LARGE SCALE RENEWABLE ENERGY INTEGRATION ISSUES: A PRIMER

A White Paper in Support of The Hawaii Clean Energy Initiative

Prepared For:
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and the
State of Hawaii

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Purpose

This Large Scale Renewable Energy Integration Issues white paper is intended to provide a primer and summary of prior wind (and other intermittent renewable energy sources where applicable) integration studies to stakeholders, decision-makers, and participants in the Hawaii Clean Energy Initiative (HCEI). Intermittent generation sources such as wind energy present issues and challenges to existing generation infrastructure. However, recent studies and actual practice show the integration of renewables is achievable at material scale and moderate costs. Lessons learned in other jurisdictions shall be instructional and may be applicable in the Hawaiian electric system.

Background

<u>The Hawaii Clean Energy Initiative</u>

The State of Hawaii depends on imported fossil fuels to meet over 90 percent of its energy needs. It is estimated that Hawaii can potentially meet between 60 and 70 percent of its future energy needs from clean, renewable energy sources. In January 2008, the Hawaii Clean Energy Initiative was formed under a Memorandum Of Understanding to establish a long-term partnership between the State of Hawaii and the U.S. Department of Energy (DOE) that will result in a fundamental and sustained transformation in the way renewable energy efficiency resources are planned and used in the State. [1] As of January 2008, Hawaii's energy mix included less than10% renewable energy (not counting energy conservation), with the rest coming primarily from imported oil. This energy mix is typical of island states and nations throughout the world. As such, the HCEI's attempt to conduct the large scale integration of renewable energy into the electric and transportation systems will be closely watched and potentially copied by many island nations.

Fortunately, most island states/nations have a multitude of possible renewable energy resources. Potentially dispatchable resources include: biofuels, Ocean Thermal Energy Conversion (OTEC), geothermal, and hydropower. Non-dispatchable, variable/ intermittent energy sources include: wind, wave, solar thermal, photovoltaic (PV), concentrating solar power (CSP), and others.

Most renewable energy integration studies have focused on a single source of renewable energy, specifically wind. In actual operation, utilities will need to integrate a number of variable energy sources of various technologies onto the grid. A search of the literature found very little work addressing the combination of different variable energy supplies at large scale. The Crete study [2] and a Danish study [3] address this issue at low to moderate levels of integration, but nowhere near 70%.

<u>International</u>

Iceland receives most of its electrical power from hydropower and geothermal power (both dispatchable) [4]. For brief periods of time Denmark produces as much wind energy as it uses, essentially becoming electrically self-sufficient, and actually exports excess wind energy to the German or Scandinavian grid as necessary to maintain the Danish grid stability. [5] Neither of these cases provides a good example of the problems that an island state/nation will face. Consider the cases of Crete or Spain instead. Crete is an island cut off from the Greek mainland, dependent on oil, and trying to reduce its dependence on imported oil. A case study for Crete can be found in reference [2]. Although part of the European mainland, Spain (tightly linked with Portugal) operates an independent electrical grid, connected to the rest of Europe by a small 2,000 MW tie line. As a leader in wind and solar development, Spain has successfully integrated renewable energy into the electric grid to cover about 20% of its electricity needs. In order to make this work, they found it necessary to set up a special operations center (Centro de Control de Regimen Especial – Control Centre for Special Regime) to deal with renewable energy control and integration issues. [6]

Large Scale Renewable Energy Integration Issues:

A number of wind integration studies have been completed in the United States and Europe. These studies typically dealt with wind integration levels in the area of 20-30%, short of HCEI's ultimate goals, but a significant penetration nonetheless. While each study came to the conclusion that wind integration could be achieved at these levels (with a certain amount of integration cost), most also agreed that additional studies were needed when integrating above these levels. With that said, certain lessons have been learned that are certain to carry over at higher levels of wind integration, and are equally important for most other forms of variable/intermittent renewable energy.

Load Forecasting and Market Making

Forecast accuracy is important as it is one of the largest factors used to determine the amount of reserve power (spinning reserves, standby reserves) required at any given time during the day. Maintaining excessive reserves on line increases pollution and causes thermal power plants to operate below their maximum efficiency point. [3] Two major forecasts are required, load and weather. Over time, utility companies have developed models to allow them to accurately forecast system load. Weather forecasting tends to be less precise, resulting in greater uncertainty in the expected power generation forecast for the future. More accurate weather forecasts allow for reduction of the reserve power requirement, thus lowering the need to maintain unnecessary equipment on line and paying the unnecessary fuel costs, hence lowering the total cost to produce power.

Where energy markets are used, most deal with a day-ahead market and a short term market (normally about an hour-ahead). The bid for the one day market may be required more than 1 day in advance of when the power is actually required; hence the bid is based on weather data and forecasts made far in advance of the time period being predicted. As an example, the day-ahead market may require bids to be submitted 26 hours before the beginning of the day of concern. The weather forecast supporting this bid may be based on readings taken 24 hours previous to the bid. This forecast is then used to predict the delivered power level through the end of the day being bid. As such, the power (wind/solar/wave) data for the 24^{th} hour of the day of concern may have been predicted based on data taken at least 50 hours in advance (more likely 60-72 hours in advance).

Forecast accuracy gets progressively better as the supporting data gets closer to the time being predicted. As such, providing better resource (and power) prediction tools (weather and modeling) and/or reducing the advance time required when bidding on the various energy markets will improve forecast accuracy and therefore reduce reserve power requirements. [3, 7] The European Wind Energy Association found that, "On an annual basis, reducing the forecast horizon from day-ahead to a few hours ahead reduces the required balancing energy due to prediction errors by 50%." [8] Advanced wind forecasting tools and services are commercially available (3Tier, WindLogics, AWS True Wind, etc.). The challenge is to ensure that they are consistently integrated into wind farm power predictions. [8, 9]

Low Voltage ride-through

Power generators use output circuit breakers to protect equipment from damage caused by excessive power draw due to a short or ground in the transmission and distribution (T&D) system. However, there are also circuit breakers within the T&D system specifically designed to isolate a ground or fault. If properly designed the T&D system breakers should isolate/clear the fault in sufficient time to prevent tripping the power generator output circuit breakers. The ability of a power generator to remain on-line during the fault clearing period is called low voltage or fault ride-through. If the generator output circuit breaker trips are not set in a manner to allow fault ride-through, the system operator will have to cope with the loss of one or more power generators in addition to the fault that was properly isolated by the T&D system. Tripping wind turbines too quickly during a low voltage transient increases system instability. [3] [10]

Geographic Diversity

Variable renewable energy sources, such as wind and solar, may be very site specific. Gusts of wind, or shadows from clouds may rapidly influence the power produced by individual wind or solar generators. The use of many geographically distributed generators will allow this short term effect to be averaged out. In addition, large scale geographic dispersion of generators allows some larger scale phenomenon to be averaged out as well. [11] "A large geographical spread of wind power will reduce variability, increase predictability and decrease the occurrences of near zero or peak output." [8] In addition, "The capacity value {of a dispersed wind system} is generally insensitive to the wind penetration level, mainly due to good wind geographic diversity…" [12] Said another way, "Wind plants concentrated in a small region will exhibit a much higher degree of correlation in their output than plants separated by larger geographic distances." [13] Figure 1 shows this phenomenon. Although the data was taken from wind farms in Germany (across land, not the ocean), the affects of distance on power (actually the change of power) are well illustrated (even thought these exact curves may not be valid for other locations).

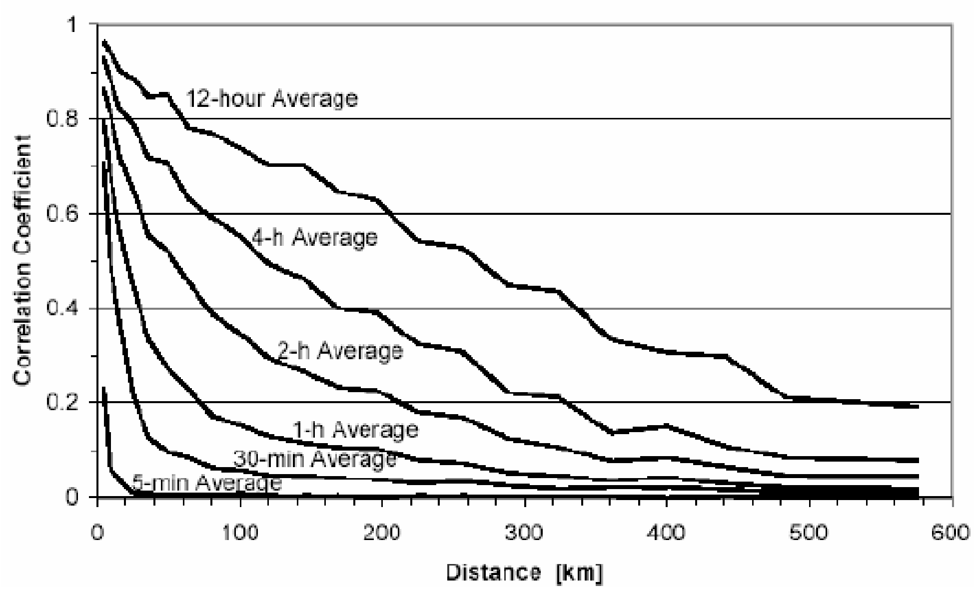

Figure 1: Example of wind correlation vs. distance between wind plants. From NREL/CP-500-26722, July, 1999 [14]

Balancing Area

Many of the studies extolled the virtue of utilizing a large electrical balancing area. Not only would this allow for the aggregation of a number of distributed generators, but it would aggregate the distributed load. Increasing the size of the balancing area (hence the total load represented by the balancing area) would allow for averaging the effects of individual load and generator changes, hence requiring a smaller spinning reserve for load regulation than would have been required by summing the reserve required for the same geographic area separated into smaller balancing areas. [15] [8] A Minnesota study estimated the reduction in regulation capacity (within the confines of that study) to be almost 50%. [16]

Integration Costs

Many of the previous wind integration studies were focused on developing "integration costs" i.e., ancillary costs that would be incurred by bringing on a new source of generation. Each of these studies required the use of a company proprietary generator Loading Program (computer program that determines the lowest cost order of loading available generators – while at the same time ensuring that other constraints – such as ramp rate and minimum loading – are met). Each study came up with different wind integration costs; however all of the studies reviewed for this paper concluded that these costs were low, at least with wind integration levels below 30%.

In very basic terms, the electricity generated minus the electricity used (load) is equal to the electricity converted to some form of energy and delivered to storage (assuming that a positive number implies energy being saved). From a practical point of view there are two key concerns: the energy storage device must be big enough to contain all of the energy delivered to it, and the energy storage device must be able to receive and transmit energy at the rate required by the mismatch between the generator and the load.

$$(\text{Generation}) - (\text{Load}) = (\text{Storage}) \qquad (1)$$

In most conventional electrical systems the generator is assumed to be controlled whereas the load varies based on millions of fairly independent decisions being made by consumers on a random basis. As a result, the system load is variable in each time period being considered.

Regulation - In the shortest timeframe (seconds) there is no effective storage attached to the grid, hence generation must be controlled to match the load. In this situation, if the instantaneous system load exceeds the instantaneous system generation, the deficit energy will be taken from the rotational energy of the generating machines – or in other words, the machines will slow down and the system frequency will fall. Maintenance of system frequency is called "regulation" and is normally accomplished by sensing system frequency and using computer programs to order adjustments (throttling) to the motive force (fuel, steam, water supply) of one or more operating generator. The system operators must ensure that the generator(s) being used for regulation have sufficient range up and down to adjust to the changes in system load, AND can essentially match the rate of change of the load.[1]

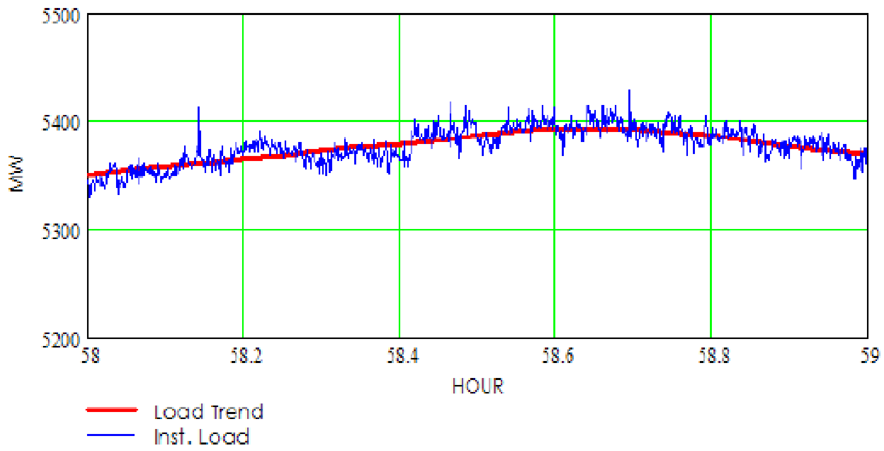

Figure 2: Example of instantaneous load vs. load trend - the need for regulation. [17]

Load Following - On an hourly scale, system loads change in a somewhat predictable manner. On most days, system load roughly doubles during hours of day and evening activity as opposed to hours of sleep. This change of power level greatly exceeds the expectation of regulation activity and normally entails the starting and stopping of generators. This regime is called "load following". The system operator must ensure that adequate generation capability is scheduled to be on-line in order to support expected system loading (with an acceptable cushion in the event the load forecast is wrong).[2]

System Capacity - On a yearly scale, system loads change due to changes in season, population and technology. These changes can often be forecast. It is the duty of the system operators / public utility to find adequate electricity supply to satisfy expected customer needs. This may involve finding new sources of energy, and ensuring that this energy will be available at the time that it is needed (normally at periods of peak loading), or establishing Demand Side Management (DSM) initiatives to provide control of the load. Some facilities are paid a capacity credit to be available whereas some users are paid a fee to allow the utility to reduce their load (via DSM) when system loading demands. The determination of capacity credit/value is critical to determining if sufficient generating facilities exist to meet expected system load. Capacity value determination is often based on a Loss of Load Expectation (LOLE) calculation using a specified threshold value (often but not always 0.1 day).

Under conventional electrical system assumptions, almost all of the regulation and load following is caused by the variable load, whereas the existing thermal generators are assumed to be highly stable (but adjustable). The introduction of variable/intermittent generators to the system (wind, wave, solar) causes these assumptions to be challenged.

[1] Energy storage devices in testing include flow batteries, super capacitors, and flywheels. None are widely adopted in the US or Europe.

[2] Energy storage may include pumped water or air. Pumped hydro facilities are normally considered separate from dams, although both may provide load following services.

Variable generators increase and decrease their output based on the availability of the resources (wind speed, wave height, and solar insolation), which may vary based on the second, minute, hour, day, season or some other time period (such as the phase of the moon). As such, two separate, independent sources of variation are induced, requiring conventional generators to compensate for both. In some cases, conventional thermal generators will be required to operate at a less efficient point in order to allow for increased regulation action. Compounding the problem is the issue of forecasting. In addition to dealing with errors in the load forecast, the system operator must now deal with errors in the power generation forecast. The combination of these errors is normally manifested in the load-following regime (minutes to hours). In many cases, additional generators must be brought on-line (whether efficiently loaded or not) to account for the actual change of load plus the forecast errors associated with the load and the power generation. The additional costs associated with regulation, load following, and forecasting errors are all included in the integration costs.

Each type of generator has a technical maximum power generation point, minimum power generation point, efficiency curve, and maximum ramp rate. In addition, each energy storage facility has unique characteristics of maximum energy level, minimum energy level, energy conversion efficiency during storage, energy conversion efficiency during discharge, and associated maximum ramp rates. In addition to storage, some utilities have the ability to buy and sell power on an outside market. To the extent that this is possible, there are constraints on maximum transmission rates. Because each utility/ISO/RTO[3] has access to a different configuration of generation, storage, transmission and loading, each will have a different program for scheduling and loading available generators.

Higher wind penetration levels generally result in larger variations in regulation and load following, hence higher integration costs. [13] The prior integration studies indicated that, although rare, large ramp rates and changes of load do occur. With higher wind penetration levels the size of these changes gets larger, potentially requiring an increased operating reserve, or more generators to be operated below peak efficiency to ensure adequate system control and security. [12] These findings reinforce the need to consider allowing the system operator to externally control wind generator loading (i.e., dump wind, temporarily disconnecting generators).

When existing dispatchable generators are run below peak efficiency in order to provide ancillary services (regulation, load following, etc.) required by the addition of variable generators, an integration cost is assessed. This cost is associated with the resulting inefficiency rate and the cost of fuel. As such, as the cost of fuel increases there is a correlated increase in the cost of integration. [13]

The actual generator assigned to provide the added ancillary services may change over time, hence the integration cost is directly associated with the generating costs associated with the assigned generator. As higher cost generators tend to be used as the system loading increases, integration costs can be correlated with the system loading (and indirectly the time of day). As such, wind integration costs may be high, even when the wind generation for the period of time may be low. [17] An example may illustrate this case. Wind that blows during the late evening hours (when system loads are low) may be compensated by reducing the load on a large thermal generator. Although no longer

[3] ISO = Independent System Operator, RTO = Regional Transmission Organization

operating at its most efficient point, it is still lower in cost than any other generator that may be available. On the other hand, wind that blows in the late afternoon (when system loads are high) may be compensated with a gas turbine that operates with high operating costs. Assuming (for this example) that insufficient regulating capability exists on the dispatchable (thermal) generator to account for the added variability imposed by the potential wind variability, the system operator will start up a more expensive gas turbine and partially load it (taken from the load on the more cost effective thermal plant) in order to give it sufficient up and down regulation and load-following ability. In the end, both the gas turbine and the thermal plant are operating under suboptimal conditions, and the resulting integration cost is high, even if little wind power is actually generated. [17]

Geographic diversity of variable generator assets (or lack thereof), has a direct influence on integration costs. Large geographic diversity tends to make the various wind farms independent of each other (or at least less correlated), reducing the expected variability and ramping rate of the outputs (compared to a highly correlated set of wind farms), hence producing less variability, requiring less compensation, and ultimately lower integration costs. [12, 13]

The inclusion of "clean" energy doesn't necessarily displace "dirty" generation. Despite the clean nature of wind (and other variable renewable) energy, Colorado and New York studies found that the wind energy was displacing the use of (relatively clean) fast reacting natural gas as opposed to reducing the use of coal or nuclear energy. [7, 18] A Washington State study found that wind energy essentially displaced hydroelectric power, producing little net environmental improvement.

As noted, most of the integration studies used for this paper dealt with wind alone, however the issues discussed are common for all variable renewable energy generators, specifically additional reserves needed for regulation, balancing, and forecasting. A review of solar electric (PV) integration concerns also addressed voltage control and anti-islanding concerns directly associated with inverter design and cost. [19]

Regulatory Caused Instability

At times, market concerns and regulatory guidelines can cause instability of an electric grid. In Spain, such a problem existed when a bonus was provided for maintaining a leading power factor during peak loading periods and a lagging power factor during non-peak periods. At the moment the peak period ended, all energy producers had incentive to adjust their generators from a leading to a lagging power factor. As would be expected, the rapid change of generator setpoints associated with these power factor adjustments caused potential grid instability. While this example may have been specific to the Spanish market, the general concern (regulatory caused instability) is generally applicable to all deregulated markets. [20]

Operations Control

Many thermal power plants are expensive to start up and shutdown, hence these plants tend to remain on-line at all times. Most of these plants are designed to be most efficient near maximum power and thus become less and less efficient as they are reduced in power. As a result, power companies tend to operate these plants close to their most efficient points. In many situations the large thermal power plants, operating at their most efficient points, provide all of the power that is needed during the late evening and early morning hours. A regulatory scheme that would force the acceptance of power from renewable sources during this period of time would require the thermal plant(s) to operate at a less efficient point (more costly on a per-unit of electricity basis). [20] The inclusion of renewable power may also cause the utility to increase its power reserve requirement in order to account for expected fluctuations in the renewable power source (wind, wave, solar). In addition, the utility would need to determine if it retained the flexibility to adjust the thermal unit(s) quickly enough to compensate for a potential down ramp of renewable energy at the same time as they experienced an up-ramp in the load (a common occurrence in areas of the country where the wind blows at night and dies off in the morning hours as system load rapidly rises). If sufficient "ramp rate" control does not exist, the utility will need to adjust its generator mix to provide the required ramp rate, even if additional power is not immediately required. In addition to these economic and technical issues, there may be times when it is in the best interest if the utility to control the renewable energy provider. This may occur when the renewable energy source is introducing significant instability into the grid, or when a curtailment of the renewable energy source may be economically advantageous.[4]

Curtailment may also be required to maintain safe operating conditions in the event of a loss of generator or substation (often called the N-1 situation). The Iberian grid is essentially isolated from the remainder of the European electric grid with the exception of a small High Voltage Direct Current (HVDC) connection to France. In an effort to protect the T&D system (as well as the connection to France) from overload and trip, the CECRE (Control Center for Special Regimes) operates a software program (GEMAS – Generacion Eolica Maxima Admisble en al Sistma) which checks for the consequences of the individual loss of each of 70 key distribution substations, specifically looking for overloads within the distribution system and potential overload of the link to France. If overload is found, the system analyzes a reduction of various renewable energy generators until the overload condition is resolved. After checking each substation, CECRE issues limitation orders for wind generators that need to be controlled/curtailed. This cycle happens every 20 minutes. By working in near real time, Spain is able to be more accurate (less conservative) in its assumptions of the initial conditions of a casualty and can therefore allow more generation than would otherwise be allowed. Despite being distributed throughout the grid, at times renewable energy must be curtailed (due to congestion on the T&D network). In 2007 this curtailment resulted in a loss of only 0.09% of renewable energy in Spain. [20]

The Ontario Wind Integration Study noted that at times the night time load may be reduced below the minimum loading needed for the on-line generators. This has "serious implications for the online generation resources during the low load periods and may require curtailment of wind power output or other mitigation measures." [12] Some mitigation measures discussed include: shedding wind or using wind farm controls to provide flexibility; export wind output to other control areas; or modifying the load by adding loads during the low load periods (such as using pumped hydro for energy storage). [12]

[4] It should be noted that many power purchase agreements do not allow for curtailment on solely "economic" reasons. [13]

Energy Storage

The studies discussing renewable energy in Spain and Crete each expressed the need for energy storage units. "A key issue in renewable energy integration regarding power balance feasibility is the amount of hydro-pump storage units available in the system" [20] and, "Installation of the pumping storage hydro units is vital for the operation of the electrical system of Crete because these units can transform the variable production of wind farms (due to the stochastic nature of wind) to a uniform production at pre-selected hours of operation (usually at peak demand)." [2] Energy storage (with subsequent power generation capability) must be addressed as a key part of any large scale renewables integration (especially of an isolated/island system). The Crete example addressed the need for additional energy storage to provide power capacity to meet peak loading conditions. In order to convert variable energy generation into firm power, (especially for higher levels of renewable energy integration) energy storage must be considered (potentially in conjunction with DSM) to make up for short term lulls in renewable energy resources – potentially for up to days at a time

Active Networks

Most modern electrical distribution systems are designed for electrical power movement in one direction, i.e., from the substation to the consumer. This one way movement allows for accurate estimation of voltage drop along the transmission lines and allows the power company to insert appropriate transformers and compensation mechanisms to ensure that the delivered voltage is within the agreed upon limits. When distributed generation (wind, wave, solar, CHP) is introduced in the distribution network these assumptions may no longer apply. An electrical distribution leg with an injection of power will see a voltage rise (or at least a smaller voltage drop) within portions of the leg As such, the voltage at the end of the line may be above the agreed upon voltage limit. If the power company compensates by reducing the voltage (such as by changing the power tap on the main substation transformer), the voltage on the leg may return to within limits but the voltage on the other legs, legs without power injection, may now be below their voltage limits. In addition, the source of distributed power generation (CHP, wind, wave, solar, etc.) may increase or decrease during the day and night, requiring the power company to also compensate throughout the day and night. Such a situation is highly undesirable. A more technical explaination of the problems can be found in reference [21]

Academic work on active distribution networks has been conducted to address this issue. In Europe, the motivation is primarily to allow for large scale distributed renewable energy generator connection to the medium voltage/low voltage distribution grid. "Technical analysis…has demonstrated that, by employing active network management methods, distribution networks can accommodate ~3 times more distributed generation connections than equivalent networks without active management." [22] In the United States, the motivation also includes solving issues of grid congestion. Although many potential solutions are being studied, one such solution utilizes a regional dispatch/aggregation system (man and computer) to control the output of all distributed generation systems (wind, PV, battery, fuel cell, storage, generator sets, etc) providing services to the distribution grid. Using "active control, adaptive and integrated protection and control systems, power electronic network management devices, real time network simulation and performance analysis, improved sensors, communication, and data interpretation technologies", the distribution network operator can ensure power quality to all customers, and when necessary, isolate appropriate subsectors into "power cells" (essentially islanded portions of the power grid) in order to maintain service to as much of the grid as is possible. [22]

This work has moved beyond the purely academic phase. A "DG (Distributed Generation) DemoNet-Concept" study has been conducted to consider active network applications on three electric distribution networks in Austria. A key conclusion from this study was: "While the passively operated grid suffers from overvoltage conditions already at 50% DG (distributed generation) of maximum load, the coordinated voltage control approach is still able to keep voltages in the limits at 150% installed DG of maximum load." [23]

Smart Grids, Microgrids, Virtual Power Plants, Islanding[5]

There are many concepts of a "smart grid", and each has some element of communication involved. In some cases the communication consists of simply passing data in one direction for information (such as advanced meter reading), while in other cases, the information is used to direct action on the part of the consumer, the utility, or the power generator (such as providing demand side management orders, or the control of home/building Energy Management Systems (EMS)).

Under one vision of the smart-grid, two-way communication will occur between the generator, the transmitter, the distributor and the customer. Smart meters (which receive present and projected energy pricing information) will be a key device for the smart-grid, helping the consumer (or the customer's energy management system) control equipment within the home/business/industry.

Microgrids may also be utilized. Microgrids are:

> "… low voltage networks with distributed generation sources, together with local storage devices and controllable loads (e.g. water heaters and air conditioning). They have a total installed capacity in the range of between a few hundred kilowatts and a couple of megawatts. The unique feature of microgrids is that, although they operate mostly connected to the distribution network, they can be automatically transferred to islanded mode, in case of faults in the upstream network, and can be resynchronized after restoration of the upstream network voltage." [15]

Acceptance of the microgrid concept will require a rethinking of the electric grid philosophy and architecture.

Something similar has been studied in Denmark and is called the Danish Cell Project. Denmark uses a "district heating" concept where a small scale, local power plant provides hot water to the local homes and businesses. This hot water is used for space heating, as well as hot water needs. Combined Heat and Power (CHP) units (diesels, gas turbines, combined cycle gas turbines, and steam turbines) are used for this process. By

[5] Although not included in the tasking for this paper, DOE's Office of Electricity Delivery and Energy Reliability *Renewable and Distributed Systems Integration (RDSI)* work addresses many of these same issues. DOE's RDSI website can be found at: http://www.oe.energy.gov/our_organization/rnd.htm

adding a generator, electricity is produced as a biproduct of the heat production process. In most cases these units are operated for the heat, and utilize the electricity generated by the machines as a byproduct for on-site electrical needs. In some cases the CHP units produce electricity far in excess of the local needs, resulting in excess electricity being "exported" to the distribution grid. [21] In the past the major transmission system operator (TSO/ISO) (as opposed to the distribution system operator) was not informed of this export and at times this lack of knowledge caused problems. "The uncontrolled operation of WTs (wind turbines) and to a lesser extent the heat constrained operation of CHP plants have caused severe uncontrolled reactive power flows both ways through the 150/60 kV transformers of each radically operated 60 kV network…." [10] The Danish Cell Project has considered adjusting the electrical infrastructure to operate in cells. Each cell would have sufficient domestic resources to balance the cell's supply and demand, and the automated controls to do so. Each cell would remain connected to the main grid during normal operation, however when a major instability occurred, the Transmission System Operator (TSO) would provide a signal of impending failure, giving the cells about 1 second to separate from the grid and remain operating. Under an alternate plan, the cells would go "down" with the grid, would then separate and self-start as independent cells. Under other visions, each cell would have sub-cells, each capable of independent operations (essentially a system of system of microgrids). [10]

The article indicates that the Cell Controller must be able to perform at least the following functions:

- "On-line monitoring the total load and production within the cell,
- Active power control of synchronous generators,
- Active power control of wind farms and large wind turbines,
- Reactive power control by utilizing capacitor banks of wind turbines and grid,
- Voltage control by activating automatic voltage regulators (AVR) on synchronous generators,
- Frequency control by activating speed governing system (SGS) on synchronous generators,
- Capability of remote operations of 60 kV breaker on 150/60 kV transformer,
- Capability of remote operation of breakers of wind turbines and load feeders,
- Automatic fast islanding of entire 60 kV cell in case of severe grid fault,
- Automatic fast generator or load shedding in case of power imbalance,
- Voltage, frequency and power control of island,
- Synchronizing cell back to parallel operation with the transmission grid,
- Black-starting support to transmission grid in case of black-out." [10]

Rather than forming self-supporting independent cells, the Virtual Power Plant (VPP) concept was developed and continues to be refined. The term "Virtual Power Plant" has taken on many meanings around the world. It's the name of a software program, another name for Combined Heat and Power (CHP), another name for finding energy efficiency; and sometimes used to describe a private energy network. However, the term is primarily used in academic and industry circles to describe the concept of controlling distributed non-power plant electricity generating assets in a concerted manner to provide firm (dispatchable) power (normally spot power) to a market.

> "At Detroit Edison, we are creating a 300-MW Virtual Power Plant using customer-owned generation located on the distribution system. These generators, dispersed throughout our distribution system, can be aggregated to act as one plant to provide the lowest-cost solution for peaking capacity. Our DR-SOC, an Internet-based system operations center, takes on a role similar to that of an aggregator by installing and securing Internet-based communication to intelligently operate distributed generators in parallel to our system."[24]

A utility, such as Detroit Edison, may utilize a VPP in lieu of building a new power plant:

> "Our integrated resource plan analysis in the Midwest Independent System Operator (MISO) footprint has shown that, for up to 250 hours per year, running an aggregated system of distributed generation (DG) is the lowest-cost option versus building a combustion turbine plant or making a power purchase."[24]

In some cases, non-utilities are jumping into the game and signing up assets to bid into the energy markets. An example would be the work of Siemens/RWE Energy who has auctioned off firm capacity power from VPP's in France, Belgium, Denmark, the Netherlands, and most recently in Germany. [25]

> "In a two-year pilot project planned until mid-2009, decentralized plants such as combined heat and power plants, together with biomass or wind power plants, will be linked together to form a virtual power plant controlled from a centralized management system. The decentralized energy resources will have an electrical power output ranging from 500 kilowatts to a few megawatts each. For the most part, they will consist of systems that operate in combined heat and power mode or use renewable forms of energy. By marketing the combined electricity production of several power plants together, sales channels which were not previously available to the operator of an individual plant can be utilized. As a result, the plant can operate more economically and efficiently. The operators of the decentralized generating plants hence share in the economic success of the virtual power plant."[26]

The VPP concept is also being used in Germany. A central entity will control the local CHP units and contract for their electrical contribution to the grid as a single unit. These CHP units can be controlled for electrical output, for thermal output, or can be run to optimize the profitability, switching between electrical and thermal control. [27]

The following quote tends to pull all of these concepts together.

> "Energinet.dk thinks that local CHP and wind turbines must get away from operating as separate and passive generators in the lower voltage distribution networks, and is in the preliminary stages of testing the division of networks

> into large numbers of independent, highly automated 'cells', each incorporating fully integrated wind turbines and gas-fired CHP plants. The concept is that each cell will operate as an adjustable virtual power plant which can be controlled by the Watch at a regional control centre or Energinet's national control room. Such cells must be able to automatically uncouple and run in isolation in the event of an impending fall in voltage." [28]

Phasors

Accurate control of the transmission and distribution (T&D) network requires the simultaneous, accurate and timely understanding of the voltage, current and phase information at many points in the network. Current Supervisory Control And Data Acquisition (SCADA) systems do provide voltage and current information, but only at intervals of every few seconds/minutes. Normally, this data is not time stamped, making it difficult for the system operators (or computers) to get a complete picture (state) of the network at any given time. Without having a complete and accurate "snapshot", it is very difficult to recognize problems in the early stages, thus delaying action until the problem is well developed. The installation of Phasor Measurement Units (PMU) allows system voltage, current, AND phase to be measured many times a second, and be sent WITH a time-stamp back to a network control station. Data from multiple stations can then be time coordinated, assembled, and fed into computer programs that look for limit violations and excessive rate changes. With this information, network operators (and associated network protective systems) may quickly identify abnormal transients and predict if they present a threat to the network. If so, the operators (and associated network protective equipment) will potentially be able to take action to mitigate the transient, or to reconfigure the network to isolate the effected area. Such a phasor network was tested by Southern California Edison (for the California Energy Commission) in California in 2001. [29] In addition, the Eastern Interconnect Phasor Project was started in 2002 and is expected to end in 2008. This project is designed to connect many phasor units throughout the Eastern Interconnect of the United States. [30] The Electric Power Research Institute (EPRI) 2008 project 39.002 (Next Generation State Estimation) will attempt to utilize phasor data and go beyond mere monitoring and alarm, and will attempt to predict the trajectory (future states) of the electric grid.

> "Conventional state estimation formulation is based on certain assumptions about the system state. As technology enables synchronized measurements to be collected, these assumptions will no longer be necessary. Furthermore, since synchronized measurements can be obtained much more frequently than conventional measurements, they can be used to capture slow dynamics associated with the states. This project aims to develop a dynamic state estimator to predict state trajectory, which will possibly indicate some instability scenarios." [31]

Dominant Generator

As more and more renewable energy generators come online, measures to ensure constant grid voltage and frequency stability may need to be reexamined. Many renewable energy sources are designed to provide direct current or non-synchronous alternating current output, resulting in its ultimate conversion to alternating current at grid frequency through a power electronics unit. The following quote was taken from the short description of a 2007-2010 PhD project being conducted at the University of Denmark:

> "Conventional power plants … are responsible for controlling the frequency of the electricity network, whereas actual WPG (wind power generators) do not contribute to this control. Additionally, the increase of WPG …. is reflected as a decrease of conventional power plants, which makes the grid frequency control more difficult. If the penetration level of WPG increases above certain value, it will become technically difficult and economically expensive to maintain the actual strategy by mean of conventional generation. In new …. architectures with intentional islanding of distribution systems, frequency control becomes a very difficult issue". [32]

This issue was also noted as being of concern in the Danish Cell Controller paper. [10]

Technical Requirements

Grid codes (European term for grid connection requirements) were written for the generation and transmission equipment of their time, hence most grid code was written for large thermal plants and radial distribution networks. There is concern that grid code is getting in the way of the implementation of new renewable technologies, specifically by requiring costly capabilities that are no longer needed. As the following quotes will show, there is not uniform agreement on this issue:

> "Grid codes and other technical requirements should reflect the true technical needs for system operation and should be developed in cooperation between TSO's, the wind sector and government bodies. … Present grid codes often contain very costly and challenging requirements (such as fault ride-through capability and primary control) that have no technical justification. …. Costly technical requirements should only be applied if there is a true technical rational for them and if their introduction is required for reliable and stable power system operation". [8]

It should be noted that the above quote (by the European Wind Energy Association) challenged the requirements for low-voltage ride-through, whereas the Spanish experience [3] indicated a need to improve this capability for wind generators.

In the Ontario Wind Integration Study, General Electric stated that:

> "…advanced control features on wind plants (voltage regulation, low voltage ride through curtailment, frequency regulation, etc.) became increasingly important to maintaining balanced, stable and secure operation of the power grid. Even though some of these control features may not be necessary to achieve adequate grid performance in the near term, they will be critical in the future". [12].

Without taking a position on any specific control or safety feature, the recommendation that the grid code/connection code be re-examined to remove requirements that are no longer technically justified will be shared by all grid users and will potentially reduce the cost of large scale renewable energy development..

Transmission

The addition of distributed generation results in the potential for transmission congestion. A California report stated that: "Intermittency analysis indicates that wind variability contributes to transmission congestion under certain renewable dispatch scenarios and that transmission congestion patterns are more difficult to predict as the penetration of intermittent resources increases". [33] A Minnesota report indicated that 20% wind energy could be accommodated "if sufficient transmission investments are made to support it." [16] The current transmission and distribution infrastructure is probably NOT optimized for large scale renewable energy integration.

Summary of North American Wind Integration Studies

In references [9] and [18] Edgar DeMeo (and others) review wind integration studies conducted in North America. This section will summarize key findings from the studies covered by these articles. It should be noted that each study covered a different portion of the country, utilized different existing power generating assets (thermal or renewable), different loading programs, and in some cases entirely different methods of determining costs. As such, none of the studies are directly comparable to each other; however, each contributed to the current state of wind integration development and deserves some specific note.

In his 2005 article [18], DeMeo opens by addressing a few key concepts that are utilized throughout the studies.

First, due to its variability, wind is currently considered an energy resource rather than a power source. Wind energy principally contributes by displacing another fuel source.

Second, the term "penetration level" is defined as being "the ratio of nameplate wind generation to peak load served by the system." [18] Hence 2,500 MW of nameplate wind in a 25,000 MW peak load system would be a 10% penetration.

Third, studies typically come in two different varieties. Most studies evaluate the "Cost of Service". They "examine the costs of serving the portion of system load not served by wind…..In particular, these operating costs are estimated both with and without the effects of wind's variability. The difference in these two cost estimates is ascribed to accommodation of wind's variability and uncertainty and is allocated over the total amount of wind energy generated." These studies do not capture the impact of the cost of wind energy on customer payments (i.e. transmission costs and the value of primary fuel not expended) nor do they deal with transmission congestion issues. Other studies tend to be Market Studies. These studies capture everything, including the cost of displaced fuel and the value of the markets, i.e., the changing value of the electricity generated based on the time it is sold. As such these types of studies do not apportion costs in the same manner as cost of service studies and the results are not directly comparable. [18]

The following table was taken from data in reference [18]. It summarizes the cost results of the various studies. Blank spaces indicate that data was not provided. It should be noted that costs are expressed in US$/MWh. For comparability, a wholesale cost of power of 6¢/KWh equates to $60/MWh. From the tables below it should be noted that the costs of additional regulation are very small. The combined regulation and load following costs appear to be less than a third of the total integration costs. In most cases the major integration cost appears to be associated with the unit commitment/scheduling. It should also be noted that none of these studies looked at penetrations exceeding 30%.

Table 1: Wind impacts on system operating costs [18]

Study	Wind Capacity Penetration (%)	Regulation Cost (US$/MWh)	Load-Following Cost (US$/MWh)	Unit Commitment Cost (US$/MWh)	Total Operating Cost Impact (US$/MWh)
Xcel-UWIG 2003	3.5	0	.41	1.44	1.85
Xcel-MNDOC 2004	15	0.23	0	4.37	4.60
CA ISO 2002	4	0.59	0		
We Energies	4	1.12	0.09	0.69	1.90
We Energies	29	1.02	0.15	1.75	2.92
PacifiCorp	20	0	1.6	3.0	4.60

In addition, GE conducted a market study for NYISO in 2005 that indicated $350M in savings could be obtained through the inclusion of about 10% wind penetration in its 34,000 MW system. No additional spinning reserves were needed. Only 36MW of additional regulation authority was required. Of note, wind primarily replaced natural gas. [18]

In his review of an Oklahoma study (Western Farmers Electric Cooperative), he noted two key points. First, the control and integration of wind systems into the electric grid takes time and experience. Second, "…as wind's role increases, the balance of the generation mix is likely to shift in favor of more units with increased ramping capability." [18]

Utilities remain interested in understanding the capacity value of wind in order to make decisions concerning planning reserves. Planning reserves, used for long timeframe planning (how many plants will be needed to fill the projected energy loading), tend to be based on long term statistical measures of power production. DeMeo indicates that the Expected Load Carrying Capability (ELCC) is the best calculation of wind capacity value. The NYISO study found wind capacity value to be about 9% onshore in New York but almost 40% offshore. The Xcel study found capacity values ranging from 26-34% in the Midwest. Values around 20% were found by PacifCorp in their Pacific operating areas. Loss of Load Probability (LOLP) may be an easier method of determining the approximate capacity value in bimodal load shape locations (summer or winter peaks that exceed most other peaks during the year). [18] It should be noted that capacity calculation methods vary across the US so capacity values should not necessarily be considered fixed or directly comparable to a different portion of the country.

After reviewing the studies listed above (table 1, Oklahoma and NYISO 2005), as well as additional studies from California and Colorado) DeMeo came to the following conclusions:

- Wind integration costs are low (normally <10% of the wholesale energy value), but not zero.
- For power systems with a significant natural gas component, wind energy tends to displace higher cost natural gas, thus hedging against spiking gas prices and reducing electricity cost to consumer.
- Wind forecasting is of great value. Forecasting is used in the system planning stage, where current state-of-the-art techniques may already capture up to 90% of the total value attainable from forecasting (demonstrated in the NYISO 2005 case). Forecasting must now be utilized in operational (real time) planning and operations. The GE-NYISO study estimated the value of state-of-the-art weather forecasting at about $14/MWh.
- The impact of wind variability on system operating cost is reduced as the balancing authority (measured in MW) is increased. In addition, “Needed regulation and ramping capability may be difficult to access within a small balancing authority with a relatively small number of generating units.”
- “Costs arising from wind variability are a strong function of the characteristics of the system, such as generation mix and fuel costs, and will increase with increasing wind penetration”.
- “Wind power plants have nonzero capacity credit.” ELCC is the preferred estimation method and is primarily applicable to system planning activities.
- “Modern wind plants with low-voltage ride-through and variable reactive power compensation capabilities can actually improve system stability following a major power system disturbance.” [18]

In 2007 DeMeo (and others) reviewed studies not yet complete when his 2005 article was written. The focus of this article was to address the impact of more sophisticated/ advanced study techniques to improve the fidelity of the studies.

<u>Wind Data</u>: While some studies utilized wind data taken over the previous year(s), newer studies tend to use complex atmospheric models to develop time sequenced wind fields that emulate the given wind statistics for that area. In the Xcel-MNDOC 2004 study previously mentioned, computer based simulation accurately characterized both the variability and geographic diversity of wind. [18] Current atmospheric modeling programs tend to be utilized for prospective (future looking) studies, and are now accepted by the industry. [9]

<u>External Connections</u>: Newer modeling studies now look outside of the balancing area to account for potential interconnects with surrounding areas (CA IAP and 2006 Minnesota Wind Integration Study). [9] This greatly increases the complexity of the study.

<u>Wind/Load Interaction</u>: Newer studies (Xcel, Colorado and Avista) increase the look at statistical analysis of interaction between the load and the wind power produced over short time intervals. Most studies consider the variability of wind and of the load to be independent of each other; however the Minnesota 2006 study improved on this assumption by noting that there was no downward variability to wind when it was not

producing power, thus the required spinning reserves needed for regulation could be reassessed. A similar consideration was applied when wind power was operating near its rated output. [9]

Some studies provided Cost of Service data which is provided in Table 2 below and can be compared to the data provided in Table 1. The Avista 2007 study included many market aspects not included in other studies hence its resultant costs may be higher than would be expected from a straight cost of service study.

Table 2: Wind impacts on system operating costs [9]

Study	Wind Capacity Penetration %	Regulation Cost (US$/MWh)	Load-Following Cost (US$/MWh)	Unit Commitment Cost (US$/MWh)	Total Operating Cost Impact (US$/MWh)
Minnesota 2006	15				2.11 - ~3.00
Minnesota 2006	20	0.11			2.80- ~4.02
Minnesota 2006	25				~2.90 - 4.41
PSCO 2006/7	10				3.51
PSCO 2006/7	20	0.05			7.50-8.00
Avista 2007	5				2.75
Avista 2007	30				8.84

The Minnesota 2006 study looked at intra-hour interaction between load and wind power. When looked at over larger balancing areas, the relationships graphed in figure 3 were developed. These relationships demonstrate the value of increasing the size of the balancing area (less reserve capacity required for regulation) than by summing the regulation required by a number of smaller balancing areas.

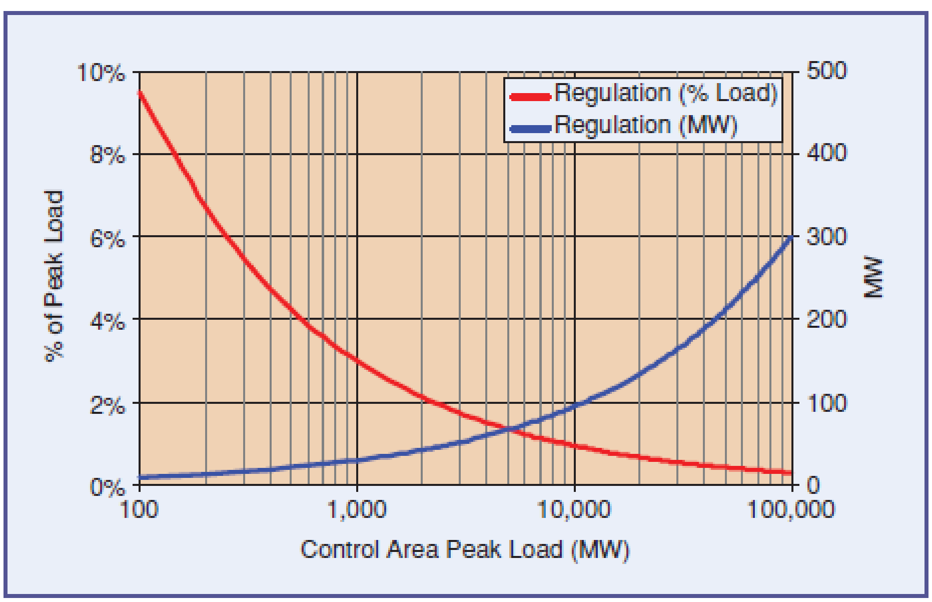

Figure 3. Regulation requirements as a function of peak load [9]

A 2005 study was conducted to consider the technical and economic impacts of developing a 10% or 20% wind penetration level in Public Service of Colorado (PSCO) territory. Much of the study considered tradeoffs against the development of new gas fired plants. The study found that wind forecast uncertainty had a negative impact on the scheduling of natural gas delivery to gas fired electric generating facilities. The negative impact was to the tune of ($1.26-1.43/MWh.). On the other hand, the study demonstrated the value of energy storage capability. "… doubling pumped storage capacity lowered integration cost by approximately $1.30/MWh in the 20% penetration case." The PSCO study further noted that, "Integration costs increase as the penetration level increases, and they increase more rapidly when penetration level surpasses 15%. This is due to the nonlinear nature of day—ahead unit commitment and the inability to flexibly maneuver low-cost resources to cover significant wind forecast errors." [9] Although not specifically noted by DeMeo, this result was noted in many of the other studies and should give the reader pause when considering the extrapolation of integration cost information above the penetration levels for which the studies were conducted. Further caution should be exercised when utilizing this information because the limiting cost factors may shift to transmission or distribution issues, which are not considered or included in the Cost of Service type studies. Such was an implied conclusion of the California Intermittency Analysis Project (CAIAP). [33]

Unlike many of the other studies, the California Intermittency Analysis Project was designed to look at transmission issues that would effect the ability of the state to increase the amount of wind (and solar) energy from key areas within the state. In addition, this study looked at wind, solar and load data at very short time frames (in the order of 1 minute), as well as longer time frames. The study confirmed some of the issues already addressed by this paper.

- The need for control of wind plant output: "Because of occasional coincidence of low loads, high wind generation, and the inability to sufficiently reduce other generation, it will be necessary to sometimes curtail wind generation. … The system would also benefit from the ability to occasionally limit the ramp rates on wind plants. "
- The need for energy storage: CA often gets wind during light load situations, hence it must find ways to minimize other generating capability, export the energy, or utilize the energy, such as pumped storage or (potentially in the future) plug in hybrid vehicles.
- "Most of the value to the system came from the displacement of natural gas in combined cycle units. "
- Accurate wind forecasting has value. Wind forecasting was worth $4.37/MWh of wind energy. [9]

The need for potential wind curtailment during certain hours of the year was also noted during the Ontario (Canada) Wind Integration Study. This curtailment was potentially needed during hours of light system loading. [9]

The Avista 2007 study considered wind integration in the Pacific Northwest. This area was unique for its high installed hydropower capacity. As would be expected this study showed that higher levels of wind penetration resulted in higher integration costs. Due to the construction of this study integration costs were correlated with wholesale market prices. As such, when wind power offset the need for hydro power during peak periods, the lost hydro revenue (peak value vs the value when the hydro power was actually sold during off-peak periods) was considered a wind integration cost.

This study further found that:

- Shorter-term (i.e. 10 minute rather than 60 minute markets can reduce integration costs by 40-60%.
- Rising day and hour ahead forecast error increases integration costs.
- Geographic diversity can greatly reduce integration costs.
- Operational coordination (i.e., ability to feather wind) between the control area and wind generators can reduce integration costs by 20-40%.[9]

Closing

This paper has summarized many issues that should be considered when planning the large scale integration of renewable energy into an existing electric grid. Many studies, which considered penetration levels up to 30%, were summarized and example data provided. One observation that becomes clear after reading these studies is that every situation is different. When considering the large scale integration of renewable energy into an existing electric grid, the specifics of the geography, the weather, the weather forecasting ability, the existing generating resources (and their cost structure), carbon taxes, emissions policy, transmission and distribution structures, and a host of other factors must be evaluated, and in many cases modeled and simulated, in order to achieve an effective integration.

Policy decisions will drive system planning decisions that will ultimately drive acquisition decisions; therefore it is important to ensure that policy decisions are provided in a form that can be utilized by system planners. Given the current method of optimizing based on cost as the primary driver, policy decisions must be provided in a form that will allow system planners to equate a decision to a cost.

Depending on drivers specific to each situation, policy could be crafted to respond to those pressures, ranging from reduction of global warming emissions, increasing fuel/energy security, increasing fuel/energy source diversification, reduction of thermal/ noise/light pollution, more sustainable land usage, etc. Many of the studies discussed in this report demonstrate the technical possibility that new renewable energy resources would displace more “conventional” resources that had low carbon emissions (natural gas, hydropower) rather than coal, based on the reduction of operating costs as the primary driver. If the primary driver of new renewable energy resources, however, was to minimize global warming potential, then displacing low-carbon emitting sources, such as hydropower and natural gas may not be a desirable outcome.

With the stated goal of increasing renewable energy penetration to 70%, Hawaii has the opportunity to be in the forefront of utility system planning. As such, the State is in the position of setting precedent for other localities to follow. A decision to address the policy drivers that are important to the State of Hawaii (the nation and the world) for implementation in utility system planning would ensure that the long term results reflect the desired outcome (policy), and would certainly set an enviable example for others to follow as the United States, and the world, move toward large scale renewable energy integration.

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