.8
8074	6.3	6.3	6.2	6.2	6.5	5.4	5.3	4.8	4.4	4.7	4.2	4.2	4.1	4.1	4.0	4.1	3.6	4.2	3.9	3.8	3.8
3397	5.8	5.7	5.7	5.7	5.5	4.8	4.7	4.3	3.9	4.1	3.7	3.7	3.7	3.7	3.5	3.6	3.2	3.7	3.4	3.3	3.7
3519	6.0	5.9	5.9	5.9	5.8	5.0	4.9	4.4	4.1	4.3	3.9	3.9	3.8	3.8	3.7	3.8	3.4	3.8	3.6	3.5	3.7
1095	5.7	5.5	5.6	5.6	5.3	4.8	4.7	4.3	4.0	4.1	3.7	3.7	3.7	3.7	3.5	3.7	3.3	3.6	3.4	3.3	3.6
2222	5.0	4.9	4.9	4.9	4.8	4.1	3.9	3.6	3.3	3.5	3.2	3.2	3.2	3.1	3.0	3.1	2.8	3.2	3.0	2.9	3.4
2340	5.3	5.1	5.2	5.2	5.0	4.3	4.1	3.8	3.5	3.7	3.4	3.4	3.3	3.3	3.2	3.3	3.0	3.4	3.2	3.1	3.4
2197	5.0	4.8	4.9	4.9	4.7	4.1	3.8	3.6	3.3	3.5	3.2	3.2	3.1	3.1	3.0	3.1	2.8	3.2	3.0	2.9	3.4
2534	4.7	4.5	4.6	4.6	4.3	3.9	3.6	3.4	3.2	3.3	3.0	3.1	3.0	3.0	2.9	3.0	2.7	3.1	2.9	2.8	3.1

Day-Time Scenario 2 Hours

Hour	AES	CEIP	HRRP	KALAE	KAHE	EWANUI	WAIAU	MAKALAPA	AIRPORT	HALAWA	SCHOOL	IWILEI	ARCHER	KEWALO	KAMOKU	KOOLAU	PUKELE	HEMA	AKU	WAHIAWA	WSCR
3091	7.3	7.1	7.1	7.1	6.9	5.9	6.0	5.2	4.6	4.9	4.2	4.3	4.2	4.1	4.0	4.2	3.6	4.2	3.9	3.7	3.5
2197	5.1	5.0	5.0	5.0	4.9	4.2	3.9	3.6	3.4	3.5	3.2	3.2	3.1	3.1	3.0	3.1	2.8	3.4	3.2	3.1	3.4
402	6.5	6.5	6.4	6.4	6.6	5.6	5.8	5.0	4.5	4.7	4.1	4.1	4.0	4.0	3.8	4.0	3.5	4.0	3.7	3.6	3.4
4482	6.4	6.4	6.3	6.3	6.3	5.4	5.7	4.9	4.4	4.6	4.0	4.0	3.9	3.9	3.8	4.0	3.4	3.9	3.7	3.5	3.4
2534	4.7	4.5	4.7	4.6	4.4	3.9	3.6	3.4	3.2	3.3	3.0	3.0	3.0	3.0	2.9	2.9	2.7	3.2	3.0	2.9	3.2
634	5.5	5.6	5.4	5.5	5.8	4.9	5.0	4.4	4.0	4.2	3.7	3.7	3.7	3.6	3.5	3.6	3.2	3.7	3.4	3.3	3.1
8464	5.6	5.6	5.5	5.4	5.7	4.8	4.8	4.3	3.9	4.1	3.6	3.6	3.6	3.5	3.4	3.5	3.1	3.6	3.3	3.2	3.1
7649	6.2	6.1	6.0	6.0	6.2	4.9	4.7	4.2	3.9	4.1	3.6	3.6	3.6	3.5	3.4	3.5	3.1	3.7	3.4	3.3	3.1
4791	5.1	5.0	5.0	5.0	4.9	4.1	4.0	3.6	3.3	3.5	3.1	3.1	3.1	3.1	3.0	3.0	2.7	3.2	3.0	2.8	2.8
2222	4.2	4.0	4.1	4.1	3.9	3.4	3.2	3.0	2.8	2.9	2.6	2.7	2.6	2.6	2.5	2.6	2.4	2.8	2.6	2.5	2.8
5604	4.7	4.5	4.6	4.6	4.5	3.7	3.5	3.2	3.0	3.1	2.8	2.8	2.8	2.8	2.7	2.7	2.5	2.9	2.7	2.6	2.7
8074	4.6	4.6	4.5	4.5	4.6	3.9	3.9	3.5	3.3	3.4	3.1	3.1	3.0	3.0	2.9	3.0	2.7	3.1	2.9	2.8	2.6
6087	4.4	4.3	4.3	4.3	4.2	3.6	3.3	3.1	2.9	3.0	2.7	2.7	2.7	2.7	2.6	2.7	2.4	2.8	2.6	2.5	2.6
2340	3.9	3.8	3.9	3.9	3.6	3.2	3.0	2.8	2.6	2.7	2.5	2.5	2.5	2.5	2.4	2.5	2.2	2.6	2.5	2.4	2.4
3519	4.1	4.0	4.1	4.1	3.8	3.4	3.3	3.0	2.8	2.9	2.7	2.7	2.7	2.6	2.6	2.6	2.4	2.7	2.6	2.5	2.4
3397	3.9	3.7	3.8	3.8	3.5	3.2	3.1	2.9	2.7	2.8	2.6	2.6	2.5	2.5	2.5	2.5	2.3	2.6	2.5	2.4	2.4
1597	3.8	3.7	3.8	3.8	3.6	3.1	2.8	2.6	2.5	2.6	2.4	2.4	2.4	2.4	2.3	2.3	2.1	2.5	2.4	2.3	2.4
1095	3.8	3.6	3.7	3.7	3.5	3.1	2.9	2.7	2.5	2.6	2.4	2.4	2.4	2.4	2.3	2.4	2.2	2.5	2.3	2.3	2.2

Night-Time Hours

Hour	AES	CEIP	HRRP	KALAE	KAHE	EWANUI	WAIAU	MAKALAPA	AIRPORT	HALAWA	SCHOOL	IWILEI	ARCHER	KEWALO	KAMOKU	KOOLAU	PUKELE	HEMA	AKU	WAHIAWA	WSCR
7244	63.86	63.68	62.03	61.27	64.69	51.62	52.83	46.17	40.75	44.17	37.80	38.18	37.24	36.88	35.04	37.11	30.77	34.93	31.77	30.14	28.2
1184	91.66	91.51	89.91	88.98	90.40	82.09	87.56	77.80	69.95	73.75	65.09	65.78	64.25	63.85	61.06	64.63	54.76	59.36	55.72	54.58	23.6
964	37.65	36.94	36.98	36.83	36.39	31.30	30.34	28.05	25.83	27.47	24.60	24.78	24.34	24.18	23.27	23.96	20.78	23.77	22.16	21.37	17.5

3.3 Estimating Grid Strength

Results from the 21 dispatch conditions presented in Section 3.2 provide valuable insights to the grid strength across the hours evaluated. However, it is also important to consider all hours across the year because grid stability must be maintained at all times. Similar to the analysis conducted in Parts 1 and 2 of this study, the simulated results from sampled dispatch conditions were used to determine a mathematical relationship (equation) that could be used to estimate WSCR at any given system dispatch from its PER. In this case, a power regression was estimated between the WSCR from the 21 dispatch conditions analyzed, and the Power Electronic Ratio (discussed earlier in Section 3.1) for each hour. A regression assumed a power function because of the underlying calculation of WSCR. If there is no power electronic equipment on the system, the WSCR would approach infinity whereas if there was only power electronic equipment on the system, the WSCR would approach zero, thus following a power trend.

The resulting trend between the WSCR and the Power Electronic Ratio, presented in Figure 8, can be used to estimate the WSCR for all 8,760 hourly dispatch conditions analyzed in the production cost analysis, without completing a rigorous power flow analysis each time. In the future, this trend could also be used to create operating rules regarding the amount of synchronous commitment required for a given amount of power electronic equipment online across the system. While Figure 8 provides a representation of the WSCR and PER across a wide range of operations, it is only the lower WSCR that are of concern for system stability. Therefore, the same chart is provided with a zoomed-in view of the lower WSCR region of the trend line in Figure 9. From these figures it can be determined that:

- There is a strong relationship between the system's WSCR and the Power Electronic Ratio (MVA rating of the power electronic equipment online divided by the MVA rating of all generation online).
- For example, a PER of 50%, which would indicate 1 MVA of power electronic equipment online for every 1 MVA of synchronous generation online, would yield a WSCR of approximately 2.5.
- On Oahu, there is a clear difference between nighttime hours (exceeding a WSCR of 15) and daytime hours (WSCR less than 5) due to the amount of PV inverters that come online during the day, however the PER is still an accurate predictor of both time periods evaluated.
- The function, $y = 1.01x^{-1.31}$, can be used to estimate the WSCR across any hour of operation given a quick calculation of the Power Electronic Ratio.
- As the amount of power electronic equipment on the system increases, there will be a continued decrease in WSCR and grid strength absent other changes to the system.

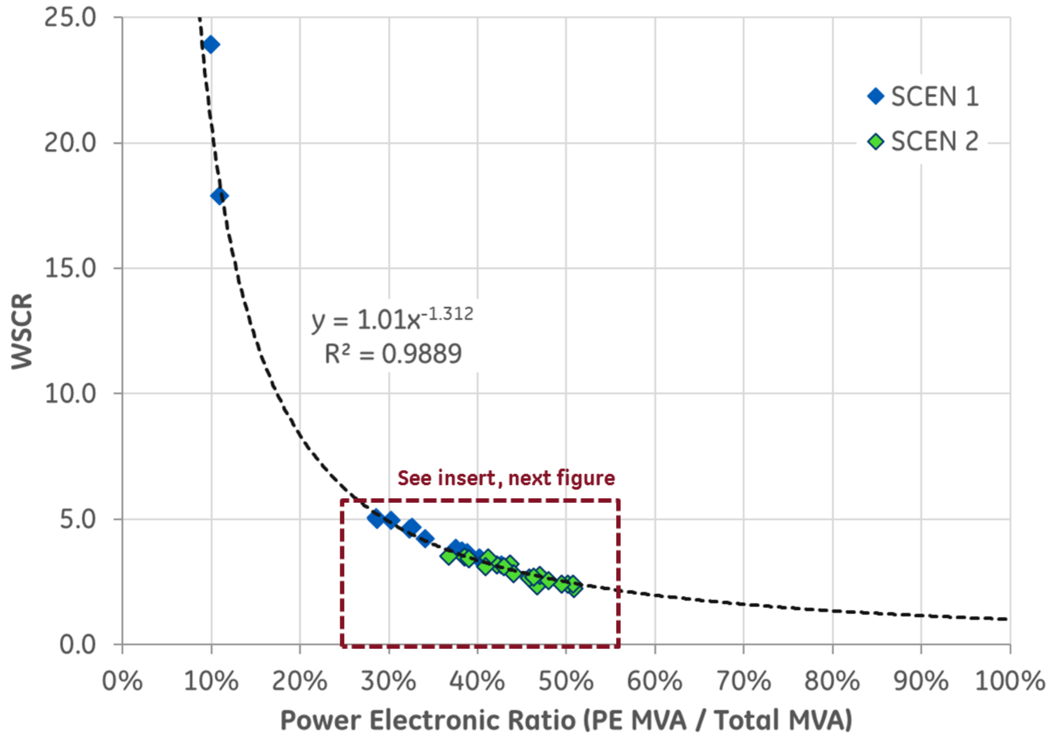

Figure 8: Regression of WSCR as a Function of Power Electronic Ratio (all hours)

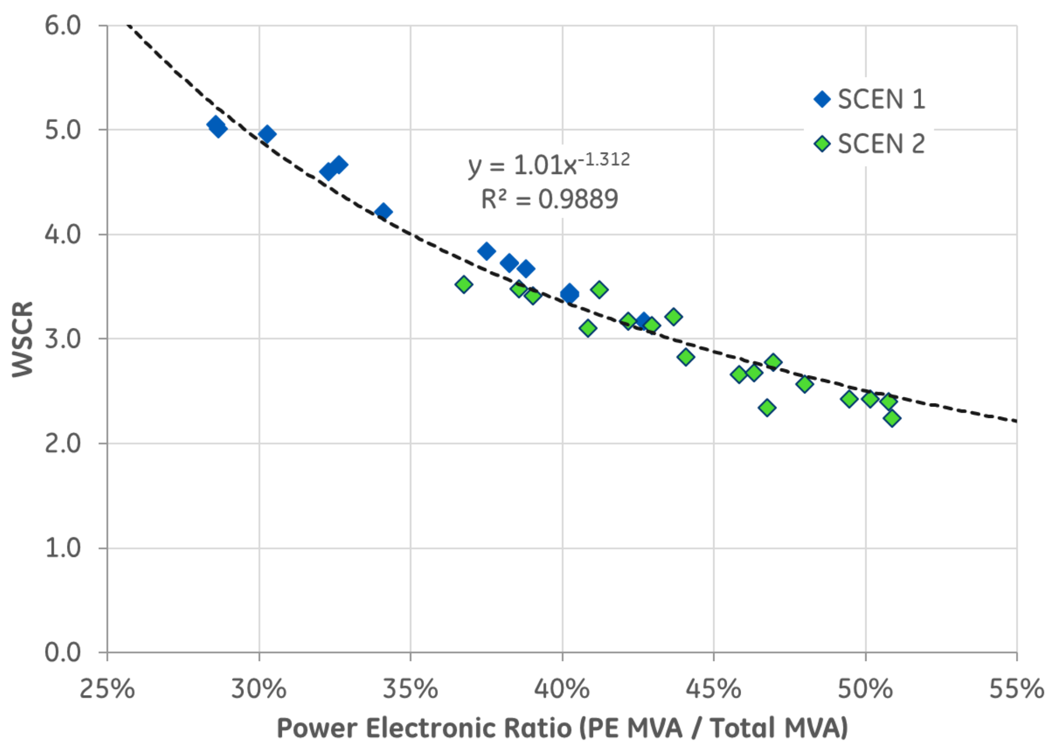

Figure 9: Regression of WSCR as a Function of Power Electronic Ratio (day-time only)

Using the trend line calculated in Figure 8, the WSCR was calculated for all hours of the year using the 8,760 hourly production cost results for Scenario 1 and Scenario 2. The results of this calculation are summarized in duration curves (Figure 10) and histograms (Figure 11). The left chart in each figure provides the results over the course of the entire year, analyzing both daytime and nighttime hours. The right chart in each figure provides a zoomed-in view of daytime hours only.

These charts indicate that there is a significant reduction in WSCR from nighttime to daytime hours. This is specific to the scenarios analyzed, which had significantly more PV inverter capacity versus wind. A scenario with additional wind penetration would also reduce WSCR during nighttime hours when the wind is online.

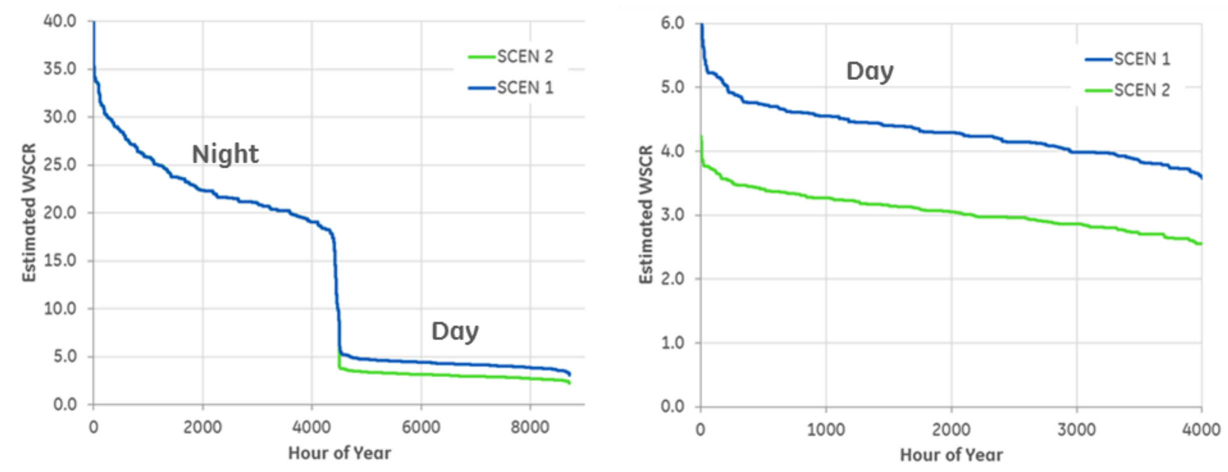

Figure 10: Duration Curves of Estimated WSCR by Scenario

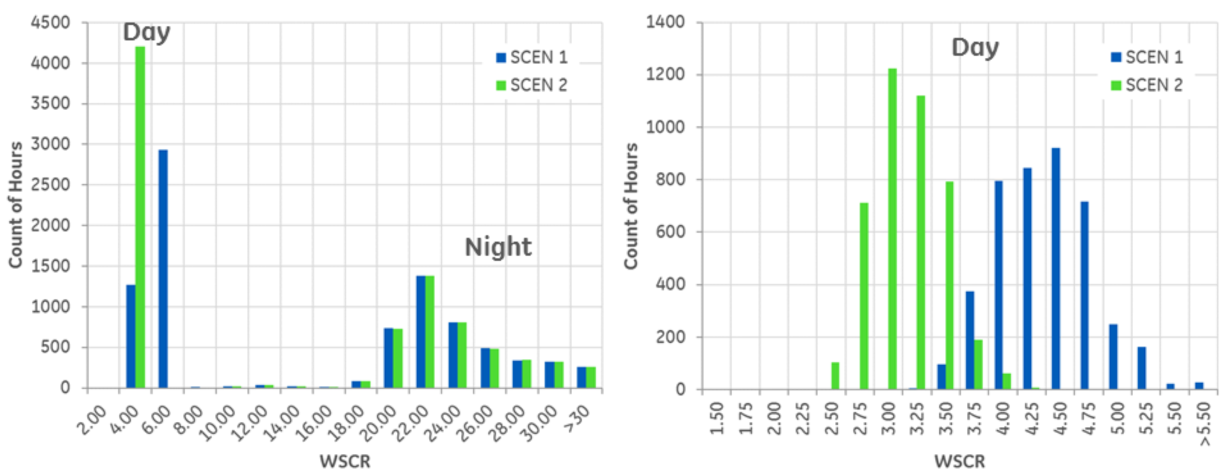

Figure 11: Histogram of Estimated WSCR by Scenario

3.4 Synchronous Condenser Sensitivity

One possible mitigation to increase the system grid strength is the addition of synchronous condensers on the grid. A synchronous condenser is a synchronous generator with an excitation system that is not connected to a prime mover like a gas or steam turbine. It consumes a relatively small amount of power to overcome windage, friction, and electrical losses and can sink or source reactive power to help regulate voltage. As a result, synchronous condensers can provide valuable reactive power and short-circuit strength without the need to utilize a conventional generator, which requires fuel and reduces the grid's ability to absorb additional renewables.

To illustrate the value of the synchronous condenser mitigation, the WSCR analysis was repeated with Honolulu 8 and 9 generating units (64 MVA each) retrofitted to enable operation as synchronous condensers. Honolulu 8 and 9 were selected for this analysis because they are already decommissioned generators, so much of the equipment is already available for repurposing, thus reducing the required capital costs. In addition, Honolulu 8 and 9 are located in a region of the grid with relatively lower grid strength (low short-circuit MVA, large power electronic capacity from DPV, and high load.

The results of the Honolulu 8 & 9 synchronous condenser sensitivity are provided in Figure 12, which shows the system WSCR for Scenario 1, Scenario 2, and Scenario 2 with the additional synchronous condensers. The results indicate that synchronous condensers increase WSCR by approximately 5-10%. This indicates that synchronous condensers are beneficial to grid strength. However, the effectiveness of this approach depends on the ratings of the synchronous condensers and their location on the grid.

As discussed previously, because system strength varies by location on the system, the efficacy of the synchronous condenser mitigation will also vary by location. In general, areas of the grid that are electrically closer to the synchronous condensers will experience a larger benefit relative to regions further away. Figure 13 provides the percent change of the SCMVA / Impedance Weighted MVA ratio with the addition of Honolulu 8 & 9 synchronous condenser. The larger the increase, the more benefit to grid strength. The geographic representation of these results is also provided in the map in Figure 14, with buses colored in darker shades of green representing areas that experienced higher benefit from the synchronous condenser (demarcated by the yellow star). As expected, the busses in closest electrical proximity to Honolulu 8 & 9 experienced the largest benefit from the mitigation.

While the grid operator can utilize additional synchronous condensers to increase grid support, they should not be viewed as a complete solution to solve weak grid issues, other mitigations, including inverter technology development will be required. These mitigations are discussed further in Section 4.2.

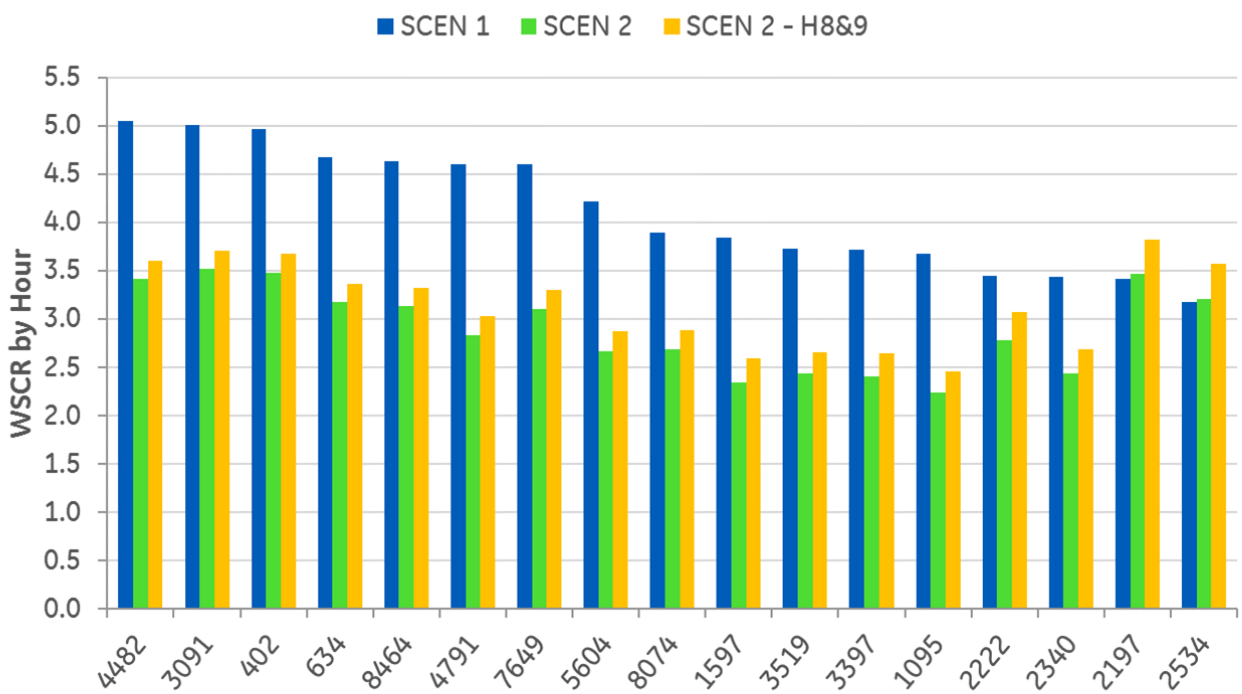

Figure 12: Weighted Short Circuit Ratio by Hour with Synchronous Condensers

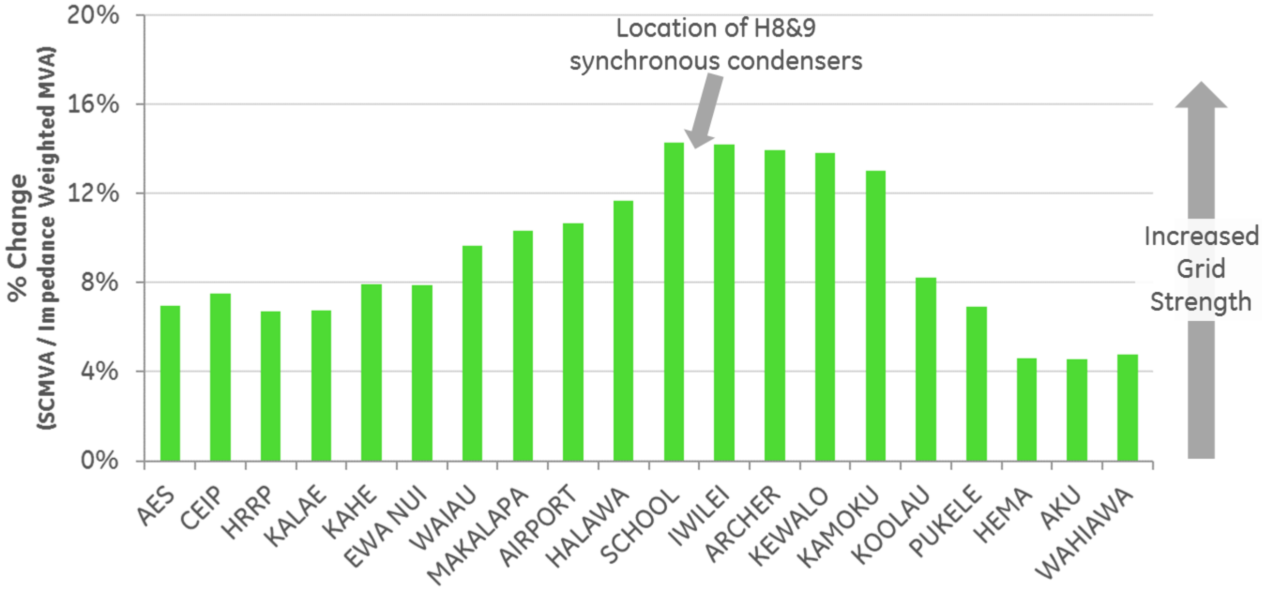

Figure 13: Percent Change in Grid Strength by Location with Synchronous Condensers

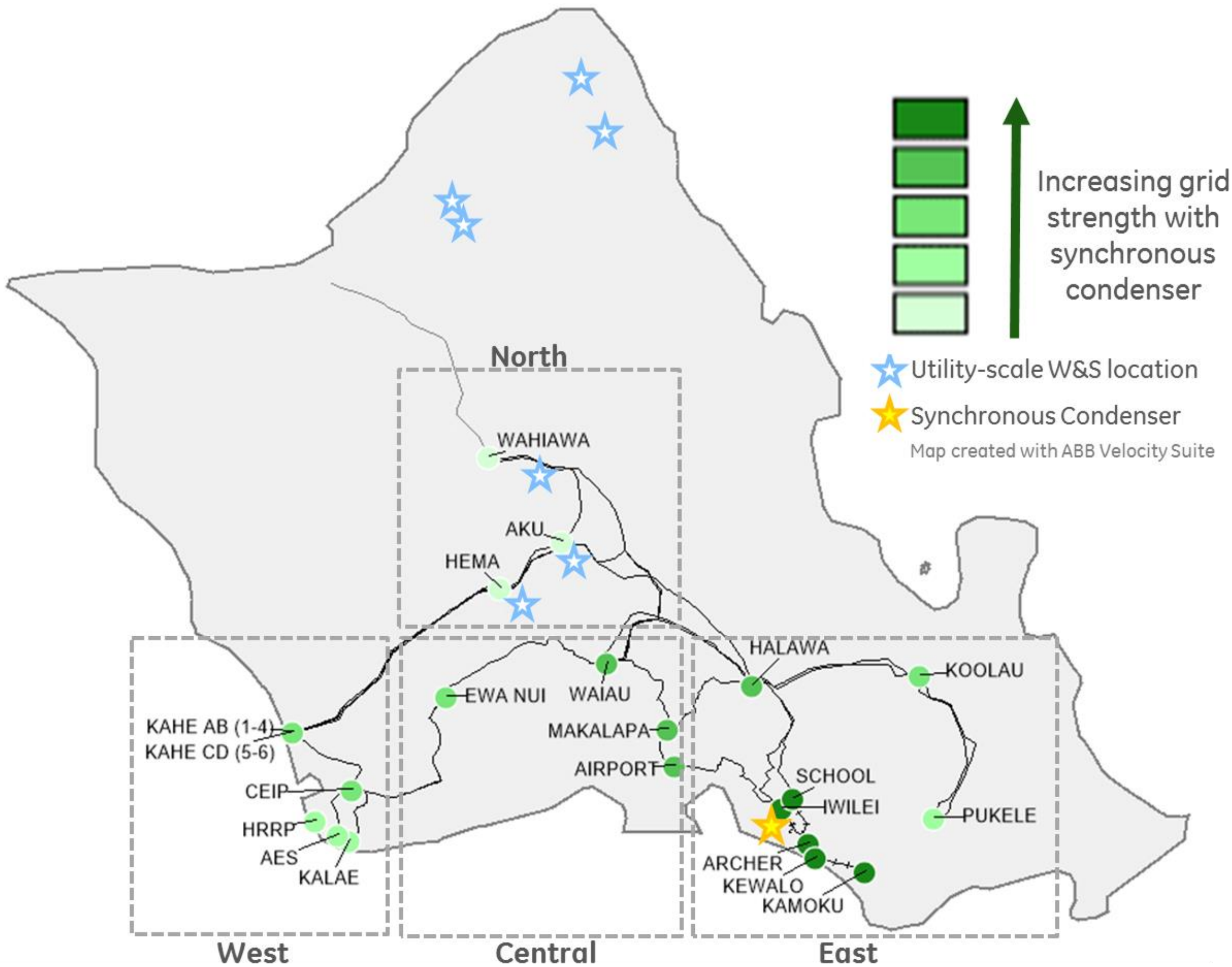

Figure 14: Map of Synchronous Condenser Grid Strength Benefits by Bus

4 KEY FINDINGS & RECOMMENDATIONS

4.1 Key Findings

The overall grid strength of the Oahu system is trending down as increasing power-electronic-based generation displaces synchronous-based generation during many hours of the year. The increase of power-electronic sources is primarily driven by the growth of distributed PV and, to a lesser extent, by utility-scale wind and PV. The risk to the system can be coarsely quantified using WSCR, which accounts for the grid strength provided by the synchronous machines and the penetration of power-electronic-based sources. WSCR is trending lower (indicative of higher risk to the system) as the two primary factors of increasing power-electronics and decreasing synchronous machines work together to weaken the grid.

Two general trends are observed in how grid strength varies with time:

- Grid strength is lowest during the daytime (when all wind and solar resources are online) and significantly higher at night (when solar resources are off).
- Grid strength is lower on weekends than on weekdays. Weekends have the same amount of wind and solar generation, but the lower weekend loads require less energy and fewer thermal plants are online.

However, the decommitment of synchronous machines does not show up significantly in the scenarios evaluated because of the spinning reserve requirement. As renewable penetration increases further, and additional decommitment takes place, the WSCR will erode further.

It should be noted that increased midday risk relative to overnight periods is specific to the current Oahu resource mix and other systems that have significantly more solar capacity installed relative to wind. If the amount of wind penetration increases further (with the addition of off-shore wind for example), then the overnight periods will also experience an erosion to grid strength.

The locations on the power system that are most affected include the East and North areas of Oahu. Specifically, the high voltage busses east of HALAWA and SCHOOL and north of HEMA have the lowest grid strength in the cases analyzed. These areas have the highest "electrical distance" between those buses and the majority of the synchronous machines that are located on the West area of the island. The North area is also the interconnection point of the majority of the utility-scale renewables and the East area is also the area with the highest DPV and system load.

While the analysis conducted in this study provides valuable information on the expected trends in grid strength and an indication to the specific areas of concern, it did not attempt to establish a minimum threshold to system WSCR similar to what was recently done in the Panhandle region of ERCOT. There are several reasons for this:

- The Oahu system is significantly more complex. Where the Texas panhandle has fewer than one hundred transmission-connected wind plants from only a few different vendors, the Oahu grid has thousands (or tens of thousands) of individual inverters spread over both the high-voltage transmission system and the low-voltage distribution feeders.

- Weak grid performance of wind turbines is well understood. Control instabilities emerged years ago and the manufacturers have responded by improving control designs to achieve stable performance under weaker and weaker grid conditions. This is not the case, currently, for DPV inverters.

DPV performance on weak grids is essentially unknown at this point in time. With little information from DPV inverter vendors on how control performance is affected by grid impedance, it is impossible to say how weak a grid the DPV can withstand. While it is not presently practical to quantify at what point WSCR becomes an unacceptable risk to system stability, the trend is clear. As additional power electronic equipment is added to the system and the utilization of conventional synchronous generators is reduced, the grid strength will continue to decline. Absent mitigations, the point at which the grid strength becomes too low is not so much a question of “if”, but rather a matter of “when.” This does not mean grid instability is inevitable, nor does it mean the growth of power electronic renewable generation should be moderated. There are several possible mitigations, discussed in the following section, that can be addressed via technological and policy advancements to reduce the risk to grid stability.

4.2 Recommendations

While this analysis does not determine minimum thresholds of WSCR and grid stability, the trend is clear. Eventually, regardless of the minimum threshold of grid stability, the issue of grid strength will have to be addressed. Absent other mitigations, the grid operator will have to increase the number of synchronous thermal units online to maintain grid strength. The decision on whether or not to commit or de-commit a unit is largely an economic decision while taking into account operational constraints and stability considerations. While keeping extra synchronous generators online will benefit grid strength, there is an economic cost of doing so. Over-commitment, resulting in more synchronous generators online than necessary, creates two potential inefficiencies. With additional thermal generators online, units are backed down to lower power output relative to the unit’s maximum operating level. In general, the lower the loading level, the less efficient the unit is, requiring additional fuel consumption per MWh of power produced. In addition, if units are unable to reduce power output further due to minimum stable operating constraints, additional wind and solar may not be able to be accepted by the grid due to over-supply. This wind and solar energy is thus curtailed in lieu of expensive, oil-fired generation.

In order to avoid over-commitment of synchronous thermal generators, the decline in grid strength can be mitigated from two different, but complementary approaches:

- By using inverter-side solutions that allow power electronic equipment to maintain stable operation at lower and lower levels of grid strength. (Note: This has essentially been achieved for wind generation, but similar understanding of DPV performance is lagging far behind.)
- By using grid-side solutions to increase the grid strength on the system via synchronous generators and condensers (as illustrated in Section 3.4).

The most immediate need to address potential weak grid instability is more information about DPV inverters. Historically weak grid issues have been confined to remote regions of large interconnected grids where utility-scale wind is located. On the other hand, typically DPV has been installed on strong regions of grids with relatively low penetration levels. As a result, weak-grid issues have not been a concern for the DPV community and there is a general lack of publicly available information regarding the weak grid performance of DPV inverters. This is the single biggest roadblock to better understanding of potential weak grid issues in Hawaii.

DPV inverter manufacturers should conduct tests to evaluate the performance of their products on weak (high impedance) grid systems and provide the resulting data to the industry. If control stability or other performance problems are uncovered, the DPV inverter manufacturers could follow a similar path as the wind turbine vendors to modify control designs and thereby improve weak grid performance.

Eventually this should lead to grid code and inverter interconnection requirements, similar to the frequency ride-through and low-voltage ride through requirements outlined in Hawaii Rule 14H, California Rule 21, and UL 1741.

As Oahu continues to increase the amount of power electronic equipment on the system to achieve RPS targets, mitigations to increase the WSCR and grid strength should be implemented to avoid stability concerns. In general, there are two categories of mitigations available to the grid operator to increase grid strength:

- **Inverter technology development:** Even with the introduction of synchronous condensers, the WSCR will continue to decline as additional power electronic equipment is added to the system. As a result, inverter technology must evolve to maintain stable operation in weaker and weaker grids. In recent years, utility-scale wind inverters have progressed considerably to operate in low WSCR environments in remote regions of the grid where this has historically been a concern. There is no fundamental barrier or physical limitation to a 100% inverter based grid, as long as controls are appropriately configured. However, this is not the status of current inverter technology. There is less industry experience regarding DPV inverters interconnected to a weak grid and thus much less is known regarding their operation in such environments. More information on DPV performance is urgently needed.

- **Utilization of synchronous machines:** One option to increase grid strength and increase WSCR is to commit additional synchronous generators (or implementing must-run practices). This has been the conventional practice of operating a stable power system in Hawaii and other regions where grid stability is challenged. However, this approach requires fuel consumption and may lead to curtailment of wind and solar generation, imposing significant economic and environmental costs on the system. While it would alleviate grid stability concerns, this mitigation should be utilized sparingly and as a short-term solution only unless cost-effective renewable fuels (biodiesel, biomass, waste, etc.) are available.

  An alternative to additional synchronous generation is implementation of synchronous condensers at critical areas of the grid. A synchronous condenser is a synchronous generator with an excitation system that is not connected to a prime mover like a gas or steam turbine. It consumes a relatively small amount of power (and no fuel) to overcome windage, friction, and electrical losses and can sink or source reactive power to help regulate voltage. As a result, synchronous condensers can provide valuable reactive power and short-circuit strength without the need to utilize a conventional generator, which requires fuel and reduces the grid's ability to absorb additional renewables.

A grid operator has the option to install new synchronous condensers or refurbish retired generators into synchronous condensers. The later has the advantage of lower capital costs for equipment as much of the original generator can be repurposed. It also does not require new site development or new grid interconnection. This mitigation is therefore a prudent use of older generators that may not be required for energy as new renewable sources come online, but can still be used to provide grid supportive functionality. However, it should be noted that the results of the sensitivity analysis conducted for this study indicate that this is not a "silver-bullet" solution that can be pursued in isolation to other mitigations.

In addition, new generators can be added to the system that would combine the synchronous generation and condenser approach allows the grid operator to provide only grid strength when need for power is low, but also gives the ability to generate power and operate as a conventional generator when necessary. To do this, generators could be designed with clutches, which allows the generator to switch quickly between generation mode (producing both real and reactive power) and synchronous condenser mode (producing only reactive power and contributing to grid strength).

Figure 15 illustrates the long-term transition of mitigations required to operate a future grid with potentially 100% power electronic equipment. While some degree of synchronous machine support is likely in even a 100% renewable future, the solution to weak grid operations is ultimately through inverter technology development. However, continuing to rely on synchronous machine support (either via conventional generators, synchronous condensers, or including clutches on new generators) is a prudent near-term solution as inverter technology improves and the power system transitions to a 100% renewable future and largely power electronic system.

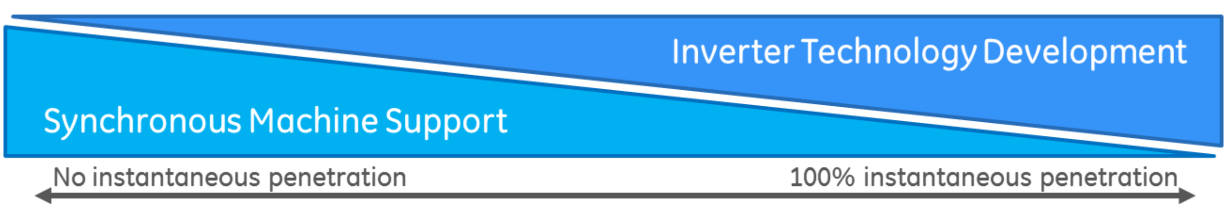

Figure 15: Long-Term Transition of Grid Strength Mitigations

4.3 Future Research

While the analysis outlined throughout this report provides valuable insight to grid stability concerns on Oahu with increasing DPV, other questions critical to assessing grid stability remain. It is therefore suggested that the following items be evaluated in future study work, as the islands strive forward towards meeting the RPS goals. Much of this material will be covered in future stages of this study using a similar modeling approach and project team.

- **Valuing Ancillary Services from Distributed Energy Resources:** As conventional generation is displaced by wind, solar, and other renewables, many of the ancillary services will no longer be provided by synchronous machines. As a result, it will be crucial that these grid supportive functions be provided in novel ways from a variety of sources. More information regarding the type, size, and costs of ancillary services should be investigated in a renewable energy future.
- **Synthetic Inertia:** The over-frequency droop mitigation evaluated in this study simulated governor controls only and did not evaluate the capability of renewables, storage, or demand response to provide synthetic inertia. Synthetic inertia would improve the stability of the grid for contingency events like generation and load trips by providing a fast-responding, stabilizing injection or absorption of power at the onset of the event and should be evaluated further.
- **Higher Renewable Penetration:** While this study evaluated a doubling of solar capacity on Oahu, annual wind and solar energy penetration remained below 25% and well below future RPS targets. Scenarios with higher renewable penetration must be evaluated to determine frequency response at higher penetration.
- **Evaluate Different Systems:** The quadratic equation formulated in this study proved to be a good predictor of frequency response. However, it is unique to the current Oahu grid configuration. As the thermal resource mix on Oahu changes or this analysis is extended to neighboring islands, the metric needs to be recalibrated based on additional dynamic simulations.
- **Grid Support from Wind & Solar:** While not evaluated in this study, curtailed utility-scale wind and solar can provide under-frequency governor response for generator trip events. While curtailing wind and solar specifically to provide this ancillary service may not be economic, utilizing already curtailed generation due to other constraints could increase grid security.
- **Examine Mitigations:** Although grid stability with increasing DPV penetration can be effectively mitigated with over-frequency droop controls, several additional mitigations should be evaluated to improve frequency response, reduce UFLS, and increase grid stability. Such mitigations could include demand response, energy storage, electric vehicles, dynamic UFLS schemes, minimum number of units online, and spinning reserve adjustments.