Final Report:

Potential Mitigation of Dynamic Reliability Challenges with High Levels of Variable Energy Resources

Prepared for: **Western Interstate Energy Board**

Prepared by: **Debra Lew**

Robert D'Aquila

Nicholas Miller

April 24, 2015

Imagination at Work

Legal Notices

This report was prepared by General Electric International, Inc. as an account of work sponsored by the Western Interstate Energy Board. Neither the Western Interstate Energy Board, General Electric International, Inc., nor any person acting on their behalf:

1. Makes any warranty or representation, expressed or implied, with respect to the use of any information contained in this report, or that the use of any information, apparatus, method, or process disclosed in the report may not infringe privately owned rights.
2. Assumes any liabilities with respect to the use of or for damage resulting from the use of any information, apparatus, method, or process disclosed in this report.

Acknowledgment: "This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award Number(s) DE-OE0000422."

Disclaimer: "This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

Foreword

This paper was prepared by General Electric International, Inc. acting through its Energy Consulting group based in Schenectady, NY, and submitted to the Western Interstate Energy Board. Questions and any correspondence concerning this document should be referred to:

Debra Lew

Technical Director

GE Energy Consulting

1 River Road

Schenectady, NY 12345

(303) 819-3470

debra.lew@ge.com

Table of Contents

List of Figures

List of Acronyms

AC	Alternating current
CSP	Concentrating Solar Power
DER	Distributed Energy Resources
EI	Eastern Interconnection
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FFR	Fast Frequency Response
GE	General Electric International, Inc.
GHG	Greenhouse gas
MRITS	Minnesota Renewables Integration and Transmission Study
MW	Megawatt
NERC	North American Electric Reliability Corporation
PSCO	Public Service of Colorado
PFR	Primary Frequency Response
PV	Photovoltaics
RPS	Renewables Portfolio Standard
VAR	Volt-amp reactive
VER	Variable Energy Resources
WECC	Western Electricity Coordinating Council
WWSIS	Western Wind and Solar Integration Study

1 INTRODUCTION

Additions of variable energy resources[1] (VER) and retirements of coal plants in the Western Interconnection may lead to reliability challenges in a system that was originally designed around large thermal power plants. This paper seeks to provide Western states and provinces, the Western Electricity Coordinating Council (WECC) and Order 1000 Regional Planning Group with the beginnings of a roadmap to carefully and credibly analyze reliability challenges and mitigation options. This paper includes:

1. **Analysis types and procedures that illuminate potential reliability problems**. This includes knowing where to look for issues and how to quantify them, types of data and boundary conditions to be used, sensitivities, and consequences of the problems.
2. **Mitigation option analysis**. This discusses mitigation options for various issues that are likely to be encountered in the future. Potentially promising solutions will be discussed.

The grid of the future will be very different from today's system. We envision the following changes:

- More renewable energy – Renewable Portfolio Standards (RPS) and greenhouse gas (GHG) reduction targets will lead to additional renewables on the system. Declining photovoltaic (PV) and wind prices are already resulting in these resources being added as a least-cost resources in some areas.
- Less coal – EPA's Mercury and Air Toxics Standards, visibility regulations, local air quality issues and EPA's new Clean Power Plan (Section 111d) have been and/or will continue to lead to faster coal retirements than might otherwise occur.
- More gas – Low gas prices due to shale gas extraction will continue to encourage gas generation.
- More distributed energy resources (DER) – DER, especially rooftop solar, is rapidly growing in many areas of the country. Some states have specific DER or rooftop solar targets. Customer-sited storage, electric vehicles and eventually vehicle-to-grid technology may become more common.

All of these changes will lead to changing power flows in the Western Interconnection, potentially weak grid areas, and impacts on system reliability.

2 BACKGROUND

Reliability refers to two different concepts: 1) resource adequacy (supply exceeds demand, even if there are unscheduled outages) and 2) operational reliability (ability of the system to withstand disturbances such as short circuits or unanticipated loss of elements). In this

[1] The Federal Energy Regulatory Commission defines a variable energy resource as a device for the production of electricity that is characterized by and energy source that: 1) is renewable, 2) cannot be stored by the facility owner or operator, and 3) has variability that is beyond the control of the facility owner or operator.

paper, we discuss *operational* challenges from VERs, so the term "reliability" in this paper will refer to the latter definition. In particular, we discuss how frequency response and transient stability can be affected by VERs and potential mitigation options for these impacts.

VERs are different from conventional generators and impact the system in different ways. The variability and uncertainty (forecast error) of the VERs lead to challenges in balancing supply and demand. The fact that wind and PV are non-synchronous generators – they are connected to the grid via inverter-based controls – leads to challenges in operational reliability and stability. Conventional generators such as nuclear, gas, coal, oil and hydro plants are all synchronous generators.

Note that in this paper, concentrating solar power (CSP) is treated the same as a conventional generator. For the purposes of operational reliability and stability discussed here, CSP, powered by steam turbines, shares the same attributes as coal and combined cycle plants that are also powered by steam turbines.

2.1 Frequency Response

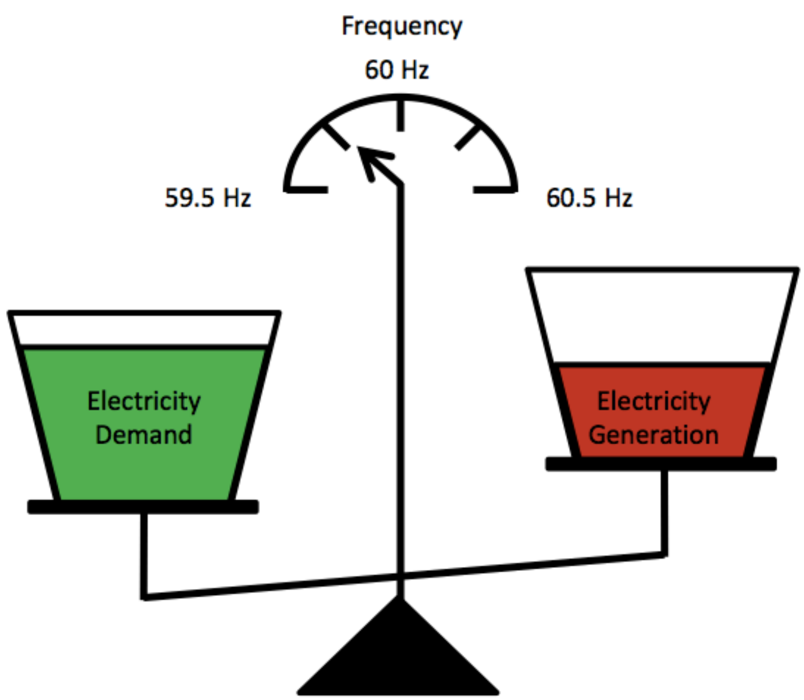


Figure 1 – If demand (load) exceeds supply (generation), then frequency declines.

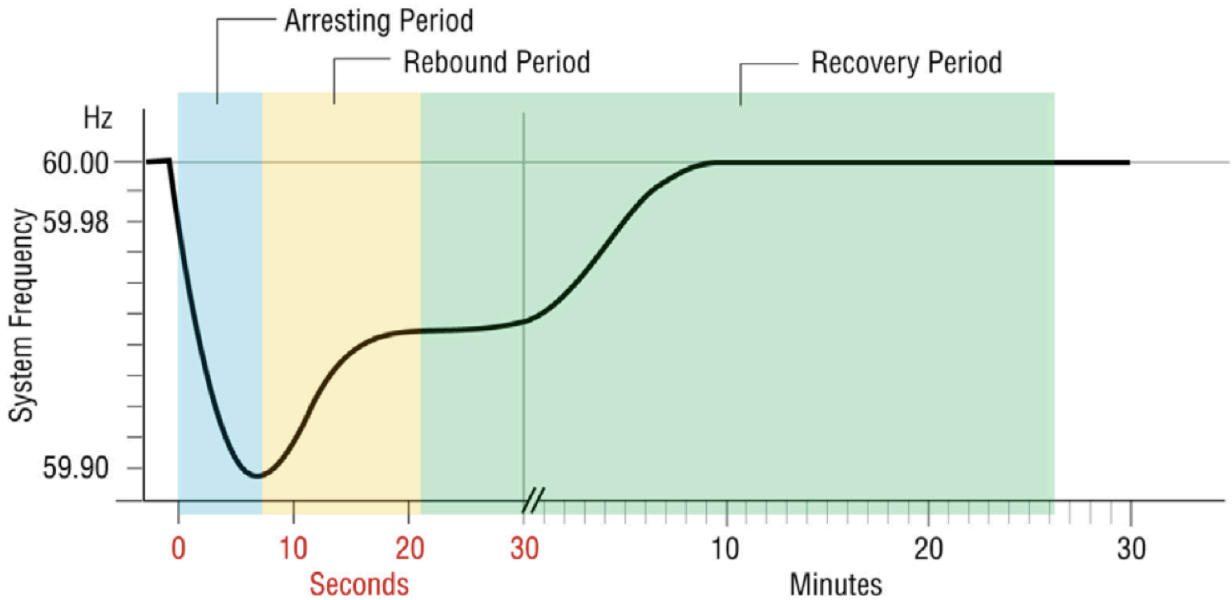


Figure 2 – Frequency response to a loss of generation[2].

Frequency response is the ability of the system to stabilize and restore grid frequency following large, sudden mismatches between generation and load. For example, if a generator trips offline, load will exceed generation and as a result, frequency across the interconnection will decline (see Figure 1). Figure 2 shows the frequency response to such an event:

- A large generator trips offline at t=0.
- ***Inertia*** from the rotating mass of generators and induction motors that are online will define how fast frequency falls in the first few seconds (the arresting period).
- ***Primary frequency response (PFR), also called governor response***, will stabilize frequency in the seconds to tens of seconds time-frame. Governors in conventional thermal or hydro units will sense the frequency drop and instruct the unit to increase its output. This is the rebound period. The frequency minimum is called the 'nadir' and is defined by a combination of the inertia and the PFR in the system. The PFR will allow the frequency will settle at a new point based on the load/generation balance.
- Secondary frequency response, also called regulating reserve, will increase output during the recovery period to return frequency to nominal. This occurs in a few minutes.
- Tertiary reserves are used to restore the system back to normal, replacing the primary and secondary reserves, so that it can be ready for the next event. This occurs in the tens of minutes time-frame.

[2] J. Eto, et al. "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation", LBNL-4142E, Dec. 2010. http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

If frequency drops to below some level, such as 59.5 Hz, under-frequency load shedding kicks in to drop blocks of firm load to help restore frequency.

It is important to recognize that frequency is a *system-wide* measure. When generation and load are out of balance, the frequency across the system moves away from nominal.

2.2 Transient Stability

There are many stability issues but here we focus on maintaining synchronism, frequency and voltage. Following a disturbance such as a fault on a transmission line, the system needs to move into a new stable operating condition. This is fast phenomena, occurring in the seconds to tens of seconds time-frame. Transient stability is the ability of the power system to maintain synchronism between all elements following disturbances. Transient stability concerns are an issue in WECC and the Electric Reliability Council of Texas (ERCOT), where the grid is not dense and where long transmission lines connect generation to load.

Voltage stability depends on the ability of the system to balance reactive power. Reactive power (measured in VARs) is the result of voltage and current being out of phase. When voltage and current are completely in phase, real power is transmitted, and this real power does work, like providing heat, light or motion. When voltage and current are out of phase, then some reactive power is transmitted. Reactive power doesn't do work, but it sustains the electromagnetic field. Supplying reactive power increases voltage; consuming reactive power decreases voltage. Any load that has a coil or capacitor can cause reactive power, like induction motors, transformers or transmission lines. When they are heavily loaded, transmission lines consume reactive power. Real power can travel far on transmission lines but reactive power cannot. Consequently, we want to generate reactive power at the location where it is needed. In contrast to frequency response, voltage stability is very *location-dependent*.

2.3 Weak Grid

Synchronous generators (conventional plants or synchronous condensers) are pure voltage sources and contribute short-circuit current to the system. When a fault occurs in a power system, the current flowing into the fault is determined the characteristics of the synchronous machines and by the impedances in the network between the fault and the machines. Systems with high levels of synchronous generation, and extensive transmission will have in high short circuit currents. This is referred to as a "strong" grid. A strong grid is less prone to voltage stability issues and will have a faster post-fault voltage recovery than a weak grid.

Non-synchronous generators (wind turbines, PV, HVDC converters) do not contribute to system strength. Additionally, the controls of non-synchronous machines require a relatively "strong" grid to operate stably.

2.4 Studies

Analyses of these issues are typically conducted in a positive sequence load flow model that examines system dynamics. Because the phenomena are fast, the simulations are run for seconds to minutes. This is very different from production simulation models which are typically used in integration studies. Production simulation models typically model 8760 hours of a year and simulate dispatch of each generator and transmission flows. They give high level economics, emissions, and fuel use results. Dynamics models, on the other hand, start with a moment in time, simulate an event like a fault on a transmission line, and look at system response for the next tens of seconds to see if the system can recover and stabilize.

A simple, but incorrect, way to set up a snapshot for a dynamic model is to remove some MW of conventional generation and insert the same number of MW of VERs. The reason is that in grid operations, VERs don't displace conventional generation in that way. The National Renewable Energy Laboratory's Western Wind and Solar Integration Study[3] (WWSIS) found that for every 3 MW of VER generation, 2 MW of conventional generation were decommitted, or taken offline, and 1 MW of conventional generation was dispatched, or backed, down. These amounts would change for different VER/generation mixes or systems. This is why it is very important to carefully select the appropriate commitment and dispatch from production simulation output to input into the dynamic models. Consequently, there is interest in "round-trip" analyses, that establish consistency between the production simulation and the power flow models: they use production simulation results in power flow cases and use power flow changes in the production simulation model.

3 WHAT KINDS OF GRID CHALLENGES MIGHT WE FACE?

In a future with more renewables, less coal, more gas and with more DER, what kinds of challenges might we face? With higher penetrations of wind and PV, we could face reliability challenges with the loss of a large generator. Steam, gas, or hydro turbines such as those found in conventional coal, gas, hydro, or CSP plants, are synchronous machines and their large rotating masses naturally provide inertia. If their governors are enabled, synchronous machines can provide PFR. Wind and PV are non-synchronous and do not naturally provide inertia or PFR, although these features can be enabled as we will discuss later. Figure 3 shows the synchronous penetration levels (gray plus red slices in pie charts) decreasing as one goes from the base (moderate renewables) to the high renewables case in phase 3 of WWSIS. Non-synchronous as a percentage of total generation is 21% in the base case and 37% in the high renewables case (41% in the desert southwest subregion). Low inertia or PFR levels can lead to inadequate frequency response. Weak grid issues can result from low synchronous penetration levels.

[3] GE Energy, "Western Wind and Solar Integration Study," NREL/SR-550-47434, May 2010. http://www.nrel.gov/docs/fy10osti/47434.pdf

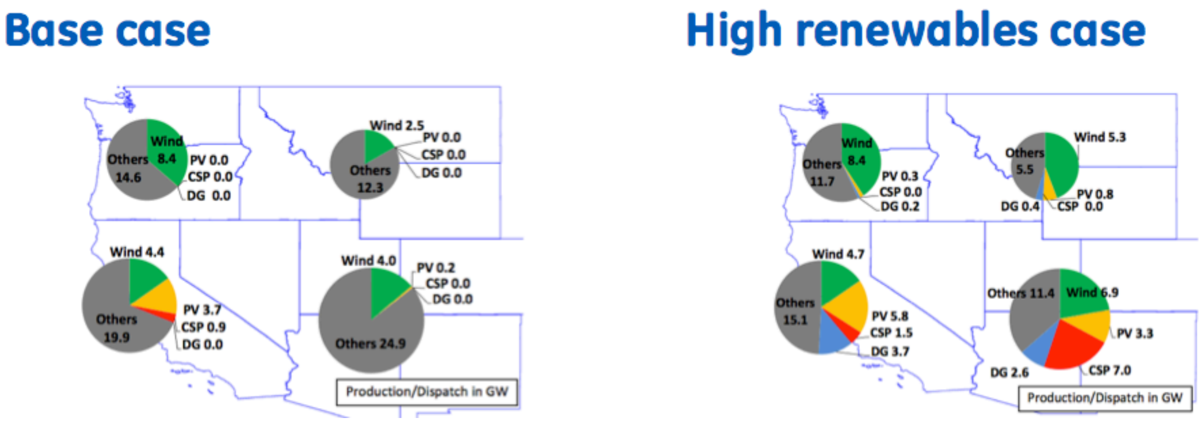


Figure 3 – Western Wind and Solar Integration Study Phase 3 scenarios show levels of synchronous penetration dropping in the high renewables case[4].

In the future, DER may be supplying a significant portion of our load. This can create reliability challenges because DER interconnection requirements were not designed to be used for significant DER penetration levels. For example, Germany recently spent about half a billion US dollars retrofitting their rooftop solar inverters[5]. About 12 GW of rooftop PV systems had been installed with over-frequency trip settings of 50.2 Hz (remember that Europe is 50 Hz nominal frequency as opposed to 60 Hz in the US). This led to a reliability issue in that if there were a loss of load and frequency increased to 50.2 Hz, then 12 GW of generation would trip offline. The European system is designed to handle a loss of only 3 GW, so a 12 GW loss would result in a significant frequency drop. Inverters were retrofit so that instead of tripping offline at 50.2 Hz, their output would decrease proportionally, depending on how much frequency exceeded 50.2 Hz. This kind of retrofit required a great deal of human and financial resources and could have been avoided with system studies and advance planning.

It's important to be proactive in studying these types of potential futures. Mitigation options are limited if there is little time available to address problems, such as the retirement of a large generator. Having more time to plan and implement solutions allows for a broader range of options, some of which could be much more beneficial in the long term as well as less expensive.

The types of analysis that should be investigated in a high renewables, low coal, high gas, high DER future include:

- Frequency response to loss of large unit (or two)

---

[4] N. Miller, et al, "Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability", NREL/SR-5D00-62906, December, 2014. http://www.nrel.gov/docs/fy15osti/62906.pdf

[5] B. Ernst, SMA, "Evolution of LV PV Interconnection Requirements in Germany," Utility Variable Generation Integration Group Spring Technical Workshop, Anchorage, AK, May 2014.

- Stability issues – flow patterns and generation changes will likely lead to new path limits in WECC.
- Stability – Fault response when the system is stressed with high loadings on key interfaces
- Weak grid issues – in load centers where large nuclear or coal plants are being retired, there may be a loss of short circuit strength which reduces ability to recover voltage if there is a fault.
- Weak grid issues – in remote areas where coal plants are being retired and wind plants are being installed, there may not be enough short circuit strength on the system to keep the wind controllers stable in an event.

4 IDENTIFYING PROBLEMS

North American Electric Reliability Council (NERC) and WECC transmission planning standards specify tolerances for how voltage and frequency can deviate from pre-fault conditions after different categories of faults on the system. But to which events do we apply these reliability criteria? In the past, defining snapshots to evaluate was straightforward. We would evaluate a low load, high load, and shoulder period[6]. In a high renewables, low coal, high gas, high DER future, this becomes more complex. We need to develop new metrics and screening tools so that we can look at new stress points on the system in terms of which generators are online, path flows, and different test events.

4.1 Mapping production simulation to powerflow

New metrics for selecting hours of the year for in-depth study could be based on:

- **% Non-synchronous**, defined as the percentage of total online capacity that is wind and PV – This is an indicator of AC system strength. It also indicates how much inertial response is online.
- **% VER penetration**, defined as the percentage of total dispatched generation that is wind and solar – this shows when dynamic performance of the system may be dominated by dynamic performance of the VER.
- **High path flows** – this helps to examine resilience to transmission faults

Screening should be conducted in multiple ways, for example by season, subregion, load level, VER penetration level, etc. For example, Figure 4 shows a screening step from the Minnesota Renewables Integration and Transmission Study[7] (MRITS) study. MRITS started with conventional powerflow cases (light, shoulder and peak load) that represent snapshots in time. This specific screening process was aimed at selecting challenging high % Non-synchronous conditions. MRITS then examined the production simulation results and

[6] A low load snapshot might be during the spring when loads are typically lower, versus a high load snapshot that might be during the summer when loads and path flows are both high.

[7] GE Energy Consulting, "Minnesota Renewable Energy Integration and Transmission Study", Oct. 31, 2014. http://www.minnelectrans.com/documents/MRITS-report.pdf

screened those 8760 hours for load level, season, time of day, and highest % Non-synchronous. These multi-step screening processes yielded handfuls of hours for each metric. Commitment and dispatch of the conventional units and path flows were then examined in these handfuls of hours to understand trends of operation. For example, what does a particular generator typically do during a light load hour on a spring morning when VER levels are high? This kind of analysis informed how to set up the dynamics case. Sensitivities could then be performed on any of these cases, for example, to examine different path loadings or locational issues.

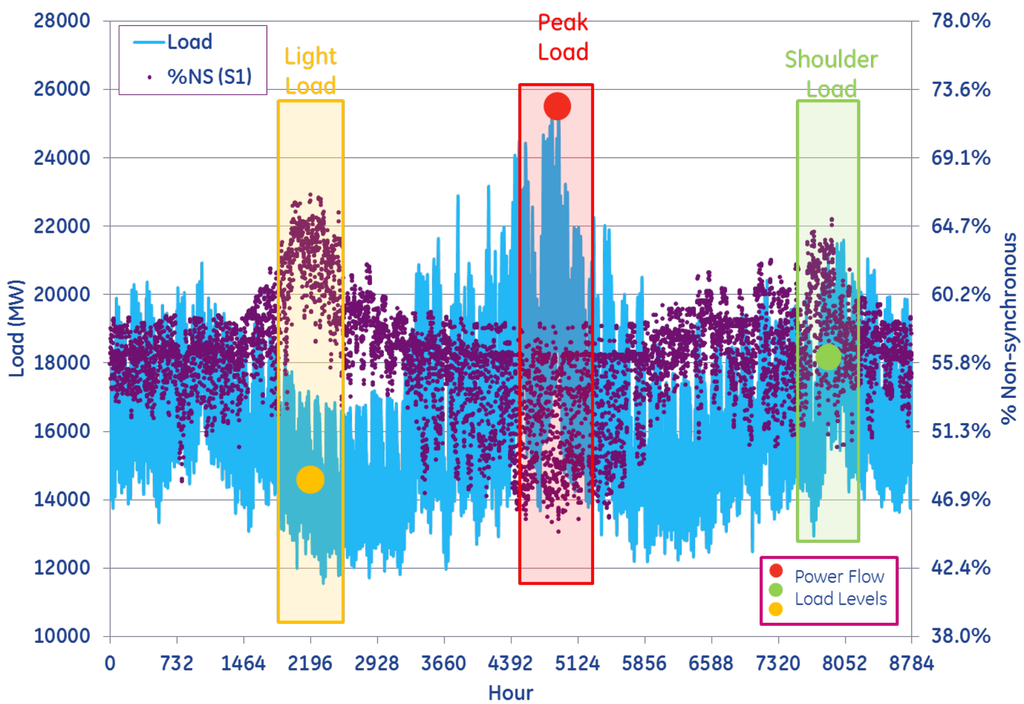


Figure 4 – Chronological load and % Non-synchronous from MRITS study[8].

Powerflow cases could then be developed based on the trends seen in the representative hours of production simulation. The commitment and dispatch of larger units were set directly from the selected hours of production simulation results. The generation of VERs were typically set based on regional averages over the selected hours. This process was repeated for each load level and screening metric.

The new set of powerflow cases should be carefully analyzed, checked, and fine-tuned to ensure they do indeed match the critical periods in the production simulation. For example, the % Non-synchronous across all of WECC and within each region was calculated and compared to the selected production simulation hour used to develop the cases. In addition, bus voltages and line flows were checked to ensure they were within the normal expected

8 GE Energy Consulting, "Minnesota Renewable Energy Integration and Transmission Study", Oct. 31, 2014. http://www.minnelectrans.com/documents/MRITS-report.pdf.

range. Dynamic reactive reserves were then be quantified. This indicated the ability to survive transient system disturbances, because reactive power is needed to support the voltage after a fault.

4.2 Selecting tests

Once cases have been selected, tests need to be defined. The retirement of coal plants and the addition of VER will change the system's dynamic response. Classic frequency response tests include the NERC design outage (loss of 2 Palo Verde units in WECC). Stability tests investigate the loss of key paths like the California-Oregon Interface. But with coal retirements and increased VERs, the dynamic response will change and where the system is stressed will change. So critical outages instead might examine areas where there is high VER or high DER or low synchronous generation levels. For example, follow-on work to phase 3 of WWSIS focuses on the northeast part of WECC where there are low levels of synchronous generation and where weak grid issues may challenge the system. Tests should include the traditional contingency set plus additional outages that address these types of issues.

Weak grid issues can be examined by identifying areas with low short circuit currents relative to the amount of inverter-based generation. This is typically measured as a short circuit ratio, or the ratio of short circuit MVA (available fault current times rated voltage) to the installed MW of renewable generation. This is an area receiving significant attention, with new measures and study methods being developed.

5 MITIGATION OPTIONS

Nearly any problem can be mitigated. The challenge is whether the costs, time and effort make it worthwhile. This section examines some mitigation options for common problems. However, it is important to note that the mitigation process is really a problem-solving process. For example, an experienced engineer may be able to identify that changing the location of some system components could avoid new and more expensive infrastructure. This is why it is essential to conduct the studies and ensure there is adequate time and resources to examine mitigation.

5.1 Inadequate frequency response

What can be done if frequency drops too low, e.g., hitting under-frequency load shedding, as a result of a loss of large generation? Options to examine include increasing inertia, primary frequency response and fast frequency response.

5.1.1 Wind inertial response

Increasing inertia will slow the frequency decline. In a high VER future, it will be important to get this response from VERs as appropriate because synchronous generators may be offline. For example, the major manufacturers of wind turbines currently offer a synthetic inertial response for wind. The wind turbine's power electronics can extract some of the rotating mechanical inertia from the rotor to provide this response. This can be done without pre-curtailing the wind turbine. The reason that wind turbines in the US don't currently use this response is that no one requires it, although ERCOT is analyzing inertia as one of its future ancillary services[9]. Quebec and Ireland are among some of the regions that require wind inertial response.

5.1.2 Synchronous condensers

Synchronous condensers are basically electrical generators that are online and spinning. They do not produce real power; instead they produce or consume reactive power, depending on how their field is magnetized.

The primary motivation to installing synchronous condensers is to increase system strength (short circuit current). However, because they are spinning, they also provide inertia to the grid. While the inertia of a synchronous condenser will be lower than a generator with a prime-mover, they do contribute to overall system inertia and can help with initial frequency response. Several new synchronous condensers are being installed (or are in the planning phase) in high load and/or high renewable areas throughout WECC, ERCOT and the Eastern Interconnection (EI).

An alternative to a new synchronous condenser is the conversion of a retired conventional plant into a synchronous condenser. Essentially, the steam or gas turbine is removed and the existing generator is operated as a synchronous condenser. The existing transformers and transmission lines and some of the other infrastructure may be re-used, reducing costs. Several large steam turbine-generators in the EI have recently been converted to synchronous condensers.

To give a very rough sense of synchronous condenser costs, ERCOT's Panhandle Renewable Energy Zone Study of April 2014[10] estimated that a new 200 MVA synchronous condenser would cost $43M. Additionally, it has been reported that FirstEnergy is converting their 1257 MW Eastlake coal plant to 5 synchronous condensers at an estimated cost of $60M[11].

5.1.3 Clutches on gas plants

New gas capacity will provide more inertia on the system. However, it is important to realize that in a high VER future, gas plants may not be running 24/7. Here is an example of potential gas plant operation:

- Started in the morning to meet the morning load
- Shut down mid-morning when solar output is sufficiently high enough

[9] ERCOT, "ERCOT Concept Paper: Future Ancillary Services in ERCOT", http://www.ercot.com/content/news/presentations/2014/ERCOT_AS_Concept_Paper_Version_1.1_as_of_11-01-13_1445_black.pdf

[10] ERCOT, "Panhandle Renewable energy Zone (PREZ) Study Report", April 2014, http://www.ercot.com/content/news/presentations/2014/Panhandle%20Renewable%20Energy%20Zone%20Study%20Report.pdf

[11] http://www.news-herald.com/general-news/20140527/firstenergy-in-middle-of-converting-eastlake-power-plant-coal-generating-units

- Restarted as sunset approaches, to meet the evening peak
- Shut down again as wind picks up and load drops.

In order to provide voltage support and inertia while the gas plant is shut down, a clutch could be installed that allows the generator to continuously spin, despite the fact that the gas turbine may be shut down. Clutches are not new (for example, the Los Angeles Department of Water and Power, LADWP, has clutches on two of their gas plants) but they are not very common.

5.1.4 Primary Frequency Response from VERs

PFR helps to restore frequency to a new settling point. Wind and PV can provide PFR if their controls are enabled appropriately. Again, this is a response that can be purchased as a feature, but it typically is not purchased because it is not required, except in ERCOT. Over-frequency response (reduce output when frequency is high) is an easy response for VERs to provide. Under-frequency response (increase output when frequency is low) requires pre-curtailment of the VERs. In ERCOT, wind is required to provide this under-frequency response if conditions allow, i.e., when the wind is being curtailed anyway and has room to move up.

5.1.5 Governor response from other generation

Not all conventional generators are equipped with governors or have those governors enabled. For example, a nuclear power plant that is designed to run baseloaded would not provide governor response. However, there may be generators that could provide governor response if they were appropriately incentivized. And CSP can provide governor response.

5.1.6 Fast Frequency Response

Fast frequency response (FFR) is similar to PFR but on a faster time-scale than governors can provide. In PFR, governors need to sense the frequency deviation, increase the fuel feed, raise temperatures and increase power output. Full FFR response is delivered within 0.5 seconds at specified frequency thresholds (eg 59.97 Hz or 59.98 Hz) and arrests frequency decay to provide time for PFR to deploy. Load can provide FFR. For example, ERCOT currently procures 1400 MW of a Responsive Reserve Service from load resources that meet FFR specifications. It may be possible for some storage and some VERs to provide this fast response. For VERs to provide an upward response, they would have to be pre-curtailed. Depending on system conditions, a smaller amount of FFR can provide the same system support as a larger amount of PFR, making this faster response more valuable.

5.2 Stability Issues

It is important to note that path ratings will very likely change in a high renewables, low coal, high gas, high DER future. It is difficult to say, without doing the analysis, whether path ratings may increase or decrease. For example, during an event, conventional generators may swing relative to each other, meaning that they can start to get out of phase with each other. VERs, on the other hand, don't swing, and so can be more stable in that respect.

5.2.1 Traditional transmission reinforcements

There are traditional transmission reinforcements that can be used such as new lines and transformers. Other common infrastructure includes shunt and series capacitors, static VAR controllers (SVCs), and static synchronous compensators (STATCOMs). SVCs and STATCOMs provide dynamic reactive power compared to static capacitor banks, but STATCOMs are superior to SVCs as voltage decreases.

5.2.2 Voltage regulation from VERs

VERs can regulate voltage by providing or consuming reactive power. VERs can provide good reactive power support to the system but they do have hard limits to this provision, as opposed to conventional generators that will typically have high overload capabilities. It is important to note that VER power electronics can provide reactive power even when the sun is not shining or the wind is not blowing, by drawing real power from the grid and converting it to reactive power.

5.2.3 DER response and ride-through

The response of DER to voltage and frequency transients is important. If DER has no ride-through capability and trips offline, this can make an event, such as an under-frequency event, worse. DER interconnection requirements were not designed for DER to provide a significant amount of generation on the system and instead required DER to trip offline at very sensitive voltage and frequency thresholds. The IEEE 1547 standard for DER interconnection is currently undergoing revisions, but this process may be lengthy. In the meantime, an interim amendment allows for voltage and frequency ride-through and also active voltage regulation, but none of these were made mandatory. To maintain reliability and stability of the bulk power system with high DER penetrations, DER interconnection standards should include voltage and frequency ride-through and active voltage regulation.

5.3 Weak Grids

Weak grids result from not having enough synchronous machines. For example, retirement of coal plants in the northeast part of WECC could result in a weak grid in that area. The first problem induced by weak grids is voltage recovery. After a fault clears, voltage may be depressed across the load for many seconds afterwards. This is because induction motors, such as air conditioners, may be trying to restart and are stalling. This draws a lot of reactive power which in turn depresses voltage. Depending on the situation, under-voltage load shedding can result.

The second problem is that wind and PV controls are less stable in weak grids. During a disturbance, these controls can oscillate and go unstable.

Traditional transmission reinforcements such as those listed above can provide mitigation. VER voltage regulation can also help. But the main need here is synchronous generation. Clutches on new or existing generation and synchronous condensers can provide mitigation as described in section 5.1. More intricate tuning of controls on generators can also help and this requires much more detailed analysis.

6 CHECKLIST

Here are some items to consider in conducting and reviewing studies. This is meant to be a simple guide and not a substitute for detailed analysis and experience.

- Which snapshots are selected for dynamics analyses?
  - Don't focus on just a worst case hour from a production simulation. The goal is to get an understanding of the system dynamics when the system is stressed. Capture a trend using representative snapshots from analysis of many hours and then run sensitivities to capture the worst case but also other realistic possibilities.
- How is production simulation mapped to powerflow?
  - Don't try to map all units directly, which is very tedious and time-consuming. Many assumptions are needed because powerflow is more detailed than production simulation in some ways. Instead of getting every small plant right, get the important and the large plants right. Relate the powerflow and stability cases back to the production simulation. Double-check the powerflow case with careful analysis because it is easy to end up with an unrealistic situation.
- How is load modeled?
  - Load modeling has a huge impact on results. For example, induction motors in the load actually help provide inertia to the system and arrest the frequency decline, but induction motors are increasingly being replaced with variable speed drives and other inverter-based controls. Phase 3 of WWSIS found that WECC's new composite load model was a tremendous improvement over the previous standard load model.
- How is distributed generation modeled?
  - Do not net DER from the load. Model DER explicitly if there are high DER penetrations because DER can have an impact on system response as was found in Phase 3 of WWSIS.
- Is model benchmarked to actual events?
  - Benchmarking is important for credibility of results. While it may seem that generator dispatch and commitment are realistic, there are other inputs to the model that can have a large impact that are not transparent. For example, the number of units that provide governor response is often over-estimated, making frequency response seem better than it is. It is difficult to get information on which generators are providing governor response.
- For frequency response issues, have these been considered:
  - Active power controls on wind/PV/CSP
  - Governor response from thermal units that aren't currently providing it
  - Use of fast frequency response and load response
  - DER response and interconnection requirements

  - Clutches on gas generators
  - Synchronous condensers (new or conversions)
- For stability issues, have these been considered:
  - Reactive power from wind/PV/CSP
  - Clutches on gas generators
  - Synchronous condensers (new or conversions)
  - DER response and ride-through
  - New transmission lines or transformers
  - Traditional reinforcements such as capacitor banks, SVCs, statcoms
- For weak grid issues, have these been considered:
  - Clutches on gas generators
  - Synchronous condensers (new or conversions)
  - Reactive power from wind/PV/CSP
  - Traditional transmission reinforcements

7 CONCLUSION

In summary, a system with high VER, low coal, high gas and high DER will be very different from today's grid. It may pose challenges to operational reliability and stability. Proactive studies of potential future scenarios are important. They can reduce the risks of costly, retroactive changes to generators. They also widen the solution space, by allowing for more time in which to implement solutions.

There are many lessons learned from completed analyses regarding how to set up the reliability and stability studies: how to select and set up cases, how to select tests, how to ensure results make sense, and how to investigate mitigation options. This body of work will grow as more utilities undertake these studies and start to develop more generalizable results.

Finally there are mitigation options for the challenges that have been encountered so far. There are new options, such as advanced wind and PV controllers to provide inertia, PFR and voltage regulation, as well as applications of old options like clutches on gas generators to maintain grid strength even when the gas turbine is not producing power.

8 APPENDIX A

Presentation at the Joint Committee on Regional Electric Power Cooperation, State Provincial Steering Committee, Western Interstate Reliability Advisory Board Meeting on April 6, 2014.

Potential Mitigation of Operational Reliability Challenges from high VER penetration levels

Debbie Lew, Rob D'Aquila, Nick Miller

April 6, 2015

Imagination at work

Future will be very different from today's grid

More renewables

- RPS targets, GHG targets
- Cheap PV

Less coal

- Mercury rules, Section 111d

More gas

- Cheap gas

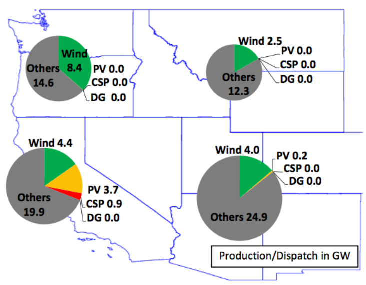
More distributed energy resources

- Rooftop solar, customer storage, V2G

Changing flow conditions, potential weak grids

Synchronous generation penetration levels may be much lower

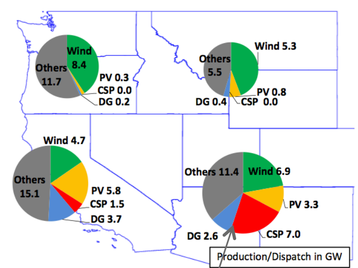
Base case



	WECC	California	DSW	Northeast	Northwest
Wind (GW)	20.9	4.4	4.0	2.5	8.4
PV (GW)	3.9	3.7	0.2	0.0	0.0
CSP (GW)	0.9	0.9	0.0	0.0	0.0
Distributed PV (GW)	0.0	0.0	0.0	0.0	0.0
Others (GW)	94.7	19.9	24.9	12.3	14.6
Total (GW)	120.3	28.9	29.1	14.7	22.9
Penetration (%)	21%	31%	14%	17%	36%

Figure 11. Wind and solar generation in the LSP Base case.

High renewables case



	WECC	California	DSW	Northeast	NW
Wind (GW)	27.0	4.7	6.9	5.3	8.4
PV (GW)	10.2	5.8	3.3	0.8	0.3
CSP (GW)	8.4	1.5	7.0	0.0	0.0
Distributed PV (GW)	7.0	3.7	2.6	0.4	0.2
Others (GW)	65.7	15.1	11.4	5.5	11.7
Total (GW)	118.4	30.8	31.3	12.0	20.5
Penetration (%)	44%	51%	64%	55%	43%

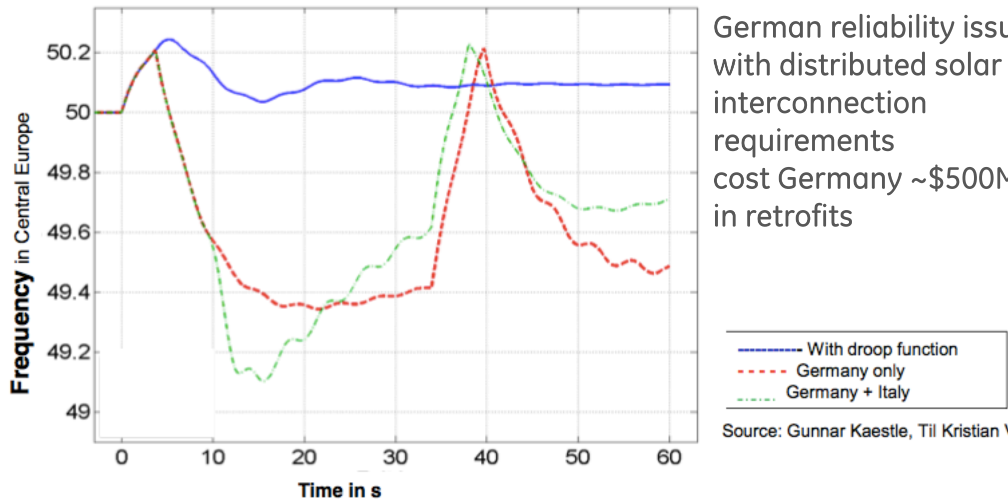
Figure 16. Wind and solar generation in LSP Hi-Mix case.

Miller et al, WWSIS3, 2014

Low synchronous penetration levels can pose reliability challenges

3

Distributed energy resources may be supplying significant portion of our load



German reliability issue with distributed solar interconnection requirements cost Germany ~$500M in retrofits

Source: Gunnar Kaestle, Til Kristian Vrana

B. Ernst, SMA, UVIG Anchorage, May 2014

4

What issues can these trends present to operational reliability in this future scenario?

Frequency response

- Response to loss of a large unit (or two) could degrade frequency response
- Is frequency response acceptable, can you avoid shedding load for critical outages?

Stability issues

- Do flow pattern & generation changes cause new path limits?

Weak grid issues

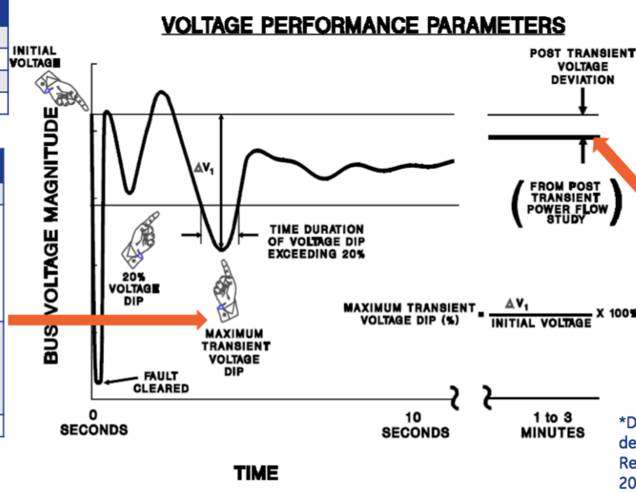
- Short circuit strength can degrade with lower synchronous levels of generation
- Is post-fault voltage recovery acceptable? Does grid strength present control instabilities for renewables (i.e. low short circuit ratio)?

How to identify reliability problems

What do you apply the WECC reliability criteria to?

Disturbance Class	Outage Frequency Associated with Performance Category
A	NA
B	≥ 0.33
C	0.033-0.33
D	<0.033

Disturbance Class	Transient Voltage Dip
A	NERC
B	Not to exceed 25% at load buses or 30% at non-load buses. Not to exceed 20% for more than 20 cycles at load buses.
C	Not to exceed 30% at any bus. Not to exceed 20% for more than 40 cycles at load buses.
D	NERC



Disturbance Class	Minimum Transient Frequency Standard
A	NERC
B	Not below 59.6 Hz for 6 cycles or more at a load bus.
C	Not below 59.0 Hz for 6 cycles or more at a load bus.
D	NERC

Disturbance Class	Post Transient Voltage Deviation Standard
A	NERC
B	Not to exceed 5% at any bus
C	Not to exceed 10% at any bus
D	NERC

*Disturbance category is defined in the WECC Reliability Criteria, April 2003

7

Dynamics analyses are snapshots

Production simulation analyses model 8760 hours of the year at hourly or even 5 minute intervals

Dynamics analyses start with a moment in time and model the 10-60 seconds after a disturbance

- Conventional snapshots today examine peak load, light spring, shoulder periods

How do we select the right snapshots to examine whether a high VER scenario is reliable?

Identify challenging periods from production simulation

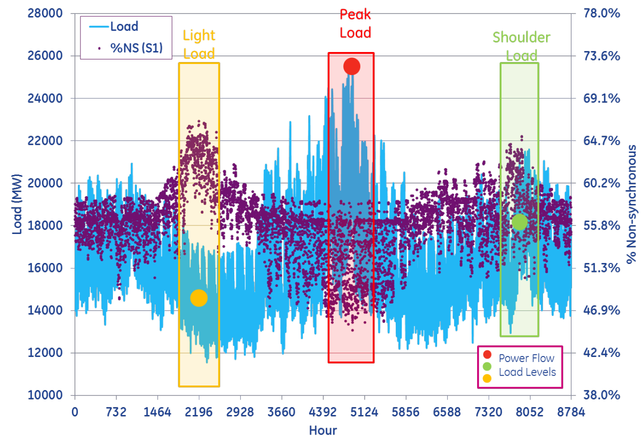
Example from MRITS study shows % non-synchronous plotted chronologically with load

Measures include:

- % non-synchronous capacity of total capacity
- % non-synchronous generation vs. load
- High path flows

Identify challenging hours by season and load level

Develop powerflow cases based on critical measures, selected hours



Let's talk about our starting point

Production simulation (PS) runs

Huge number of assumptions

- Ignores bilateral contracts for generation
- Ignores bilateral contracts for transmission

Models power plants at high level (e.g. wind on HV buses, hydro and combined cycle plants lumped)

Good for comparing runs

At a high level, you can see what types of resources are dispatched, emissions, fuel use

Fooling yourself to take the worst hour of production simulation, map it to stability and believe that this is realistic

Some lessons learned (the hard way!)

WECC-level powerflow commitment and dispatch should be guided by the representative production simulation hours

Large units can be committed and dispatched based on average from production analysis

VER can be very difficult

- Set based on regional operation, e.g. all wind in WY operating at 65% of rating

Hydro based on PS data and actual operating practice

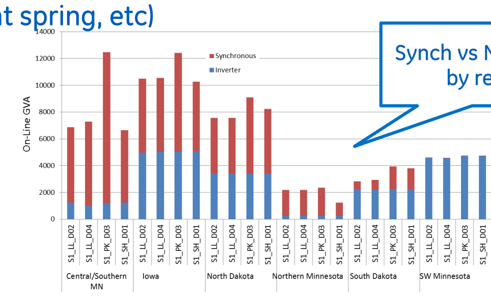
Small units – may not change from original powerflow case

Some lessons learned (continued!)

Process can be automated but still requires substantial manual effort

High-level summary to check for "reasonableness" vs. production simulation

- Commitment, dispatch, headroom & critical line/interface flows vs. production simulation results
- Voltages and dynamic reactive reserves should be reasonable
- System-wide and regionally (i.e. powerflow areas)
- Across cases (Heavy summer, light spring, etc)
- Tools needed to extract data from powerflow case



Synch vs Non-synch by region

12

Analysis

Coal retirement and added renewables will change the systems dynamic response

Critical outages may change

- Disturbances in high renewable/low synchronous regions to stress renewables
- Disturbances in load areas with limited synchronous generation
- Response of distributed generation

Analysis should consider traditional contingency set plus additional outages that address these issues

Checklist

Which snapshots are selected?

- Capture a trend using representative snapshots from analysis of many hours and run sensitivities to capture worst case but also other realistic possibilities.

How is production simulation mapped to powerflow?

- Relate power flow and stability basecases back to production simulation and get important plants right

How is load modeled?

- Load model has huge impact on results

How is distributed generation modeled?

- Don't net load. Model DG explicitly to capture DG response to events.

What model is used for generators?

- Updated models - Renewable Energy Modeling Task Force. Active power controls?

Is model benchmarked to actual events?

- FERC/LBNL study could not simulate Eastern Interconnect because model could not match real event performance

Ways to mitigate reliability challenges

Frequency Response

Increase inertia, primary frequency response, fast frequency response

Note that ERCOT finds that in some conditions, 1 MW of fast frequency response can provide same support as 2.3 MW of primary frequency response

- Are there units that could be providing governor response that are not?
- Synchronous generators, sync condensers, clutches
- Wind inertia
- Primary frequency response from wind/PV (can provide step response)
- Primary frequency response from CSP
- Storage
- Load response

16

Stability Issues

New paths and/or updated path ratings

- Based on changing flow patterns and new generation behavior
- Path ratings may increase or decrease

Traditional transmission reinforcements

- New lines & transformers and to accommodate new renewables
- Shunt capacitors, series capacitor, SVC/Statcom

VER controls and response

- Active and reactive power regulation
- DG response, ride-through

Weak Grid Issues

Two areas of concern:

- Load serving & voltage recovery: driven by retired synchronous generation
- Renewable generation control stability: high VER penetration and retired/displaced synchronous generation

Tradition transmission solutions (see last slide)

VER controls and response

Synchronous Condensers

To increase system strength (short circuit MVA), improve voltage recovery and VER control stability

Conversions: Retired coal unit is converted to a synchronous condenser

New condensers: new installation located in load or high VER region

New generation

- Clutches on new gas turbines and on steamer of combined cycle plants
- Allows flexible operation depending on market conditions & system needs

Checklist for mitigation measures

For frequency response issues, have you considered:

- Active power controls on wind/PV/CSP
- Governor response from thermal units are not currently providing it
- Use of fast frequency response and load response
- DG response and interconnection requirements

For stability issues, have you considered:

- New transmission lines or transformers
- Traditional reinforcements such as capacitors, SVC/Statcom
- Reactive power from wind/PV/CSP
- DG response and ride through

For weak grid issues, have you considered:

- Traditional transmission reinforcements
- VER controls and response
- Synchronous condensers and clutches on new generators

Summary

A low coal, high VER grid will be very different from today's grid. It is important to be proactive in studying potential future scenarios

- More time to implement solutions means the solution space is much bigger and can include more complex, inexpensive solutions such as demand-side solutions, new grid technologies, contractual solutions
- Saving money on potential retrofits/retroactive requirements

Many lessons learned from completed analyses regarding how to select snapshots, how to select tests, how to set up cases, how to ensure results make sense

Many mitigation options for a low coal, high VER future including:

- Active power controls on VER
- Synchronous condensers
- Clutches
- Traditional reinforcements

Thanks!

Western Wind and Solar Integration Study, Phase III (WWSIS3)
http://www.nrel.gov/electricity/transmission/western-wind-3.html
http://www.nrel.gov/docs/fy15osti/62906.pdf

Minnesota Renewables Integration and Transmission Study (MRITS)
http://www.minnelectrans.com/documents/MRITS-report.pdf

Debbie Lew
debra.lew@ge.com
303 819-3470