Lessons Learned: Planning and Operating Power Systems with Large Amounts of Renewable Energy-Based Power Generation

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Hawai‘i Distributed Energy Resource Technologies for Energy Security

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Project Implementation Plan

Prepared by

Sentech, Inc., a part of SRA International

And submitted to

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

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I. Purpose/Objective

The Hawaiian Electric Industries (HEI) utilities—Hawaiian Electric Company (HECO, serving Oahu), Maui Electric Company (MECO, serving Maui) and Hawaiian Electric Light Company (HELCO, serving the Big Island of Hawaii)—have experience with large amounts of renewable energy. In addition to operating experience, they have conducted planning studies and simulations. Their experiences are also relevant to microgrid operations.

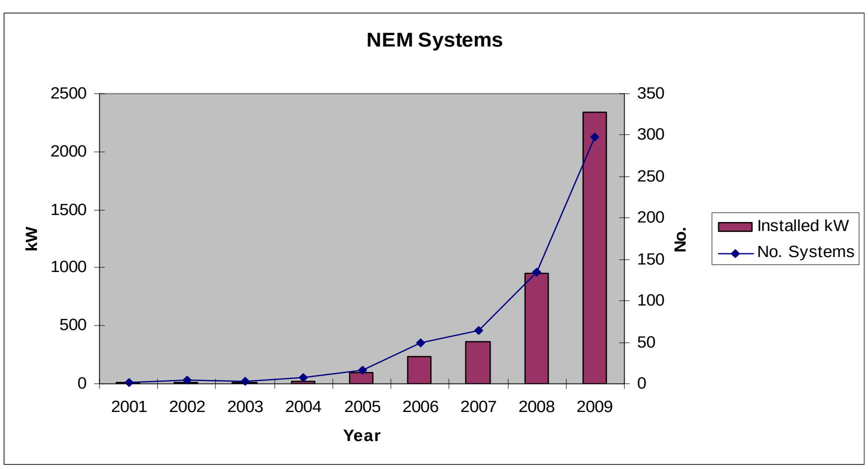
Since these experiences and lessons learned may provide guidance to other U.S. utility systems, regulatory agencies, and DOE, this report describes the utilities' experiences and observations on operating their systems with large amounts of variable renewable energy sources. The lessons learned and shared in this report are focused on the HELCO and MECO utilities. The report is not meant to be prescriptive, but simply to add to the industry's body of knowledge.

II. Renewable Energy Issues

HELCO, MECO, and HECO are aggressively adding large amounts generation to their systems powered by as-available renewable energy sources (primarily wind and solar). The Big Island also has a large geothermal generating unit owned by an Independent Power Producer (IPP). This 30 MW plant is permitted for 60 MW; it is already expanding, and may eventually be larger than 60 MW. There are also large independently-owned bio-fueled generators on Maui and the Big Island. The Big Island also has a 14 MW (at peak flow) run-of-river hydro plant.

While there are plans for large size photovoltaic (PV) installations on both islands, small residential roof-mounted PV systems have already proliferated, and an almost exponential growth of these small systems is forecasted.

Figure 1 Small Net Metered PV Systems Installed in MECO Service Territory [MECO 2010]



Most of the renewable energy resources are characterized by the term “as available,” meaning they cannot be dispatched and controlled to the extent as combustion turbines, diesels or steam generators. The geothermal units on the Big Island can be backed down to some extent (3 MW of the 30 MW capacity). The bio-fueled units on Maui and the Big Island are owned by independent power producers. While their output can be regulated, the utility is obligated to purchase as much or their energy as it can, and there may also be constraints based on thermal needs of the facilities.

MECO and HELCO are small systems (about 200 MW peak each), and do not carry traditional spinning reserve. They maintain operating reserves adequate to manage fluctuations due to the as-available nature of the renewable energy resources and variance in loads, as well as to prepare for failure contingencies (forced outage of a generator or trip/outage of a transmission line) to the extent possible. However, system simulation studies have shown that it would be prohibitively expensive – in production cost and fossil fuel consumption – to maintain enough operating reserve to rigorously guard against the most serious single or double generation and transmission contingencies.

The addition of large amounts of as-available generation present significant challenges to the system operators:

- System minimum loads (nighttime) are often not large enough to accept all available renewable generation after the minimum dispatchable generation necessary for system regulation and must-run units are committed.
- Sudden large fluctuations in wind farm output have resulted in large drops in system frequency. (time scale of seconds to minutes)
- Slower but sustained changes in windfarm output (time scale of 10s of minutes to an hour) present a dilemma to the system dispatcher: will the wind farm output continue to drop, necessitating start-up of a fossil-fueled generator? (or de-committed if windfarm output increases enough) The system operator wants to wait as long as possible to make this decision, but continuing or more rapid decline in wind farm output may require a diesel be fast-started, with a penalty in fuel efficiency. There is no suitable accurate wind forecasting procedure to remedy this.
- These variations in output of as-available generation require the utility to carry more fossil-fueled operating reserves, eroding the fossil fuel savings potential of renewable energy technologies.
- While windfarms are large and their output is monitored through the utility SCADA system, the actual electrical production of small residential PV installations is unknown. Since the utility does not know the exact amount of as-available PV, it also does not know how much it must increase its regulating reserves to compensate for the PV’s variability.
- The IEEE 1547 standard for distributed generation has anti-islanding requirements for safety issues. However, Hawaii’s grids routinely experience larger frequency deviations than do large mainland utilities. When the frequency drops because of an instability problem (or a sudden drop in wind farm output), not due to a fault, inverters on PV systems, complying with IEEE 1547, drop out. Unfortunately, in a non-fault disturbance,

this exacerbates the problem, as the grid loses additional generation just when it needs as much generation as possible to stabilize the grid.

- While not a system operations problem per se, another issue in Hawaii is that despite their high reliance on renewable energy, HELCO and MECO customers have seen their electricity prices spike as petroleum prices have increased. This is because legislatively-mandated (PURPA) provisions of the power purchase agreements with independent power producers (IPPS) require the utility to pay according to its marginal generation cost. As oil prices rise (e.g., after Katrina), HELCO's and MECO's marginal generation production costs rose. The IPPs were paid more for their power generation, and these costs were passed along to the consumers through the energy cost Adjustment Clause (ECAC).

III. EXAMPLES OF AS-AVAILABLE GENERATION ISSUES

3.1 Curtailment of Wind Generation during Low Loads on the HELCO System

HELCO's minimum load level remains around 70 – 80 MW. Although HELCO's peak has seen significant growth, the minimum load has not seen comparable growth rates. HELCO's operating practice is to have at least three units with frequency regulation capability on-line at all times. In general, HELCO operates Hill 6, Hill 5 and Puna steam as the regulating units during low load periods. HELCO is also required to accept at least 27 MW of capacity from PGV (geothermal) during the off-peak period. The combined minimum from the four units equals 56.4 MW out of the 70 MW minimum.

It is HELCO's practice to accept as much energy from as-available wind and hydro units as operationally possible. (There may be 14 MW of run-of-river hydro on line.) At times some of the as-available units are curtailed because there is more on-line generation than what is needed to meet the system load. Future contracts may be subject to curtailment during the off-peak periods.

A typical day is used as an example to further explain the impacts to the HELCO system. Figure 2 shows the system load measured on March 21, 2002 (shown as the blue line), which includes the total customer energy usage plus transmission/distribution losses. Note that the load varies throughout the day, being lowest at early morning and highest at dusk. The peach area is the actual total generating capacity on the grid at that time of day. Note that the total online capacity is always slightly higher than the system load. This provides some reserve to increase generation production if load increases. The system frequency is 60 Hz when the generation production matches system load. There is usually not enough reserve to cover a large loss of generation, so these events usually result in low frequency.

The low frequency results in automatic load shedding of selected loads to bring the generation and load into balance.

Figure 2 HELCO Load Curve for 3/21/02
Generation Capacity (MW) from Actual Measured Data
[DBEDT 2004]

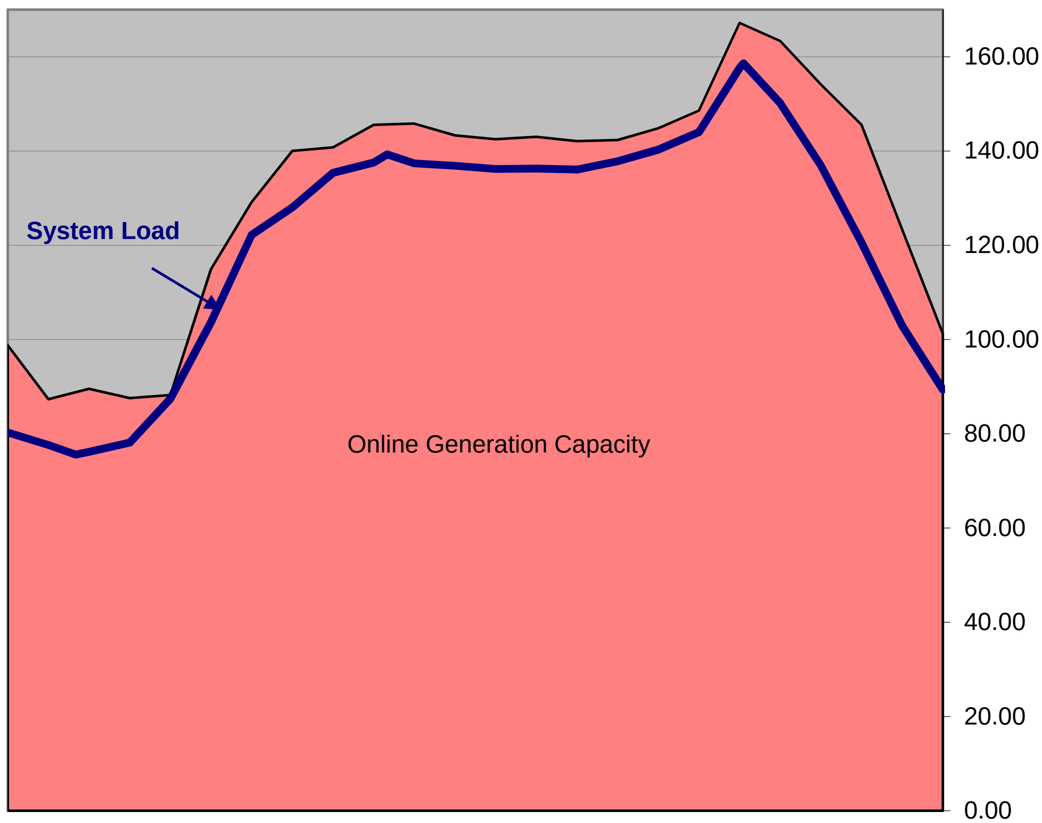


Figure 3 shows the present mix of generation based on actual dispatch from March 21, 2002. This figure has the same system load line and total system capability as in Figure 2 but has the breakdown of generation mix. The bottom burgundy layer is the fixed generation that is not under AGC control, but firm power. It has Hilo Coast Power Company (HCPC) at contract levels and Puna Geothermal Ventures (PGV) at a derated level. The yellow and blue areas are the hourly and peak instantaneous measured production for hydroelectric and wind power, respectively. Note that the hydro power is more stable. On this day, one of the small HELCO units was put online.

The peach area shows the amount of regulation that is the difference between the regulating units' maximum output and actual output. The amount above system load line is available to increase output (regulate up) should another source of generation drop out. The amount below the system load line is the regulating reserve down, available to back off production should customer load be lost – such as when a tree falls on a transmission line that has customer loads tapped from it.

Figure 3 HELCO Load Curve for 3/21/02
Generation Characteristics (MW) from Actual Measured Data
[DBEDT 2004]

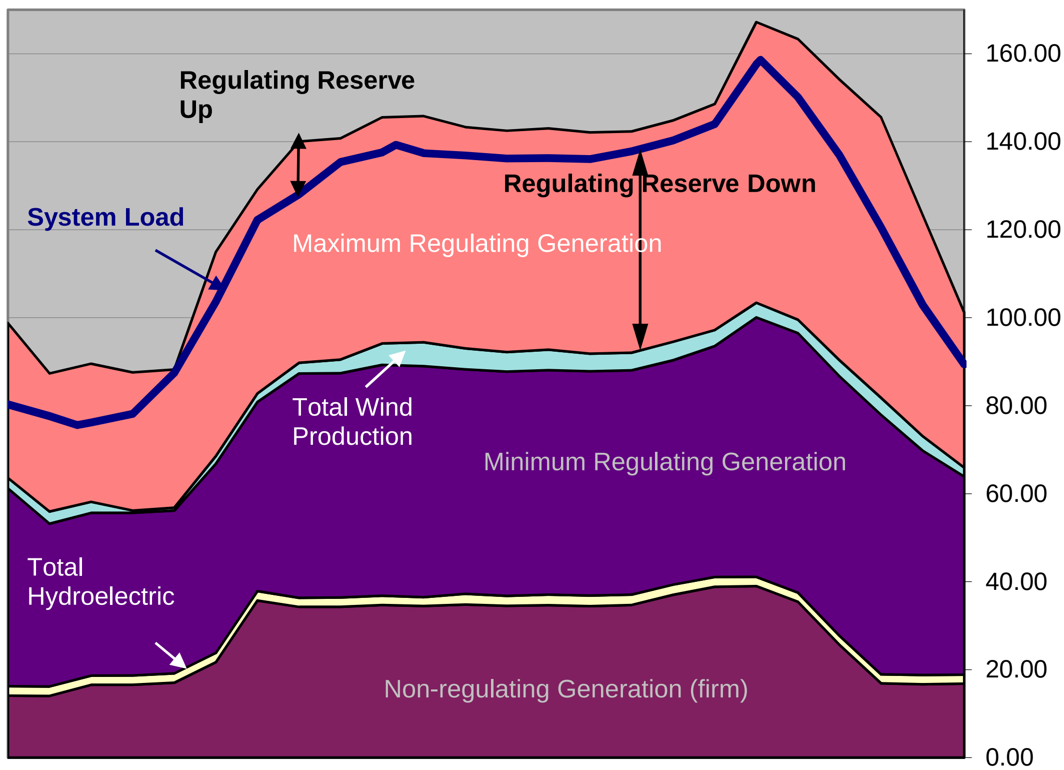
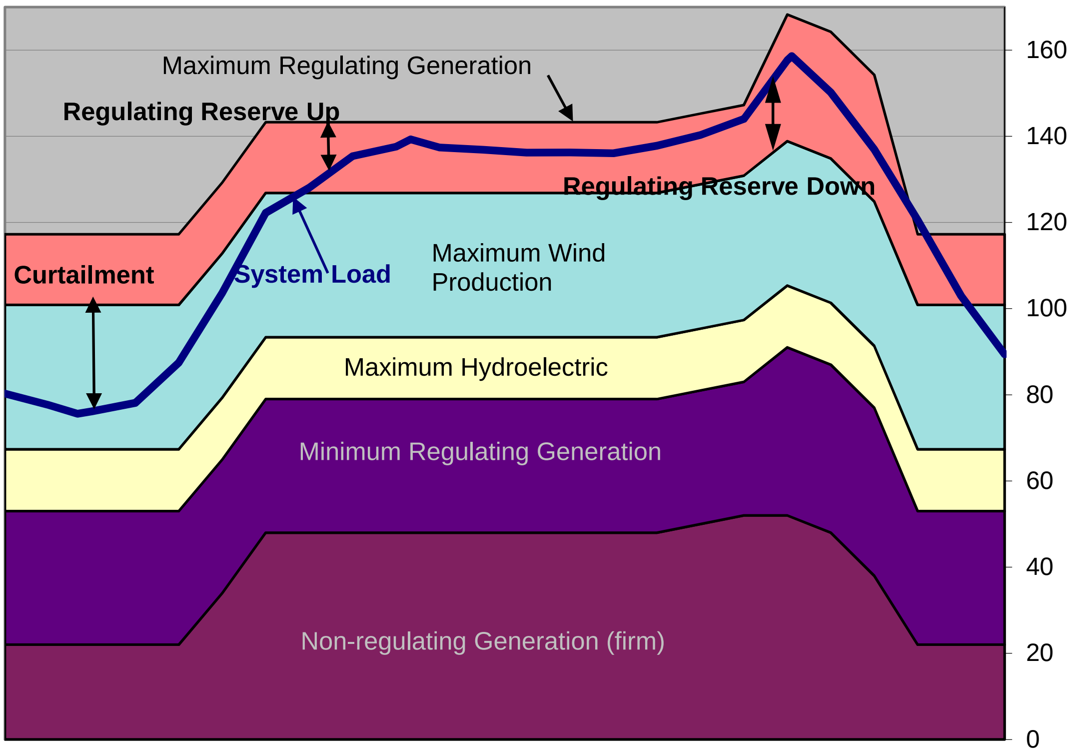


Figure 4 illustrates a scenario that HELCO will be encountering in the future. This figure assumes that three steam units – Hill 5, Hill 6, and Puna – can regulate the system frequency. (It is possible that with more renewable generation the utility may need to have more regulating generation reserves.)

Figure 4 HELCO Load Curve for 3/21/02
Generation Characteristics (MW) for Future Wind Production
(Assumes Three Steam Units can Maintain Frequency)
[DBEDT 2004]



The figure includes PGV and HCPC at contract levels for the fixed generation. Hydro is at 14.4 MW and consists of Wailuku River Hydro at 11 MW and HELCO's hydro at 3.5 MW. The expected maximum wind production, based upon planned expansion of Kamaoa, Lalamilo and Hawi, is expected to be approximately 40 MW in the near future. This example is based on wind loading at 83% and has Kamaoa at 16 MW, Lalamilo at 8.5 MW, and Hawi at 9 MW.

The peach area represents the total range of regulating power available to match production and load. Two items of particular interest are:

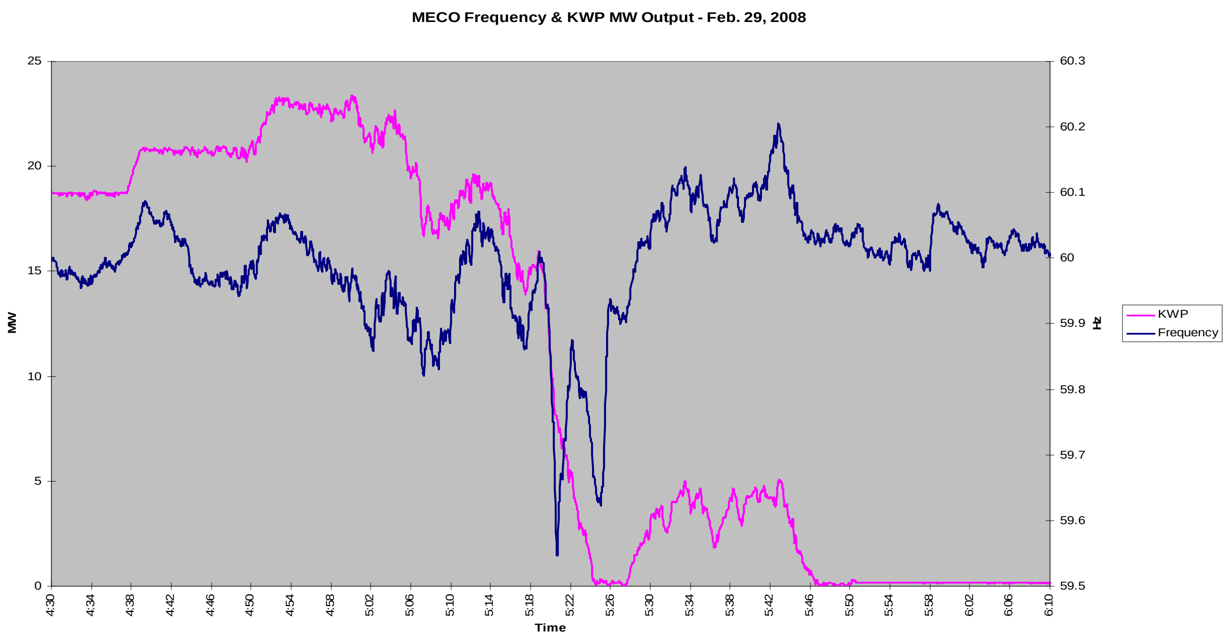
- There is no regulating reserve down during the early morning hours (left hand of chart), which will require curtailing some of the non-firm generation.
- The amount of regulating generation is significantly less than that presently available in Figure 3.

These two items may lead to problems controlling frequency since wind causes higher MW fluctuations on the system and this case is presented with only three regulating units. The addition of greater quantities of as-available units like wind will force HELCO to carry larger amounts of regulating reserve.

3.2 Impacts of Windfarm Output on System Frequency

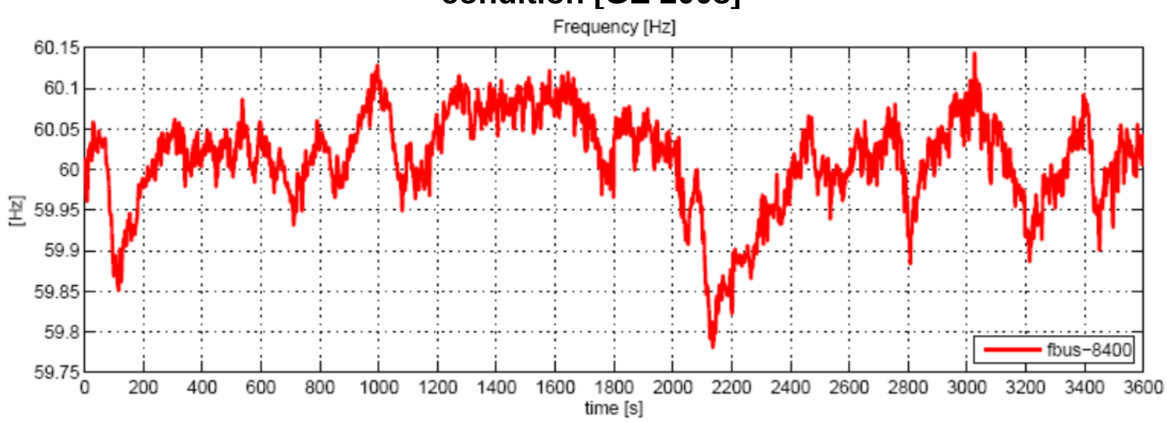
Figure 5 shows the frequency response of the MECO system to a severe – but not the worst – sudden drop in wind. MECO's small frequency bias means a single as-available generation facility can impact the system frequency.

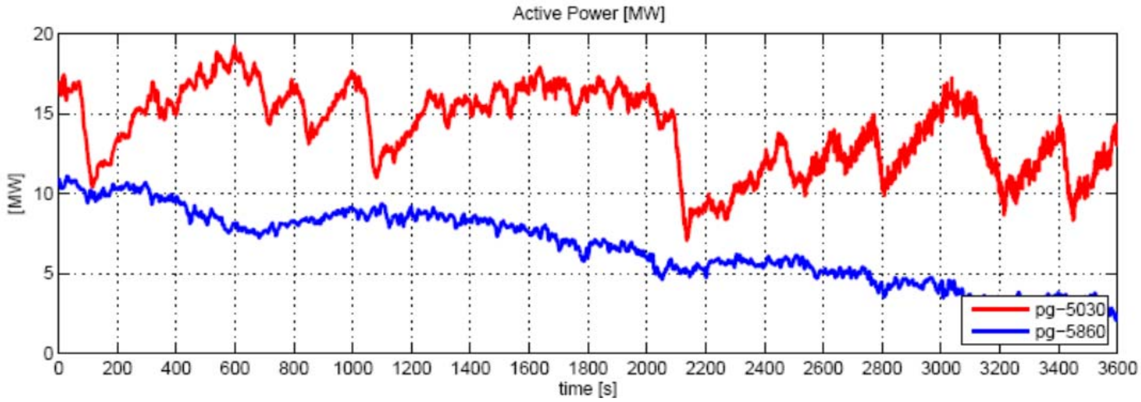
Figure 5 Wind Power Adds Variability to MECO Generation System [MECO 2010]



HELCO has experienced similar frequency excursions. Two examples (one for low load and one for high load conditions) are shown below.

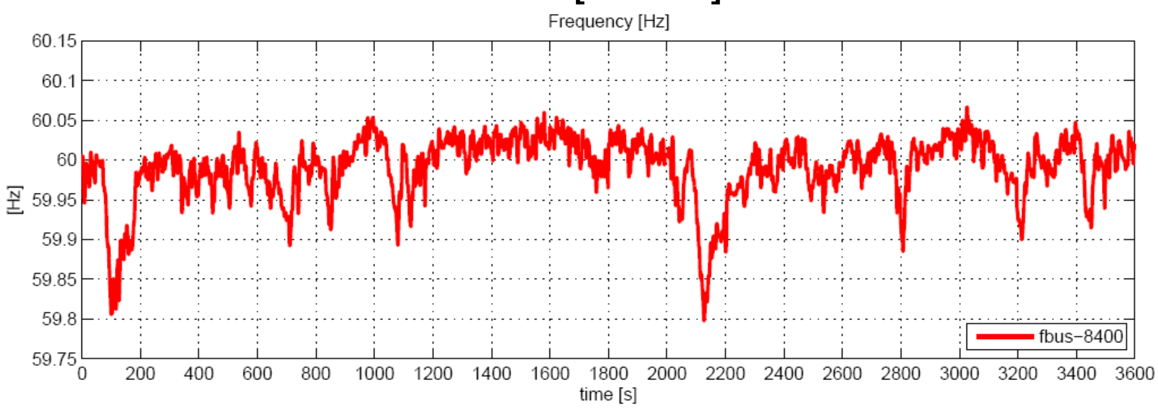
Figure 6 Frequency response to wind power variations during a low load condition [GE 2008]





System frequency (top figure, red curve), Apollo wind plant power output (bottom figure, red curve) and Hawi wind plant power output (bottom figure, blue curve).

Figure 7 Frequency response to wind power variations during a high load condition [GE 2008]



IV. Lessons Learned

As HELCO, MECO and HECO continue to gain more experience with ever larger amounts of as-available renewable energy sources, they will continue to adapt their planning and operating practices. However, already these utilities have been able to better accommodate as-available resources. Shortly after the 30 MW Kaheawa windfarm was commissioned on Maui, MECO experienced several severe system disturbances as a result of its output fluctuations. By applying what HELCO had learned operating its system with large penetrations of renewable energy sources and by gaining its own operating experience, MECO system operators were able to reduce the additional operating reserve requirements needed to manage that windfarm from 12 MW to 6 MW within a year. Further improvements are expected, and this will be necessary, as MECO expects about 90 MW of additional renewables on its system.

The following "lessons" are not rules and are not applicable to all utility situations, but they represent observations that may help other utilities deal with the large amounts of as-available and non-dispatchable power generation technologies expected to be connected to the grid.

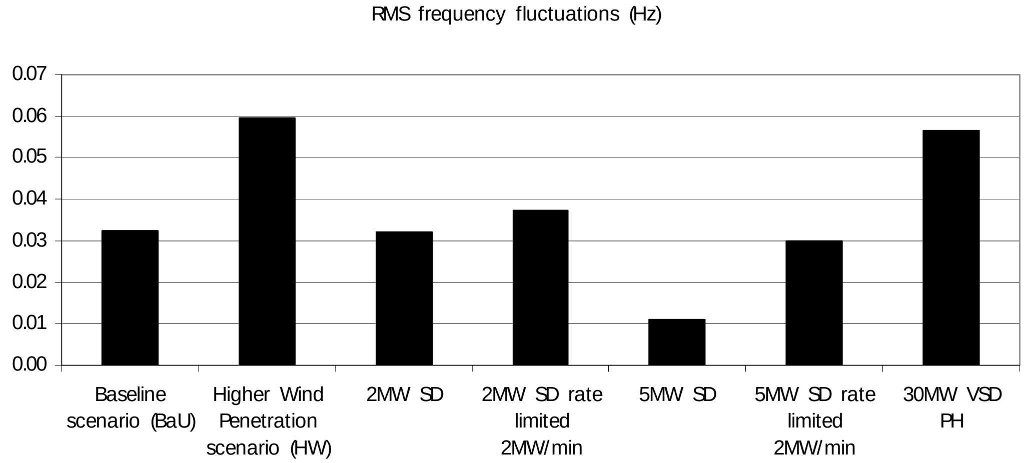
1. De-tuning of AGC to prevent “hunting.”
   HELCO found that its automatic generation control (AGC) kept “chasing” the minor frequency variations caused by windfarm fluctuations. This resulted in lower efficiencies for fossil-fueled generation (as they were being constantly ramped up or down for short periods) and increased the regulating reserve requirements. By increasing the AGC “deadband” to tolerate slightly more frequency deviation the AGC became much more stable. This was a major factor in enabling MECO to reduce the regulating reserves needed to support Kaheawa. There is a downside to this, however. During a real system disturbance (e.g., failure of a major generator or power line) the AGC may react more slowly, and this increases the risk of a system outage and blackout.

2. Energy storage to mitigate output fluctuations.
   When a generating unit is used to provide regulating reserve it may be spinning without providing energy or be operating a less than optimum levels in order to provide up reserves. While energy storage does have an energy “cost” to charge the storage medium, once charged it is available without continuing to consume fuel. Preliminary indications are that fast response storage with a small energy capacity may be very effective in mitigating short-term output fluctuations of as-available generators (minute by minute variations). Storage with other characteristics (slower response required, but more kWh capacity needed) can mitigate the unit commitment issues caused by longer term, but not necessarily sustained, ramps up or down of a wind farm.

   A study conducted by HNEI, General Electric, and HELCO looked at the potential for energy storage stabilizing devices to maintain frequency. The study simulated the HELCO system disturbance of Figure 7, but assumed that windfarms of 3 times the present size (85 MW versus 30 MW today) were on the HELCO system and experienced the same rapid drop in wind.

   Figure 8 shows the RMS value for the difference between the frequency signal and 60Hz over the simulation window. Higher values represent more variable frequency signals. Energy storage stabilizing devices (SD) of 2 MW and 5 MW were simulated, both with and without ramp rate response limits. The actual disturbance resulted in a 0.03 Hz frequency drop. The simulation predicted that with 85 MW of wind (rather than 30 MW), the frequency drop would have been 0.06 Hz. A 2 MW fast response energy storage device (simulated both assuming immediate response and a response rate limited to 2 MW/minute) would bring the frequency deviation down to what it was in the 30 MW wind capacity scenario. A faster (than 2 MW/min) response would not significantly improve the frequency support of 2 MW of energy storage, but would if 5 MW of energy storage were available. Slower responding storage (e.g., a 30 MW pumped storage hydro – PSH – unit) would not provide significant benefit.

Figure 8 RMS frequency fluctuations (Hz) observed in the simulation window for various stabilizing devices [GE 2008]

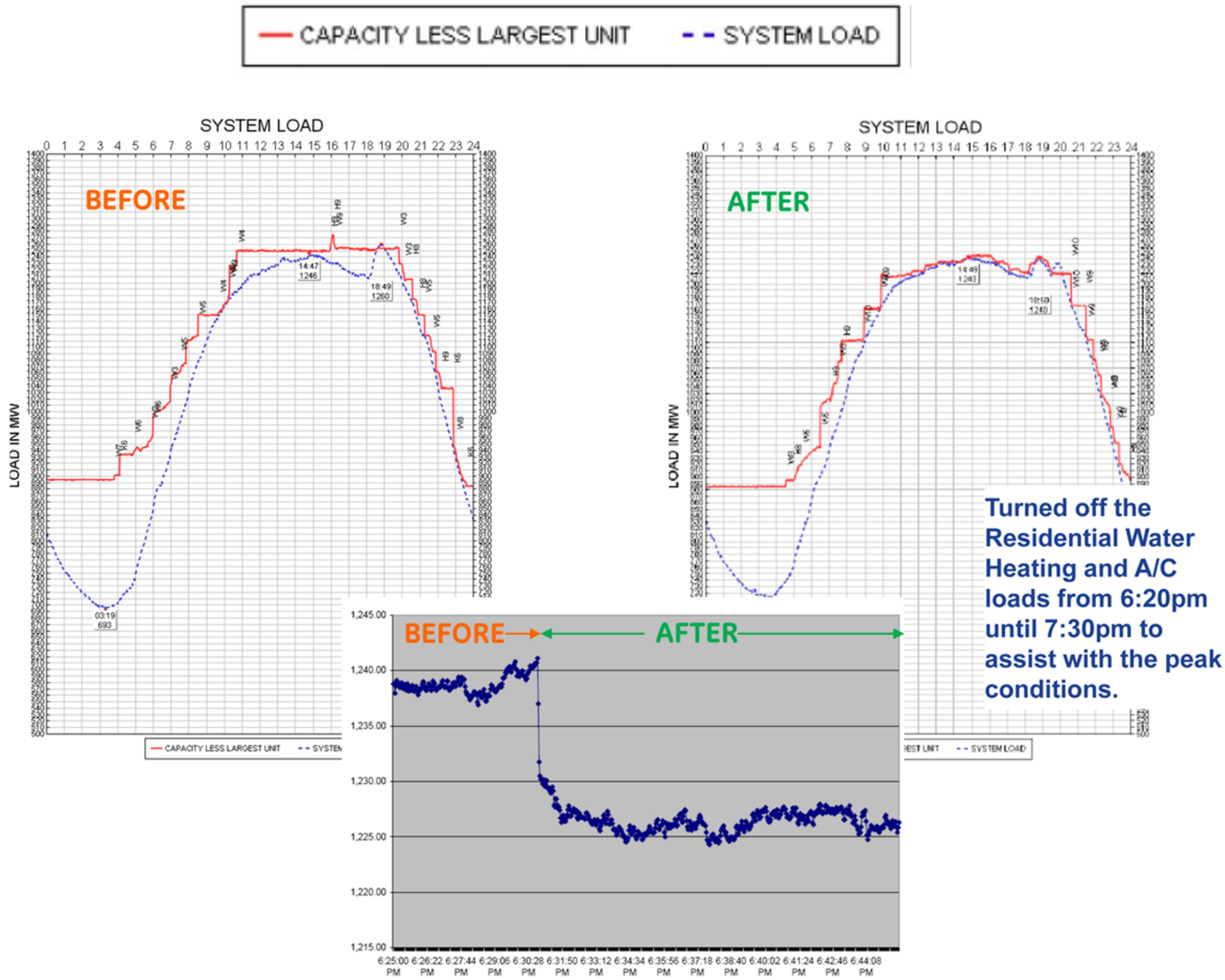


This is not meant to provide design specifications for energy storage, but it does indicate that a relatively small capacity in fast response storage might significantly improve frequency stability. MECO will be further investigating energy storage on its system; a large battery will be installed in a substation in 2011 for evaluation purposes.

3. Demand response to support frequency or avoid fast-starting units
   HECO has a water heater demand response (DR) program that it has used to provide several MW of immediate load relief (by scramming all controlled water heaters) in response to a system disturbance. Results of this are very preliminary, but it appears that such a DR resource could provide up reserve comparable to an energy storage unit. In the case of a slower but constant decrease in wind farm output, turning off all controlled water heaters for 15 to 30 minutes may give the operator additional time to decide whether to start a diesel. Through field trials and simulations, MECO will be evaluating this in 2012 as part of its Renewable and Distributed Systems Integration (RDSI) project with DOE. This use of DR to compensate for decreases in renewable energy output may prove more valuable – at least for Hawaii – than using the DR resource to reduce system peak.

   Figure 9 below shows the observed 10 MW load drop resulting from shutting off controlled water heaters on the HECO system in October 2009.

Figure 9 Using Demand Response Program to Manage System Peak [HECO 2010]



4. Structure of Power Purchase Agreements
   As stated at the end of Section 2, tying the price paid to IPPs for electricity in their Power Purchase Agreements (PPA) to the marginal production cost of utility generation results in the renewable energy IPPs' being paid as if they were using fossil fuel, and the ratepayers' not receiving the economic benefit of their supporting a diverse, non-fossil-fueled generation mix. With the "traditional" PPA, wind or solar become the most expensive energy resource on the utility's system and the ratepayers do not see the benefits of petroleum independence. As a related matter, with a 100% pass-through Energy Cost Adjustment Clause (ECAC), the utility has no immediate economic incentive to promote renewable energy technologies.

   The Hawaii Public Utilities Commission, the Consumer Advocate, the State's Energy Office within the Department of Business, Economic Development and Tourism (DBEDT), the legislature, and the utilities are still trying to equitably balance these economic and social benefits and costs. While no one claims to have found the best PPA and ECAC formulae, a number of points/issues need to be kept in mind:

- Current tie to marginal energy cost that are linked to oil prices. As a result, ratepayers do not see economic benefits of petroleum independence, and wind becomes the most expensive energy resource on the HELCO system. In return for not tying RE payments to price of oil, a 100% pass-through ECAC doesn't provide incentive for the utility to promote renewable energy.
- The first MW of wind or PV displaces more fossil fueled energy than the next. As more non-fossil fueled generation is introduced, the amount of reduced petroleum consumption per MW added of renewable energy decreases.
- There is a finite amount of variability the system can manage. This is exacerbated by the limited geographic diversity of renewable energy sites (wind, geothermal).
    - Therefore, one can't allocate all available ramp rate tolerance to the first wind farm if the goal is to support more wind and other renewable energy installations
    - One should consider setting a realistic goal for penetration of as-available generation resources, then allocate the total ramp rate "allowances" among renewable energy installations as they come on-line.
    - Consequently, not all distributed energy resource installations may receive the same ramp rate constraints (Australia has recognized this principle in its regulation of PPAs.)

5. Setting firm ramp rate limits
   Sometimes the existing ramp rate limits are not adequate; the utility has option to shed additional IPP generation to preserve system stability, and often HELCO has had to do this, even if the wind farm is within its ramp rate tolerances. Conversely, sometimes HELCO can tolerate more variability than is allowed in the PPA. Dynamic ramp rate limits, according to mutually agreed-upon criteria, may be appropriate. It is suggested that there is a need for controls, communications (link to system dispatch), and cooperation in order to maximize renewable energy output as well as system integrity.

6. Reviewing utility system performance metrics
   In the past, the Hawaii PUC used average heat rate of the utility's generating units as a measure of how efficient the utility was in dispatching its system. However, using fossil-fired reserves to support as-available renewable energy will significantly degrade the fossil units' average heat rate in terms of energy produced per Btu of fuel consumed. Average system heat rate not a proper metric for power system efficiency; it does not recognize the benefit of supporting additional renewable energy. The PUC is re-examining its utility performance metrics.

7. Using forecasts of as-available renewable energy when committing fossil units
   Because as-available generators cannot be scheduled or dispatched with certainty, HELCO's practice is to assume that there is no wind generation when developing the preliminary unit commitment schedule each day. The system operator will then adapt the preliminary schedule by dispatching generators according to the actual observed

conditions (load level, wind farm output). In the GE study [GE 2008] to model the HELCO system and examine various renewable energy and system control scenarios, the simulation program predicted slightly lower production costs if instead of assuming no wind generation was present, the initial assumed that the wind farm output over the day was the same as the day before. Since Hawaii's winds are primarily tradewinds, and often fairly similar from day to day, using yesterday's winds to forecast today's seemed to result in the system operator's having a better initial dispatch schedule from which to work, requiring less revising of the dispatch schedule. Since solar insolation will also be similar from day to day, and the Hawaii utilities are seeing a rapid increase in PV installations, it is expected that including a PV forecast (see #8, bullet 1 below) when scheduling unit commitment will similarly improve the initial dispatch.

While this is just a simulation program result, the suggestion is that even if there is no reliable daily forecast for as-available generation, it may be advantageous for the system operator to assume an energy production schedule from as-available resources similar to the previous day's production rather than assuming no as-available generation. (In either case, the dispatch schedule is then adjusted in response to actual conditions, but the actual conditions, in Hawaii, at least, seem to be closer to the previous day's than to a "no renewable energy" assumption.)

8. Managing numerous small distributed PV installations
    - The Hawaiian utilities have seen a rapid and continuing increase in the installations of small distributed PV systems. These installations are not individually monitored or controlled, and consequently the utility does not have a good estimate of the amount of PV-supplied power at any particular time. This is important, as PV output is variable, and will require additional regulating reserve (either in the form of dispatchable generation, demand response, energy storage, or other controllable resources). Present means to estimate the real-time PV resource are probably not resulting in the proper amount of reserves.
        - HELCO has placed small PV panels in its substations; but monitoring their output it hopes to be able to estimate real time PV power production based on percent of nameplate capacity of connected PV in the area.
        - MECO will be monitoring residential PV installations in a subdivision (as part of its RDSI project) and will also be comparing their actual output with estimates based pyranometer reading and/or output of sample PV panels in the substation or on poletops. Since PV panels are configured with strings of cells, shading of a portion of a panel (e.g., 15%) may unbalance the output and result in lower power production (e.g. 25%) than the 15% decrease in solar incidence. The MECO monitoring is expected to better correlate pyranometer readings with actual PV electric output.

    - The IEEE 1547 anti-islanding requirements are seen as being too constraining for the Hawaiian systems. All the utilities (including KIUC on Kauai) feel there is an immediate need to "relax" IEEE 1547 to allow inverters to ride through minor disturbances if not caused by a fault. HELCO is already requiring larger PV installations to ride through frequency deviations larger than permitted by 1547.

There is interest in the use of a permissive power line carrier signal to indicate electrical connectivity from PV panel to substation. (Inverter stays connected if it detects a PLC carrier – indicating electrical connectivity – and disconnects if the PLC signal is not detected – indicating a fault between the inverter and the substation.) Sandia National Laboratories is sponsoring research and commercialization activities to develop this capability.

- Another consideration about PV is that installations and PPAs are designed to maximize kWh output. However, additional power production may be more valuable to a utility – and displace more fossil fuel consumption – at certain times. The Hawaiian utilities peak (and therefore have the highest transmission and distribution losses) later than the time of maximum solar incidence. On could consider whether orienting a fixed solar array to maximize output at 2 PM rather than noon, for example, might provide greater overall benefit. If so, PPAs, net metering agreements, and design guidance may be modified accordingly.

- Inverters are capable of providing both real (Watt) and reactive (Var) power. However, PPAs, renewable energy credits, net metering, and energy efficiency metrics are all focused on real power, so inverters are almost always set at unity power factor. Air conditioner (A/C) compressors are an inductive load, requiring Vars. The utility incurs costs, increases transmission losses, and use power plant capacity to supply Vars to the end users. Since A/C units are more likely to be at full load when the solar radiation is highest, one could evaluate the overall benefits of supplying reactive power locally, by having the PV inverter produce electricity with a leading power factor.

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