University of Michigan

100% Variable Renewable Energy Grid: Survey of Possibilities

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science (Environment and Sustainability) at the University of Michigan

By Ansha Zaman
4-17-2018

Faculty Advisors:
Jose F. Alfaro, Assistant Professor of Practice, School for Environment and Sustainability
Todd Levin, Computational Engineer, Argonne National Laboratory

This project was done in collaboration with the International Renewable Energy Agency (IRENA)

Acknowledgement

A number of people have contributed to the completion of this work. I owe my gratitude to all of them, for making this project possible.

I would like to thank my advisors Professor Jose Alfaro and Dr. Todd Levin for introducing me to the project, guiding me through development of the research objectives and providing invaluable feedback along the way. I am grateful for their constant support and encouragement.

I would like to thank the team at IRENA – Francisco Gafaro, Asami Miketa and Daniel Russo for the opportunity to collaborate with them. The team was gracious enough to host me over the summer at their Bonn, Germany office. Under the supervision of Mr Gafaro I was able to gain insights on the topic from IRENA staff, receive feedback and further define my research interests.

I would like to thank the 17 experts who participated in the study. Without their generosity this project would not exist.

Finally, I would like to thank my parents, family and friends for their love, strength and patience.

100% VRE Grid: Survey of Possibilities

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Executive Summary

Due to favorable public policy and falling technology costs more and more jurisdictions around the world are adopting higher shares of variable renewable energy into their power systems. Although some countries and jurisdictions, as part of larger interconnected systems, have been able to operate for extended periods of time with 100% of their demand covered with VRE, operating a self-sufficient power system annually with only VRE sources is not yet possible (with the exception of a few micro and mini grid systems, with state of the art technologies and practices). This study through a high-level qualitative assessment, identifies limitations of current and future power systems to host very high shares of VRE. To develop insights on power systems with high shares of VRE current academic literature was reviewed, seventeen experts in the field of renewable energy integration were interviewed and case studies of power systems already operating with high shares of variable renewable energy were analyzed.

Power System Stability – a central challenge to achieving high shares of VRE: As a result of its unique characteristics (variability, uncertainty, modularity, asynchronous), the integration of VRE into today's power systems poses unique challenges. Particularly at high shares maintaining power system stability becomes a critical challenge. Unlike synchronous generators, VRE generators do not inherently provide inertial response or governor response to frequency deviations. A high VRE share grid might not have sufficient reactive power sources to provide voltage stability. Without fault ride through (FRT) capability, VRE generator (such as wind turbine) disconnections in the event of system disturbances negatively affect transient system stability. A 100% VRE grid will require power systems dynamics to remain stable in an inertialess grid. Grid codes would need to be defined to ensure VRE generators are built in with FRT and voltage control capabilities. Industry and market structures do not yet have experience with this since power systems have historically relied on synchronous machines to provide stability. Even island power systems that have operated with 100% instantaneous share of VRE have always had conventional generators online as back up.

Solutions require a paradigm shift: Experts overwhelmingly reiterated that a large power system operating with a 100% share of VRE would require transformation in technology, operational practices and market design. In terms of technological transformation, solutions that add to system flexibility such as energy storage and demand response, will need to evolve to accommodate the variability and uncertainty associated with VREs at time frames ranging from seconds to days. VRE

generators will need to provide grid reliability services through advanced inverters. Grids will need to incorporate information and communications technology into every aspect of electricity generation, delivery and consumption. Institutional transformations would involve changes in power system planning methods from deterministic approaches to probabilistic approaches. Apart from increased coordination between different balancing areas, communication between transmission and distributions systems would also need to evolve. Power markets would need to adequately compensate for services that enhance system flexibility, provide greater grid stability and support VRE integration.

Lack of modeling exercises: Due to the lack of practical examples of large systems with very high penetrations of variable generation, researchers have focused on models to simulate behavior of such systems. However, there are only a limited number of comprehensive studies modeling the behavior of power systems with close to 100% VRE penetration. Some studies use unrealistic forecasts of energy demand; do not take transmission or ancillary service requirements into account. Most studies do not provide whole system simulation or provide simulations at the hourly instead of sub-hourly time scales. This fails to acknowledge reliability challenges a system might face at sub hourly time scales and during transient events.

Majority of experts believe there is no technical limit to VRE penetration level: Experts cited challenges such as grid strength, frequency stability, and lack of controllability for mid- to long-term operations for achieving a high VRE share grid. However, many of the experts consider these challenges to be solvable. Technical limits are defined by how the system is designed, inputs the system can handle and how the system is operated. 12 out of 17 experts identified no technical limit and asserted the ability of the system to evolve and accommodate new technology and new inputs. Alternatively, experts who did see a technical limit, assumed a static grid and weighed in on the existing system’s limitations.

Economic limits exist even if technical limits do not: All of the 17 experts interviewed stressed the importance of economic viability of a 100% VRE grid. Even if there is no technical limit to grid integration of VREs there might be an economic limit. Grid integration studies have found VRE penetration levels well below 100% to be economically desirable for large power systems such as the US, pan-European electricity system. However, the economic limit is not fixed and technological breakthroughs, strategic investments, or evolving social preferences can push the economic limit

The relevance of a 100% VRE grid: There is a lack of robust modeling studies that examine the technologically and economically optimal pathways to a decarbonized power system; therefore it is still difficult to concretely assess whether or not a 100% VRE grid is one of those pathways. However, most large power systems (peak electricity demand above 1 GW) are still far away from a decarbonized grid with most VRE penetration levels standing at below 20%. Research and conversations around a 100% VRE grid can be significant in stimulating innovation and breaking the institutional inertia that govern our power systems. Research on 100% VRE grids can also be an effective advocacy platform for pushing greater political commitment towards cleaner sources of energy.

Chapter 1: Background

In recent years, there has been a rapid growth in market shares of variable renewable energy technologies (VRE). The global installed solar capacity has grown by approximately 35 times between 2006 and 2015, from a mere 6.5 GW to 226 GW (IRENA 2016). According to IRENA's REmap 2030 report, market growth could accelerate further from today's growth and reach around 1500 GW of wind and 1250 GW of solar PV capacity in 2030 (IRENA 2014). With decreasing prices, VRE technologies are becoming increasingly competitive. Solar PV module prices have fallen more than 75% since 2009, and wind turbine prices are approximately 40% cheaper than in 2010 (IRENA 2017a). Onshore wind is now one of the most cost-competitive sources of electricity in many countries, generating power for as little as USD 0.04 per kilowatt-hour (kWh) without financial support (Taylor et al. 2015). Due to rapid growth in technological innovation and falling costs, wind and solar will play a central role in shaping the world's future energy demands.

VRE technologies are critical to meeting global sustainability goals. Most climate stabilization pathways envision near zero emission power sectors. High shares of VRE in the grid can play a significant role in reaching these emission targets. Thus, understanding what power systems dominated by these technologies would look like is extremely crucial.

As a result of its unique characteristics (such as variability, uncertainty), the integration of VRE into today's power systems poses certain challenges. Although some countries and jurisdictions, as part of larger interconnected systems, have been able to operate for extended periods of time with 100% of their demand covered with VRE, operating a self-sufficient power system annually with only VRE sources is not yet possible (with the exception of a few micro and mini grid systems, with state of the art technologies and practices).

This study aims, through a high-level qualitative assessment, to identify limitations of current and future power systems to host very high shares of VRE. It will specifically focus on the technical feasibility of power system operation with 100% VRE technologies.

Introduction

A 100% VRE grid is achieved when all of the annual electricity demand (kWh) is met by VRE sources in an independent AC grid. A 100% instantaneous VRE penetration level is achieved when all instantaneous power (kW) is met by VRE sources at any point in time (Kroposki et al. 2017). 100% instantaneous VRE penetration levels have been achieved but in general there are currently no large power systems capable of operating with all annual electricity produced from VRE sources. The imperative question is whether a 100% VRE grid is technically feasible and if it is, what are the barriers facing the transition to 100% VRE.

The body of literature focused on a 100% VRE or even a 100% renewable energy (RE) grid is still relatively limited. Recent research papers such as Fernandes et al. 2014, ClimateWorks Australia 2014, Jacobson et al. 2014, Jacobson et al. 2015, Becker et al. 2014, Gillespie et al. 2015, Pleßmann et al. 2017, Williams et al. 2015, Gils et al. 2017, Birkman 2015, GE Energy 2014a, E3 2014, Miller et al. 2014, GE Energy 2014b, Mai et al. 2014 imagine high shares of VRE integration for jurisdictions such as Australia, Europe, UK, US, Western United States, California, PJM, Minnesota etc. Global 100% RE scenarios exist from WWF and Greenpeace (Teske et al. 2012, Jeffries et al. 2011). Critics of some of these studies also exist that identify analytical deficiencies (Clack et al. 2017).

Discussion papers and review papers have emerged to highlight the research gap in this area. Jenkins 2017, Heard et al. 2017 and Cochran et al. 2014 perform a thorough literature review on research focusing on high shares of renewable energy in the grid. Similar to this REN21 2017 gathers 114 expert opinion on the feasibility of a 100% RE future but focuses on the policy and macro-economic impacts it would entail.

This study presents the results of a comprehensive literature review and survey of technical experts that provides:

- A review of technical challenges grids face with high VRE penetration levels
- Possible technical solutions to reach high VRE penetration levels.
- Analysis of a survey of technical experts on the feasibility of 100% VRE penetration

Methodology

The study aims to deliver clear and accessible information to policy and decision makers on the technical limitations and solutions to achieving a 100% VRE grid. It is based on a literature review of the latest technical discussions, industry and research projects, discussion papers, surveys with top experts and own assessments of collected information.

To capture insights from recent research, this study reviews 23 studies on the topic of integrating high shares of renewable or variable renewable energy published since 2014. The 23 studies include review articles, discussion papers and industry papers. To capture expert opinion 17 experts in the field of electricity systems and renewable energy integration were interviewed through online survey and/or phone interview. The interview questions focused on the technical feasibility of a 100% VRE grid, long term and short term operational challenges to such a grid, possible technical solutions and future grids they foresee. This study includes quotes and analysis from the 17 expert interviews. The sample of energy experts represent a variety of backgrounds and fields (power system operators, researchers, academics, industry). Refer to Appendix A to see details on the institutions represented by these experts and details on the survey questionnaire.

This report consists of four chapters. Chapter 1 gives background information on the study. Chapter 2 explains characteristics of VRE resources and VRE grid integration challenges. Chapter 3 discusses possible solutions to VRE grid integration challenges. Chapter 4 consolidates feedback gathered from experts and reviews current research to formulate broad conclusions on the topic of a 100% VRE grid. Chapter 4 analyzes case studies of power systems with high VRE penetration levels to find empirical evidence of the feasibility of 100% VRE penetration levels and highlight the technical/economic challenges of such systems.

Chapter 2: Challenges

VRE resources are different from other renewable energy (RE) resources because their output is determined by local weather conditions such as wind and solar. They exhibit certain characteristics that pose a unique set of challenges to grid integration.

VRE Characteristics

Variability and Uncertainty

The changes in output is the variability of the VRE resource and the unknown change in output is the uncertainty (Ela et al. 2013). Variability refers to the phenomenon of output of VRE changing over time and this change can be forecasted. The gap between the forecast and actual VRE output is referred to as the uncertainty in VRE output. Both variability and uncertainty occur across multiple time scales. PV power varies during the day and follows a diurnal cycle with no power being produced at night. Cloud covers cause rapid changes in output and the presence of a cover cannot be predicted accurately well ahead of time. Wind energy variability follows less pronounced diurnal cycles. Depending on the location, wind energy speeds can be higher during nighttime than during the day. Storm fronts can cause rapid and uncertain changes in wind output (Kroposki 2017). The variability and uncertainty make it more difficult for VRE output to follow demand.

Inverter based technology

Conventional sources of power (nuclear, coal, natural gas) interface with the electric grid through synchronous generators. These generators use a rotating magnetic field to induce a voltage in a stationary machine part (stator). As a result of this process electricity at a system specific frequency is produced. The rotational speed of the machines and the system frequency are directly correlated. Using this frequency, the machine is synchronized to the rest of the electric grid. To ensure reliable operation of the entire power system, system operators need to maintain constant frequency which requires a balance of input mechanical power and electrical load. System frequency and voltage levels are tightly regulated. Any time system frequency shifts from its nominal value, system operators use a combination of controllers to restore the frequency level. The rotating components of the generator cause the machine to exhibit mechanical inertia. High inertia allows these machines to absorb variations across net load and generation (Kundur 1994).

Another important characteristic of synchronous generators is the synchronizing torque. It is a torque that acts on the synchronous machine when the rotational speed of the rotor deviates from the synchronous speed due to system disturbances. The torque keeps the machine in synchronism. The higher the inertia and synchronizing torque the greater the ability of the system to withstand power imbalances in the grid and maintain stable frequency and voltage levels (Kroposki 2017).

VRE resources interface with the grid through power electronic devices called inverters. They have fundamentally different characteristics and interact with the grid differently than synchronous generators. Since inverters do not contain any mechanical parts, they do not exhibit any of the physical properties (such as inertia or synchronizing torque) of synchronous generators. They use controllers to regulate the output to the AC grid. Hence, maintaining a stable power system requires a different set of control strategies with VRE sources than one employed by conventional power plants.

Location Specific

VRE resources are location bound. Only certain locations have sufficient wind or solar resources to be appropriate for a plant siting and the location might not be close to the load or the grid. For instance, good wind sites are often located far away from load centers or existing transmission systems. In contrast to conventional power sources, wind or solar farms are harder to site since they have fewer degrees of freedom. Often there are environmental and social concerns associated with wind or solar farm siting. VRE sources are also dispersed and granular. Harnessing large amounts of energy from wind/solar can require the development of several granular sites. VRE project sitings face an entirely new set of challenges that conventional power plants do not.

VRE Grid Integration Challenges

The integration challenges identified by interviewing 17 experts and through a literature review have been broken down into two broad categories: long term planning and operational challenges.

Real Time Operational Challenges

Power System Dynamics

In general, modern VRE resources use power electronic devices or inverters to connect to the grid instead of synchronous generators. When the instantaneous share of VRE (percentage of electricity demand met by VRE sources for brief periods of time) becomes more than 50%, the system operates as an inverter-dominated grid (Kroposki 2017). As mentioned earlier, such a system has unique characteristics that change the power system dynamics of the grid.

> **Experts think**: “Relying on VRE and power electronics is a whole new approach with no prior experience”

As such the dominance of power electronics in the grid brings with it a new set of challenges.

Frequency Stability

The electrical frequency of an interconnection must be maintained very close to its nominal level (either 50 Hz or 60 Hz depending on the country) at all times. Frequency deviations occur when there is an imbalance between generation and load. A stable system maintains a steady frequency level following a large power imbalance event. Significant frequency deviations can lead to load shedding, instability, machine damage, and even blackouts (Kroposki 2017).

When a system disturbance occurs (e.g. loss of a generator), system frequency begins to drop. The rate of initial decline in the frequency or the rate of change of frequency (ROCOF) is related to how much inertia exists in the system. System inertia which is directly related to how much synchronous rotating mass exists in the system, slows down the initial frequency deviation. This is called the inertial frequency response. As the system frequency decline approaches its minimum (the frequency nadir), generators with governor control begin to act. Power output increases and the frequency settles at a point somewhat below the nominal. Eventually even more generators begin to respond, and the frequency is restored to its nominal level (Miller et al. 2015). The frequency response of a power system is comprised of the following steps:

1. Inertial Response (few seconds)
2. Primary frequency response - Governor response (1- 10 seconds)
3. Secondary frequency response - Area Governor Control response (seconds to minutes)

VRE plants do not inherently participate in frequency regulation. Unlike synchronous generators, they do not contribute to system inertia. Thus, they do not provide inertial response to frequency deviations. Neither do they provide governor response without incurring significant operational costs.

High VRE shares lead to low inertia in the system which results in high ROCOF events when a power imbalance occurs. This increase in ROCOF can lead to a cascade effect of disconnecting VRE generation if the VRE generators are protected against islanding (part of a power system becoming electrically isolated from the rest of the power system) by ROCOF relays. If the ROCOF relays end up disconnecting much of the VRE generators, then this further aggravates the original power imbalance. High penetration of VRE also leads to a higher maximum or a lower minimum frequency nadir (Sharma et al. 2011). Thus, recovering from a grid event with high VRE shares becomes more challenging.

Voltage Stability

The voltage stability of a system is its ability to maintain steady voltages at all buses when a disturbance occurs. Maintaining acceptable voltages at all buses in a power system is essential to ensuring that power is delivered securely across the transmission and distribution networks. Voltages crossing safe limits may cause outages and blackouts. Loads might not be served efficiently if proper voltage levels are not maintained (Kroposki 2017).

Synchronous machines in conventional generators quickly react to voltage disturbances and maintain stable voltage levels by providing required reactive power. Electric power consists of active power and reactive power. Active power is measured in watts (W) and reactive power is measured in volt amps reactive (VAR). Active power is needed to run loads and reactive power is needed to maintain stable voltage levels that allow real power to efficiently serve load. In AC electric systems reactive power is also needed to support delivery of real power in high voltage transmission lines. Conventional synchronous generators are sources of reactive power on the transmission system. Thus, they inherently participate in voltage regulation activities unlike asynchronous generators (Hossain et al. 2014).

Inverters that connect VREs to the grid can also provide voltage regulation if they are built in with voltage controllers. Unless grid operators define grid codes to ensure that such capabilities are made available, power systems with high VRE shares might not have sufficient reactive power sources to provide voltage stability. Generally, reactive power also cannot be transmitted over long distances. Thus, the location of voltage control sources plays a role in determining how effectively power systems with high VRE shares will be able to maintain voltage control.

In a 100% VRE grid the power systems dynamics would need to remain stable in an inertialess grid. Developing new control strategies for inertialess systems as well as new mechanisms to include synthetic inertia in the system is an important area of ongoing research. One study asserts that an inertialess grid would need fundamentally different grid operation mechanisms and new control features for inverter connected devices and generators to maintain power system stability (Tielens, 2017).

Transient and small-signal stability

Transient stability is “the capability of a power system to return to a stable operating point after a disturbance that changes its topology” such as tripping of a generator, sudden change of a load, or a short circuit (Chowdhury et al. 2015).

Transient stability is mainly dominated by synchronous machines in the power system. In most cases, an automatic protection system comes into play and prevents larger deviation of the steady state values by removing the faulted component (e.g. by disconnecting a generator, a load or a line or cable) from the power system. When high shares of VRE are introduced to the grid, such as through installation of a doubly fed induction generator (DFIG) wind farm, it causes a major change in the operating conditions of the power systems during transient events (Hossain et al.. 2012). During faults, DFIG wind turbines are usually required to be disconnected from the grid as part of the automatic protection system. Unlike synchronous generators, wind turbines cannot support the declining frequency of the grid immediately after the disconnection. Without fault ride through (FRT) capability (which means remaining connected to the grid following a fault), wind turbine disconnections negatively affect transient system stability (Slootweg and Kling 2002).

A 100% VRE grid will require power systems dynamics to remain stable in an inertialess grid. Industry and market structures do not yet have experience with this since power systems have historically relied on synchronous machines to provide stability. Even island power systems that have operated with 100% instantaneous share of VRE have always had conventional generators online as back up.

> **Experts think:** “Hydro Tasmania's 100% renewable systems always have synchronous machines either as generators or synchronous condensers. Without them, challenges are likely to be 1. unsafe system operation due to inability to clear faults, 2. inability to control voltage adequately, 3. risk of

> cascading loss of inverter-based generation where one-unit trips, causes voltage excursion leading to more trips etc."

> **Experts think:** "We don't know many of the answers - what is trade-off between large rotating machines (inertia/freq response) vs. power electronics."

Even if technical solutions were found and agreed upon to operate an entirely inverter dominated grid; the operation of the transition state with few synchronous machines might be more challenging than operating an entirely inverted dominated grid. Solutions that are adapted for a 100% inverter-based generator might not support synchronous machines simultaneously.

> **Experts think:** "Technically: ways to switch quickly between converter-based operation mode and synchronous operation mode; possibly this may prove more difficult than maintaining in just one mode."

> **Experts think:** "Provided technical solutions can be found and agreed for operation at 100% inverter generation then operation at 100% should not be an issue. What IS tricky is the transition between the two states, and operation with only a few synchronous machines - what happens with those machines?"

This brings up an important discussion around how much system operation would need to evolve to integrate a 100% share of VRE - What would the transition state look like? What would be the new control strategies for inertialess systems? What will the new mechanisms be to include synthetic inertia in the system?

Balancing Intermittency (Ramping Capability)

A grid with large shares of VRE must function with an underlying fluctuating resource. Balancing generation with load in real time can be a challenge since the high variability and uncertainty of the generating resource requires greater power system flexibility.

High shares of VRE in the grid may lead to steeper ramps (rate of increase or decrease in conventional generation to follow changes in demand during times when VRE output is not able to follow demand), deeper turn downs (inefficient operation of conventional generators at low levels during high VRE output periods), and shorter peaks (periods where generation is supplied at a higher level and peaks are shorter in duration, resulting in cost inefficient low operating hours for conventional plants) in system operations. Without flexibility, high ramp rates, deep turndowns and short peaks lead to base load generators having to shut down or startup with short notice. This can lead to a technologically and economically inefficient grid.

> **Experts think:** “Systems Operators will need to make sure they have adequate online ramping capacity to meet the needs during shoulder periods when renewable energy is rapidly coming online or offline. This could adversely impact real-time prices for energy.”

An inflexible grid may cause system operators to curtail (decrease the output of to avoid risking the security of the system) wind and solar generation. Although low levels of curtailment may be a cost-effective source of flexibility, significant amounts of curtailment can degrade project revenues and contract values, impact investor confidence in renewable energy revenues, and make it more difficult to meet emissions targets (Cochran 2014).

Long Term Planning Challenges

Resource Adequacy

Operating reserve is the generating capacity available to the power system operator to meet demand in case the scheduled/forecasted supply of power gets disrupted (Refer to Appendix B to see the different operating reserves categories). The way in which operators determine reserve requirements dramatically impacts the reliability and efficiency of the power system. It is generally agreed that VREs increase the variability and uncertainty of supply in a power system and hence impact the amount of operating reserves that need to be held to maintain reliability.

> **Experts think:** “The long-term system planning need to evaluate adequacy of resources as VRE are intermittent. VRE may not produce power when the customers need it.”

> **Experts think:** “Operators need to procure more reserve to cope with it.”

Operators still find it challenging to determine how much each reserve product needs to be increased with high VRE penetration levels. Ela et al.. 2011 concludes that no additional contingency reserves (instantaneous event reserve) are needed for high VRE share grids. Some studies suggest that the increase in Regulating Reserve (nonevent automatic without optimal dispatch reserve) would need to be increased significantly for high VRE share grids, whereas others say that the required response to variability and uncertainty is much slower and should be added to the Following Reserve (non-event manual reserve) (Ela et al. 2011). Some further studies try not to segregate the reserve categories and determine a total Operating Reserve that can be used for any imbalance on the system. The development of a consistent and accurate method for calculating reserve requirements in systems with high shares of VRE is still a work in progress.

Transmission Adequacy

A central challenge to scaling up VRE is the development of required transmission infrastructure. Viable wind and solar resources are often not located near load centers or existing transmission systems. Unlike conventional generators, VRE plant siting is less flexible and more location constrained. Thus, new transmission infrastructure is often needed to connect the VRE source to the load. Stoft et al.. (2011) points out the need for up to 60 billion dollars in long term investment to reach 20% wind capacity in the US. In the UK, to accommodate the rapid growth of renewables, the Office of Gas and Electricity Markets estimates an investment of 7.7 billion dollars over the next ten years. Thus, with higher shares of VRE in the grid timely and cost-effective transmission planning becomes an important factor.

> **Experts think:** “The need for transmission grid and investment decisions must be based on market modelling of the quantified long-term scenarios (efficient VRE integration requires more transmission grid).”

A geographically diversified portfolio of resources will be beneficial in a 100% VRE grid by helping to smooth out the variability and uncertainty of the resource from each individual site. Thus, aside from larger investment in transmission, greater coordination between existing regional grids to develop larger balancing areas will be needed.

> **Experts think:** “More regional interconnection will be required in order to take advantage of geographical diversity of renewable energy availability.”

> **Experts think:** “The electricity market in Europe is not centrally planned. The main policy driver for decarbonization is the ETS and the main policy drivers for RES-E are national targets. Greater coordination in national RES-E targets is required for 100% VRE systems as well as coordination in IC planning. Non-market areas need to develop large BA, fast dispatch”.

> **Experts think:** “Co-optimization across previously siloed parts of the system at high temporal and spatial accuracy. Independent planer with no interest in particular asset class”.

However, traditional operational practices limit cooperation and coordination of resources over larger areas. Balancing areas have limited ability to exchange power and energy with neighbors over various timescales. In the North American context, bilateral exchanges of power and energy sometimes occur between load serving entities and power producers, but these transactions must be negotiated between individual entities and typically well in advance of the actual need (Denholm 2015). Within the European Union, currently, balancing reserve planning and management is mainly dealt with at national level. After the intraday markets close, national Transmission System Operators (TSO) are responsible for maintaining the balance between demand and supply. A number of ongoing initiatives and pilot projects are already exploiting the benefits emerging from a tighter collaboration between TSOs, but no EU legislation currently binds TSOs to enter such collaborations (European Commission 2016).

Economic Challenges

The value that VRE adds to a power system is assessed in terms of the avoided costs. This includes avoided costs related to energy, capacity, balancing and transmission. Energy value is often based on the ability of a resource to offset the production costs of other resources. Capacity value measures a generator's contribution to overall long-term resource adequacy and transmission value measures contribution to overall long-term transmission adequacy. Balancing value refers to the VRE generator's contribution to flexibility needs (continuous operational balance between supply and demand) of the system. This concept of 'system value' can be used to comprehensively understand the economic impact of additional VRE generation (Wiser et al 2017).

Modeling studies have demonstrated that high VRE penetration levels are associated with a decline in system value. Most of these studies focus on the energy and capacity value. The system value of solar falls more rapidly than wind with increasing penetration levels. The MIT *Future of Solar* study, illustrates how adding more solar affects the summer and winter demand in the UK. While solar helps offset the midday summer peak at the outset, eventually with higher penetration levels the remaining demand shifts into the evening and adding more and more solar has little effect on the system. It might even negatively affect the grid (thereby creating negative value or incurring costs) if excess electricity is being produced at midday and there are limited curtailment and/or storage options available.

In regions with wholesale electricity markets, there are concerning power market impacts as well with growing penetration of VRE levels. VRE generation incurs roughly zero marginal cost. When wind and solar displace expensive fossil fuels like oil, gas, or coal, they save the system money and deliver energy value. However, at 100% instantaneous shares of VRE when all fuel consuming resources have been displaced the cost of generation drops to zero. As such whenever a VRE plant is generating, the supply curve in the electricity market shifts and prices drop. This is called the merit order effect – when wind and solar reduce market prices during times of generation. As more and more VRE shares enter the market, prices drop, and the revenues earned by VRE generators fall.

> **Experts think:** "Well, if we look long enough term, we need to start thinking about how we operate a grid with largely $0 marginal cost resources, and how we ensure incentives exist to get to 100% renewable energy."

Hirth (2013) shows how the ratio between the market prices earned by wind generation and the average market price goes down as wind penetration grows. The study also conducts a literature review on the merit order effect of VRE plants and finds that for the European power market, the value of wind power is slightly higher than the value of a constant electricity source at low penetration; but this ratio falls to 0.5–0.8 at a market share of 30%. Solar reaches a similar level at 15% penetration, because its generation is concentrated in fewer hours. Thus, with higher penetration levels VREs provide diminishing returns to its investors.

Hirth (2013) concludes that for the European power market, without subsidies, serious technological breakthroughs or extensive transmission investments it will be challenging for renewables to remain economically competitive at higher penetration levels.

Chapter 3: Solutions

The solutions identified by interviewing 17 experts and through a thorough literature review have been broken down into two broad categories: technological innovation and change in operational practices.

Technological Innovation

Advanced Forecasting

Effective VRE forecasting will be crucial to integrating wind and solar resources into the grid especially at high penetration levels.

> **Experts think:** "Forecasting level of renewables would assist understanding if generation will meet demand."

Forecasting helps reduce some of the uncertainty associated with VRE generation. It is one of the most cost-effective tools available to system operators. Accurate forecasts can help reduce the amount of operating reserves needed for the system, reducing costs of balancing the system. Xcel Energy reduced its mean average errors from 15.7% to 12.2% between 2009 and 2010, resulting in a savings of $2.5 million (Bird et al. 2013). An NREL study of the independent system operator for New England found that making solar forecasting 25 percent more accurate would offer potential cost savings of $46.5 million a year across the region (Bird et al..2013). Today, forecast errors typically range from 3% to 6% of rated capacity one hour ahead and 6% to 8% day ahead on a regional basis (as opposed to for a single plant). In comparison, errors for forecasting load typically range from 1% to 3% day-ahead (Lew et al. 2011). Thus, there is opportunity for new technology to improve day ahead forecasts. Even slight improvements have the potential to result in large operational and economic benefits. However, as sophisticated as this technology gets, there will always be some uncertainty associated with wind and solar resources.

Inverters with Advanced Functionality

Synchronous generators play a significant role in power system stability through inertial response, governor response and area governor controls. Inverters control the electrical generation from wind turbines/PV systems and they can be modified with additional control techniques to emulate the inertial response and frequency response behavior of synchronous generators.

Traditionally, inverters allow wind turbines (variable speed generators) to capture wind energy over a range of speeds to their maximum extent (MPPT operation) (Liu et al. 2013). During transient conditions, additional controllers could be installed on the inverters to provide an "virtual" or "synthetic" inertial response that behaves in a manner similar to conventional generators.

> **Experts think:** "If we get inverter technology with virtual synchronous machine (VSM) functionality, then perhaps it becomes easier, as we (sort of) continue as normal - making provision for the variability. Otherwise we need to consider aspects such as inertia management, voltage control planning, stability."

> **Experts think:** "inertial response must be provided synthetically from VRE, and they must provide the full range of ancillary services. Industry does not have experience yet with this."

The technique uses energy stored in wind turbines to inject more active power into the power grid within seconds. If wind turbines operate over de-loading curves (80%–90% of MPTT) rather than MPPT then some of the available power can be saved and used as reserve. Control techniques can also emulate governor response of conventional generators. Furthermore, wind turbines with advanced inverter functionality could perform automatic generation control regulation similar to conventional generators. PV systems rely on the inverter interface to connect to the grid as well. The same control techniques can be applied to PV plants to allow them to provide inertial response and frequency regulation.

Inverter manufacturers like FREQCON, Schneider Electric, and ABB provide out-of-the-box inertial response capabilities. Commercial wind turbine manufacturers, like Wind INERTIA and ENERCON, provide virtual inertia response. Montréal-based Hydro-Québec TransÉnergie, which was the first grid operator to mandate this capability from wind farms, will be sharing some of its first data on how Québec's grid is responding to disruptive events such as powerline and power plant outages (Greentech Media 2016). However, research in this area is still nascent.

> **Experts think:** "Various research on VSM technology for inverter technology is the key one I think. What is the right approach - and does everyone have to do it?"

There is a lack of research focusing on the dynamics of a system with virtual inertia. Thus, the operational behavior of systems with virtual inertia is still a black box (Tamrakar 2017). Additionally, no market structures exist to incentivize further development of such technology.

Conventional synchronous generators inherently provide inertial response. As such inertia has so far been treated as a free resource. An inverter dominated grid will need market mechanisms that compensate provision of the system's inertial requirements.

Advanced inverters can be used to support the grid through voltage regulation as well. Advanced inverters can direct a VRE generator to stay online during relatively short, minor frequency or voltage disturbances (fault ride through capability). To enable use of these functionalities market mechanisms will need to compensate these services. Grid codes and standards will need to be updated and research gaps on the performance of these controllers need to be addressed.

Smart Grid

A 100% VRE grid will require a new approach to grid management - one that makes use of data and communication tools to manage the variability and uncertainty associated with VREs. Smart grid technologies can be an important tool for effective integration of high shares of VREs. Smart grids incorporate information and communications technology into every aspect of electricity generation, delivery and consumption in order to enhance flexible operation of the grid, reduce operational costs and improve efficiency (Kempener et al. 2013).

Kempener et al. (2013) breaks smart grid technologies into four categories:

- Information collectors: Sensors that measure performance-related characteristics of electricity system.
- Information assemblers: Devices that accept information and display and analyze it.
- Information-based controllers: Devices that receive information and use it to control the behavior of other devices to achieve some optimization goals.
- Energy/power resources: Technologies that can generate, store, or reduce demand for electricity

Examples of smart grid technologies include: sensors that track temperature, vibration and other characteristics of a transformer; meters that measure electricity characteristics (voltage, current, etc.) of a distribution line; demand response, advanced inverters, advanced forecasting etc. Real-time information about transmission and distribution systems can allow grid operators to extract more value from existing lines. Demand response solutions can help absorb excess VRE generation and reduce loads when VRE generation is low. Advanced energy management solutions can provide real-time, high-resolution visibility and control of power systems that allow grid operators to manage their grids more efficiently. Advanced inverters and advanced forecasting were mentioned by our experts and have been discussed in detail in this section.

Some of these technologies such as demand response are already mature and are shown to be technically and economically viable. Jurisdictions such as Denmark, Netherlands, Puerto Rico, Singapore, Mexico have rolled out smart grid technologies to support shares of VRE in the grid. However, the proliferation of smart grids brings up institutional challenges around data ownership, access and privacy. With more availability of data through smart meters, determining which entity (the utility, transmission or distribution system operator, customer) should have rights to the data can be challenging. Apart from data ownership standards there is also a lack of universal set of standards on how different components of a smart grid should communicate and connect (Kempener et al. 2013).

Storage

Energy storage technologies increase system flexibility and help align VRE supply with demand. Shifting supply and demand patterns can help to provide important grid services such as frequency response, voltage support, and resource and transmission adequacy. Common storage technologies for provision of frequency regulation include flywheels (which store energy in a rotating mass), and certain battery technologies. Storage technologies providing resource adequacy and services over longer time scales include high-energy batteries, pumped hydro storage, compressed air energy storage, and thermal energy storage (Denholm 2015). These different types of storage are particularly important at high VRE penetration levels.

> **Experts think:** "We need energy storage with different characteristics for different applications. We need ramping storage and balancing storage with high power capability and only one or two hours of energy stored. We need energy storage with medium power capability and medium energy storage capacity to handle diurnal variability and perform peak shaving. We need low power high energy storage to handle multi-day base load power when the weather prevents significant energy harvesting for long periods (multi-day)."

> **Experts think: "**Need for energy storage and/or extensive load control".

> **Experts think:** "...ensuring real time power balance -- we currently don't have enough storage / demand response"

In Denmark for instance, multi-MW thermal heat storage projects enable the integration of large quantities of solar thermal in district heating schemes and provide seasonal storage capacity. Integration studies show that beyond 30% penetration level, demand response and storage become important considerations for the grid (Denholm, 2015). At high penetration levels they reduce the need and cost of curtailment. However, storage technologies are still costly and inefficient, and the technology is not as far advanced as it needs to be to accommodate 100% instantaneous VRE penetration for long periods of time (Hart et al. 2016). Energy storage will need to grow from an estimated 4.67 terawatt-hours (TWh) in 2017 to 11.89-15.72 TWh (155- 227% higher than in 2017) if the share of renewable energy in the energy system is to be doubled by 2030 (IRENA 2017b).

> **Experts think:** “The long-term solution needed is the energy storage, but its cost is still high.”
>
> **Experts think:** “The cost trend for storage is headed in the right direction generally, but it must compete with fuel storage; one can "store" gas by not burning it.”
>
> **Experts think:** “Energy storage technologies - as for instance batteries - are typically highly prioritized in countries with no experience in integration of VRE. For the time being battery technology is far too expensive for large scale balancing but can be relevant in relation to fast primary regulation, where only small energy amounts are involved. Hydro reservoirs are by far the most relevant storage technology for large scale balancing. Increased technical flexibility of thermal power plants is a potential source for a large part of the needed system flexibility. On long term we see the current gas systems used with synthetic gases as a potential large-scale buffer in coherent energy systems, where very large shares of the energy come from VRE (wind and PV)”
>
> **Experts think:** “Whatever the storage technology, costs need to drop - in a similar way to that of PV over recent years. Once it becomes cheap, then there is no barrier to installation and market forces will dictate the amount - perhaps we are getting close (e.g. 200MW of battery storage coming to the GB grid for fast frequency response)”

Pumped hydro storage has historically dominated the energy storage market share accounting for 96% of the total global storage capacity. However, new forms of storage – e.g. battery and thermal - have entered the market recently and the economics of providing grid services with these technologies is complicated. High upfront costs and the availability of lower cost alternatives (such as natural gas peaker plants) make the economic viability of storage market specific and service specific. For instance, Lazard’s recent analysis shows that, demand charge mitigation and frequency regulation represent potentially attractive revenue opportunities for energy storage in selected geographies. However, time-of-use energy arbitrage and spinning reserves, do not currently present economically viable sources of revenue for energy storage system owners (Lazard 2017).

Additionally, it has been difficult to quantify the value of energy storage to justify the high costs. The ability to simulate the cost impacts of VRE and benefits of storage is still limited. Despite this, industry experts expect storage future costs to fall and performance to improve.

Operational Practices

Greater Balancing Area Coordination and Fast Dispatch

Another way to increase system flexibility is through changing system operations and market design. Changing operational practices to accommodate high shares of VRE can often be the least-cost solution available. Adjusting scheduling practices allows dispatch decisions to be made closer to real time. This, allows system operators to make dispatch decisions with more accurate VRE forecasts in hand.

> **Experts think:** “Market/operational practice design, towards 5 min dispatch markets and ancillary services markets that value the fastness of response.”

> **Experts think:** “A wide range of issues related to scheduling, dispatch, forecasting etc. also needs to be figured out.”

> **Experts think:** “System operation with large shares of VRE requires a systematic approach to daily operational planning of the system balance: Continuously updating of schedules and forecasts for all elements in the system balance to be optimally prepared instead of surprised at the time of operation”

It decreases the need for expensive operating reserves. Studies have shown that integration costs have ranged from $0/MWh to $4.40/MWh in areas with five-minute dispatch, compared to $7/MWh to $8/MWh in areas with hourly dispatch (Bird et al. 2013).

Increased coordination between different balancing authorities can also be a cost-effective VRE integration solution. Sharing resources over large regions reduces operating reserve requirements and the costs associated with procuring those reserves. Milligan et al. (2011) shows that the size of the balancing area and faster dispatch reduces required operating reserves by approximately 1,000 MW (Bird et al. 2013).

> **Experts think:** “Better seams management, including crossing to neighboring (asynchronous) interconnections”

Denholm et al. (2015) suggests a number of ways in which coordination can be improved: reserve sharing, coordinated scheduling, and consolidated operation. Reserve sharing involves multiple balancing area authorities maintaining, allocating, and supplying the same set of operating reserves. Different types of reserves can be shared – from contingency reserves to regulating reserves. Reserve sharing is simple to implement and does not require any market enhancements. Coordinated scheduling refers to balancing area authorities exchanging energy over shorter time scales (short term dispatch - 5 min to 1-hour time scale). It increases dispatch efficiency by making a larger array of resources available for commitment. Coordinated scheduling requires increased communication and planning and requires market mechanisms to compensate participants for energy production. Consolidated operation is the merging of two or more balancing areas into one operational entity, for example, under one system operator. Consolidated operation combines all timescales of system operation including unit commitment (24 hour), short term dispatch (5 min to 1 hour), and reserves provision. This type of operation also facilitates the appropriate compensation for generators providing energy and ancillary services. This requires a much larger investment in redesigning of market structures, enhanced communication and planning strategies.

Chapter 4: Is 100% VRE penetration feasible?

Technical Feasibility

In the case studies analyzed as part of this study, we found evidence of systems operating at 100% instantaneous VRE penetration level. There are instances of regions or jurisdictions of small islands operating for extended periods of time with electricity generated from 100% VRE source (e.g. King Island in Australia). However, there is a lack of historical evidence for the technical feasibility of 100% annual VRE penetration levels operating at regional or larger scales. There are very few power systems with more than 1 GW system size that have over 20% VRE installed. Ireland is an example. In Ireland, there is 2800 MW of wind capacity installed accounting for 22% of all electricity generated. The instantaneous penetration level can go up to as much as 60%. The Danish government seeks to supply 100% of Denmark's energy demands with renewable energy by 2050 with wind turbines supplying 50% of electricity demand by 2020. Today, the Danish VRE production meets approx. 39% of the electricity demand, in Germany VRE supplies 20% of generation and in California 18% (Kroposki 2017). However, these are part of larger interconnections and that import and export power to help manage the variability of wind and solar. Several recent integration studies have analyzed wind and solar penetrations in the 30% to 80% range (Birkman 2015). However, there is no comprehensive integration study investigating the technical feasibility of operating a large power system with 100% VRE sources.

Discussion papers such as Kroposki (2017) and Kroposki et al. (2017) indicate the viability of integrating high shares or even a 100% share of VRE given key technological and management measures are taken. Experts interviewed as part of this study also indicate that there is no technical limit to VRE penetration level.

> **Experts think:** "There will be some technical issues that will pop up that our current models aren't predicting but I think they will be solvable and don't think 100% VRE is technically impossible."
>
> **Experts think:** "I do not think there is a technical limit"

12 out 17 experts interviewed agreed that there should be no technical limit to large scale VRE penetration. Among the experts were system operators who relayed their experience of integrating large shares of VRE.

> **Experts think:** "Hydro Tasmania has proved 100% VRE at small (MW) scale with extreme levels of resource variability and have improved reliability of the systems while increasing VRE use. The team here can't see any particular blockers to scaling up, but need different network planning, policy backup and commercial arrangements to fund the levels of storage and enabling technology that will be needed."

> **Experts think:** "In Ireland today it is currently planned at 75%-see Eirgrid Work on SNSP"

Experts cited challenges such as frequency stability, and lack of controllability for mid- to long-term operations for achieving a high VRE share grid. However, many of the experts consider these challenges to be solvable. Technical limits are defined by how the system is designed, inputs the system can handle and how the system is operated. Experts who identified no technical limit asserted the ability of the system to evolve and accommodate new technology and new inputs.

Experts think: "No (technical limit), but you may need to get stability via dedicated additional devices."

> **Experts think:** "Of course, the feasible limit technically may be based on what the legacy equipment in any given system can handle. But you can technically redesign and replace all of it if necessary, so I am not considering that here."

> **Experts think:** "There is no technical limit. The limit arises because of need to back up power when VRE is not producing power."

Alternatively, experts who did see a technical limit, assumed a static grid and weighed in on the existing system's limitations.

> **Experts think:** "With VRE or with inverter generation? The answer is yes - there is a (technical) limit but this depends on the system. The factors are mostly stability - ref CIGRE stability terms:"

Concerns experts brought up were mostly related to stability - the ability of a system to maintain voltage, transient, frequency stability with high shares of VRE in the grid.

> **Experts think:** "Frequency, angular, voltage stability. Plus, controller stability of the inverters themselves - how do the PLLs of inverters respond when there are very few synchronous machines in the network?"

> **Experts think:** Stability. We do not yet have experience what happens with close to 100% power electronics (PE) connected generation"

The recurring point brought up in these discussions was how hard it is to answer this question definitively without first defining what kind of future grid we are imagining.

> **Experts think:** “This limit is largely determined by the flexibility of other generation/storage sources and robustness of the grid and is therefore difficult to say in the abstract.”

If future grids evolve to become more flexible (through load control, energy storage, larger balancing areas, new operational practices and market design); if grids become capable of interacting with power electronics and VREs are designed to provide grid stability services then a 100% VRE system is plausible.

Lack of Comprehensive Modeling Exercises

Due to the lack of practical examples of large systems with very high penetrations of variable generation, researchers have focused on models to simulate behavior of such systems. However, there are only a limited number of studies modeling the behavior of power systems with 100% renewable energy (RE) penetration (included hydropower, biomass etc.) and fewer that focus on modeling behavior of systems with close to 100% VRE penetration.

Several of these simulation studies were reviewed and it was found that most are not comprehensive enough. Some studies in current literature use unrealistic forecasts of energy demand thereby failing to capture the challenges VRE integration faces accurately. Heard et al. (2017) compared the energy demand scenarios in the reviewed simulation studies to energy demand projection data sets from the IPCC Special Report on Emission Scenarios, the U.S. Climate Change Science Program (an interagency effort from the U.S. Government), and the World Energy Technology Outlook of the European Commission. Most simulation studies did not adhere to mainstream projections. Models based on incorrect demand projections are unreliable since projected demand heavily dictates installed capacity needs, reserve requirements etc. for a 100% RE or VRE system. Some studies (Climateworks Australia, 2014, Fernandes et al. 2014) rely on currently uncommercial technologies (such as wave, tidal or enhanced dry rock geothermal) to reach 100% RE. Few studies explicitly model transmission requirements or ancillary service requirements.

Most studies do not provide whole system simulation (Jacobson et al. 2014, ClimateWorks Australia 2014) or provide simulations at the hourly instead of sub-hourly time scales (Gils et al. 2017, Fernandes et al. 2014). This fails to acknowledge reliability challenges a system might face at sub hourly time scales and during transient events. Heard et al. (2017), Cochran et al. (2014), and Clack et al. (2017) highlight these and other errors in high RE modeling studies.

The Western Wind and Solar Integration Study Phase 3 (WWSIS-3) (Miller et al. 2014), and the PJM Renewable Integration Study (PRIS) (GE Energy 2014a) have performed analysis at the sub hourly time scale including grid performance analysis during transient events. However, few have simulated real power systems at sub hourly time scales for total (100%) RE or VRE penetration scenario. Comprehensive simulation studies with high RE scenarios (>80%) such as Brinkman 2015 heavily rely on dispatchable power capacity such as hydro, gas or biomass to meet reliability standards. The highest VRE penetration level examined in Brinkman (2015) is 56.4%.

There is clear lack of research that investigates grid performance for high VRE scenarios and the challenges and solutions to operating such high shares have not yet been comprehensively explored.

Recently, the Migrate project has been a significant step towards understanding the barriers to high penetration of non-synchronous generation. European TSOs (Estonia, Finland, France, Germany, Iceland, Ireland, Italy, Netherlands, Slovenia, Spain and UK), manufacturers (GE, Schneider Electric) and universities/research centers have joined to address these challenges and propose innovative solutions on how to adjust power system operations. So far, the deliverables have focused on gathering input from stakeholders, ranking the most significant power system stability issues related to high penetration of non-synchronous generation, investigating critical power quality phenomena in transmission networks as a result of inverter rich power systems. The power system stability issues specifically focus on dealing with the challenges of operating with inverters-based devices in the grid.

This initiative by European TSOs is an indication that system operators are still trying to understand the challenges related to operating a grid with high penetration of non-synchronous generation. It also indicates that the challenges associated with a 100% non-synchronous generation grid are still not well modeled.

Solutions require a Paradigm Shift

Experts overwhelmingly reiterated that a large power system operating with a 100% share of VRE would require transformation in technology, operational practices and market design. Current financial and institutional arrangements of power systems are evolving but it would require a paradigm shift in how they are operated and designed for a 100% VRE grid to exist.

In terms of technological transformation, energy storage and demand response will need to evolve to accommodate the variability and uncertainty associated with VREs at a larger scale. VRE generators will need to provide grid reliability services through advanced inverters. Grids will need to transform to incorporate information and communications technology into every aspect of electricity generation, delivery and consumption.

> **Experts think:** "There will be more distributed generation which will need to be monitored and preferably controlled, more storage at strategic locations around systems and more demand side management."
>
> **Experts think:** "Pressure to enhance demand side response if storage costs remain high, structural adaptation of industrial supply chains; phase-out of fossil-based flexibility options."

Apart from increased coordination between different balancing areas, experts also envision transformation in communication between transmission and distributions systems.

> **Experts think:** "Greater interconnection of regions will maximize geographic diversity of VRE sources. I think there will still be a grid used to connect all the distributed elements together, the "death spiral" concept is overblown".
>
> **Experts think:** "Greater flexibility, greater interconnection, much more storage. Also, better cooperation between TSOs and DSOs, plus a lot of innovation and new products. Personally, I don't see the benefit of 'micro grids' and rather see a smarter power system operating as a whole - specifically to make use of geographical spread for variability of VRE."
>
> **Experts think:** "Systems with move to hierarchical control architectures with less distinction between transmission and distribution systems."

Conventional power system planning methods would need to change in order to accommodate VRE sources reliably and economically. Traditionally, deterministic approaches for power system planning have been used, but with increasing penetration of VRE sources, probabilistic methods would become more suitable to address uncertainties associated with the overall system. Experts also foresee a change in market dynamics - alternative methods of charging for electricity, market structures incentivizing technologies that smooth out the variability and uncertainty of VREs.

> **Experts think:** "We need an alternative method for charging for electricity that doesn't support runaway growth. Is that a monthly access fee with an electricity limit (think data on your cell phone)? I am not sure."

> **Experts think:** "More flexibility in institutional practice (large fast markets such as MISO, SPP, PJM). Inflexible resources will continue to retire and be replaced by more flexible ones. Some bulk power market evolution may be needed in some places but generally US RTO/ISO markets are probably robust enough to handle this."

> **Experts think:** "...more fluid markets for dealing with the technical challenges."

A lot of these solutions exist today and are being implemented. Wind turbines can now provide fault ride through capabilities, virtual inertial response and governor response. California's Rule 21 requires wind, solar generators or battery storage connecting to the grid to have advanced inverter functionalities. Larger balancing area coordination is occurring in the Western US power systems through the Energy Imbalance Market. Jurisdictions such as Denmark have adopted smart grid technologies to support high wind integration (smart charging of electric vehicles and demand-response control of heating loads).

However, some solutions are hypothetical. Area governor controls through VRE generators still has not been studied sufficiently. Energy Storage is still an inefficient technology and market structures still do not adequately compensate them for value-based performance. To leapfrog from 30% - 50% VRE grid to a 100% VRE grid, the evolution of the hypothetical solutions would have to occur at a fast pace. Fossil fuels are still projected to account for 48% of the global power sector energy consumption till 2035 (BP 2017). However, 12 out of 17 experts expressed optimism in the ability of the industry to evolve and adapt to 100% shares of VRE.

> **Experts think:** "First of all, to my knowledge there are very few large-scale systems with 30-50% VRE today. However, regardless of the starting level of VRE, I think we will see a relatively fast evolution towards higher VRE levels, although 100% will be a stretch in most cases. Industry will learn how to better deal with VRE along the and hopefully also figure what are the optimal levels of VRE in a system, considering energy-environmental public policy and society's preferences, as well as the cost of maintaining reliable power supply at high VRE shares."

This paradigm shift is already happening due to VRE sources becoming cost effective and public policy pushing for cleaner sources of power into the grid.

Economic Viability before Technical Viability?

All of the 17 experts interviewed stressed the importance of economic viability of a 100% VRE grid. Even if there is no technical limit to grid integration of VREs there might be an economic limit.

> **Experts think:** "There is no technical limit, but an economic limit, where it does not make sense to increase the VRE share."
>
> **Experts think:** "I think it is more a question of cost-benefit trade-off, although industry need to develop experience with such high VRE levels"
>
> **Experts think:** "... I think the primary issue is cost."
>
> **Experts think:** "The barriers are probably economic, not reliability"

Cochran et al. (2015) argues that the technical challenges of VRE integration can be addressed by implementing a variety of solutions. There is always a technological fix to that can adopted to accommodate higher shares of VRE. Some of these solutions have been discussed in the previous sections. However, implementation costs of the solutions may not be desirable. Cochran et al. (2014b) shows the differences in cost between different types of intervention, for example changing systems operations or market designs are less costly interventions than transmission expansion or introducing large amounts of storage. The costlier interventions provide greater system flexibility and greater opportunity for higher shares of VRE. A large 100% VRE system would incur significant implementation costs. As such, the VRE penetration level that is desirable could be driven by economic limits rather than technical limits.

The economic limit or the economic carrying capacity is defined as the point at which VRE is no longer economically competitive or desirable to the system or society. It can be determined by the VRE penetration level at which the costs outweigh the benefits of the additional VRE. The costs involved would be associated with cost of the generator, new operational costs, storage costs etc. The benefits would be value of avoided fuel, avoided capacity additions, avoided emissions, reduced fuel price volatility etc. Some costs and benefits are hard to evaluate such as the value of fuel diversity, local economic impacts, and air quality. These costs and benefits could be evaluated for a static grid, such as today's transmission configuration and operational practices, or under potential future grid scenarios.

Multiple grid integration studies have followed the above framework and have found VRE penetration levels well below 100% to be economically desirable. Cochran et al. (2015) summarizes grid integration studies in the United States and concludes an economic limit of 30% VRE penetration level. Rodriguez et al. (2015) modelled a highly renewable pan-European electricity system and concluded that a technically and economically optimized European grid would have RE penetration of 50% of which 94% would be VREs. Thus, under current conditions, the economic limits do not point towards a 100% VRE system.

However, the economic limit is not fixed and technological breakthroughs, strategic investments, or evolving social preferences can push the economic limit. It is important to determine which technological breakthroughs and strategic investments need to happen to prove the economic viability of 100% VRE grids before policymakers can push for a 100% VRE grid.

Do we want a 100% VRE grid?

An ideal power system (or any energy system) is one that delivers affordable, reliable, and socially and environmentally responsible clean energy. A 100% VRE grid would fulfill the clean energy criteria. However, it is still not known whether or not the energy delivered would be economical and consistently reliable. Studies such as Williams et al. (2015) conclude that high VRE scenarios are more technologically complex and costlier than the other options. The study finds that a high-VRE pathway for the U.S. economy costs 1.6 times more than a diversified portfolio. Brick and Thernstrom 2016 (conclude) for the U.S. that total required installed capacity is 3.5 to 5.5 times larger for wind and solar-dominated power systems compared to more balanced systems. Additionally, the grid operations become more complex, exhibiting episodes of both sustained oversupply and undersupply. In particular, moving from high share range (80%) to 100% VRE becomes extremely technically and economically challenging.

> **Experts think:** “I would expect that the costs of 100% would be significantly higher than 80%.”

Including dispatchable low carbon resources such as nuclear, carbon capture and storage (CCS), hydropower or biomass mitigates some of these cost and technical challenges while maintaining decarbonization goals. Studies that employ least-cost optimization techniques often result in significant shares of dispatchable base resources in the decarbonized power portfolio. Multiple studies stress the importance of maintaining a diverse mix of low and zero-carbon resources in order to affordably and reliably decarbonize the power system (Jenkins et al. 2017). Providing energy services from a range of sources also creates greater energy security. A number of our experts envisioned future grids with high shares of wind and solar but also shares of hydro and nuclear.

> **Experts think:** "I don't see 50% as being particularly difficult. Current market design may need to be changed (i.e., too many hours with negative LMPs). I could see a future grid with 50% wind+solar, 10% hydro, 20% nuclear, 20% natural gas without too much challenge."

As mentioned earlier, there is a lack of robust modeling studies that examine the technologically and economically optimal pathways to a decarbonized power system; therefore it is still difficult to concretely assess whether or not a 100% VRE grid is one of those pathways. However, most large power systems (peak electricity demand above 1 GW) are still far away from a decarbonized grid with most VRE penetration levels standing at below 20%. In this regard, research and conversations around a 100% VRE grid can be significant in stimulating innovation and breaking the institutional inertia that govern our power systems. Research on 100% VRE grids can also be an effective advocacy platform for pushing greater political commitment towards cleaner sources of energy.

Chapter 5: Case Studies

Australian King Island Hybrid Renewable Energy System

King Island, is one of three islands known as the New Year Group, and one of more than 330 islands that make up the state of Tasmania, Australia. The island used to consume 4.5 million liters of diesel annually. However, high diesel fuel costs led to the installation of three 250 kW wind turbines in 1998, followed by two 850 kW wind turbines in 2013. The King Island electricity system is owned and maintained by a government owned generator/ retailer Hydro Tasmania. Under Hydro Tasmania, the King Island Renewable Energy Integration project (KIREIP 2013) is run with the aim of converting the island's off grid power system to a 100% renewable energy grid. To date the project has been able to deliver 65% annual generation from wind and PV. In 2013, KIREIP supplied all of the island's energy needs through renewables for a continuous period of nearly 33 hours. Thus, it was able to reach 100% instantaneous share of VRE. The following are the key elements of the King Island power system:

D-UPS: This is a hybrid system containing large mass flywheels that allow for diesel generators to work in tandem with the wind turbine. The D-UPS unit lets the diesel generators be switched off when wind generation is higher than load. When the wind generation drops, the unit contains enough inertia to start the diesel generator. It is also used as energy storage. It stores energy during periods of excess wind generation and releases the energy when immediate short-term backup is needed. (KIREIP 2013)

Energy Storage: The King Island power system has an electrochemical battery system, capable of providing 3 MW of power and storing 1.6 MWh of usable energy. The battery allows the system to operate at 100% wind for longer periods of time. Initially in 2003 a Vanadium Redox Battery (VRB) was installed. However, the battery failed due to an overheating event. It was decommissioned and replaced with the current technology. (KIREIP 2013)

Smart Grid: The Smart Grid is the next phase in the KIREIP project. Smart grids are used for demand side management. The technology controls load by encouraging use of electricity when there is more renewable generation available discouraging electricity use during low wind generation periods. (KIREIP 2013)

With the current battery storage technology in place and dispatchable diesel generators online, the King Island system is able to reliably operate at 100% instantaneous share of VRE. The diesel power plants assure the reliability of the grid when the renewable resource is not available. Storage technology failures continue to be a challenge for islands as can be evidenced by the 2003 failure of the VRB in this case. They are also a challenge in terms of efficiency and economics. To transform the entire system to a 100% VRE integrated grid, a larger sized storage technology and further evolution of demand side management would be required (Neves et al. 2014).

Ireland Wind Power Integration

The All-island power system, representing the electrical grids of the Republic of Ireland and Northern Ireland, has a binding target of supplying 40% of electricity with renewables by 2020. The power sector target has been set under the European Union's 2020 rule of requiring 16% of all energy needs to come from renewable sources. In Ireland, there is 2800 MW of wind capacity installed accounting for 22% of all annual electricity generation. The capacity is expected to grow to between 3900 and 4300 MW by 2020. There is approximately 850 MW of wind currently installed in Northern Ireland accounting for 20% of all annual electricity generation. Wind capacity in Northern Ireland is expected to reach 1325 MW by 2019.

Being an island network, the TSOs in each jurisdiction (EirGrid in Ireland and the System Operator for Northern Ireland (SONI)) place a heavy emphasis on reliability and reserve requirements especially with a growing share of variable renewable capacity in the grid. Thus, the governments of Ireland and Northern Ireland conducted two studies on the technical feasibility of high penetration of renewable sources were carried out in 2008 and 2010 (All-Island Grid Study and Facilitation of Renewables). The analyses identified potential operational challenges such as frequency instability due to loss of generation or network fault, transient instability, and voltage instability. Feasible mitigation measures were also identified such as enabling wind generators to provide frequency regulation and voltage support, and implementing transmission network reinforcements. The study concluded that under these adaptation measures an instantaneous wind penetration level of 60-80% was technically feasible. Beyond these limits, mitigation of technical challenges might not be possible with state of the art technology and would require new technology concepts. Frequency stability issues were identified as particularly restrictive in this regard.

As part of an initiative to push the technical limit and accommodate growing shares of wind, the 'Delivering a Secure Sustainable Electricity System (DS3)' program was introduced by EirGrid. The DS3 program focuses on the delivery of a suite of ancillary services to support the increasing levels of non–synchronous response in the island's power system. Ireland, has also developed a transmission plan, known as Grid 25 to develop a stronger network for the Republic of Ireland by 2025 including reinforcements to support the additional renewable generation. System wide initiatives such as the creation of a new electricity market (iSEM - Integrated Single Electricity Market) are also underway (Flynn et al. 2016). According to the DS3 Operational Capability Outlook Report (2016), demand side management and battery storage projects with short lead times are also expected to ensure reliable operation of the power system at 60% wind penetration levels

The TSOs currently limit the instantaneous wind penetration level to 60% to maintain a stable, reliable power system. However, the limit is shifted with every phase of the DS3 program study. When this limit was raised from 55% to 60% in 2016, wind curtailments decreased by almost 50%. Last year Ireland and Northern Ireland generated 7,620 GWh of wind energy. An estimated 227 GWh of wind energy was curtailed. This represents 2.9% of the total available wind energy in 2016 and is a decrease of about 215 GWh on the 2015 figure. Other contributing factors such as increase in demand and significant transmission upgrades also played a role in reducing curtailment and improving system performance.

Despite these recent system performance trends, skeptics have suggested that Ireland is in danger of coming up short on its renewable-energy targets and paying millions in penalties to the EU (IIEA, 2018). With only three years left Ireland has met only half the power sector requirement. According to the EEA's 2016 annual report Ireland is 0.5 percentage points behind meeting its national plan trajectory target with respect to renewables (EEA, 2017). The rise in economic growth and the following rise in electricity consumption has made it harder for the goal to be achieved. However, with the implementation of the DS3 program, new initiatives such as the iSEM the TSOs remain optimistic.

ERCOT Wind Power Integration

The Electric Reliability Council of Texas (ERCOT) is the market operator for the majority of the state of Texas. It manages the power flow to about 24 million Texas customers, representing approximately 90% of the state electricity demand. ERCOT has over 77 GW of installed summer generation capacity including a mix of coal, nuclear, natural gas (steam generation, simple cycle and combined cycle combustion turbines), biomass, landfill gas, hydro, solar and wind generation. ERCOT's limited non-synchronous interconnections makes it an electrical "island". Thus, maintaining consistent reliable and secure power system operation is a major priority for ERCOT.

Renewables account for approximately 17.4% of generation mix in the region with wind accounting for 11.7% of electricity generation as of 2015 (Wattles 2017). The most recent significant instantaneous wind penetration level was 48.3% (13,154 MW of wind generation and 27,244 MW load) reached in March 2016. A higher instantaneous penetration level could have been reached, but due to transmission constraints and inflexible thermal generators 800 MW of wind generation was curtailed (Du et al. 2017). Wind installations have increased in the state by a factor of more than 100, from 116 MW in 2000 to 16,129 MW as of June 1, 2016 making Texas the leading state for wind capacity in the United States (CCET 2015). If Texas was a separate country it would be 6th in the world in terms of installed wind capacity. Apart from the availability of abundant wind resources, state policy mandates such as the Renewable Portfolio Standard (mandate passed by the Texas Legislature to establish a minimum amount of renewable resources in the state's generation portfolio) and federal tax incentives such as the Production Tax Credit (2.3 cent/kWh incentive for the first 10 years of a renewable facility operation) have influenced the development of wind (Du et al. 2017).

The establishment of "competitive renewable energy zones" (CREZ) by the public utility commission of Texas (PUCT) has also been a central driving force in the development of wind energy in Texas (Wattles 2017). In 2005 the CREZ were identified by the PUCT as regions with high wind resources capable of attracting wind development. ERCOT then developed transmission plans to interconnect these areas with the existing transmission grid. The project, largely completed in December 2013, has resulted in fewer curtailments of wind power and has encouraged developers to invest in new wind generation capacity. Sparsely, populated areas in West Texas are rich in wind resources and the transmission project has enabled the connection of these resources to large load centers in the north and center of the state (CCET 2015).

Counterintuitively frequency regulation requirements in ERCOT have actually decreased while wind penetrations increased (Wattles 2017). This has been explained by the increase of geographical dispersion of wind generation resources as well as the continuous fine-tuning of methodology for determining the requirements for ancillary services. ERCOT's frequency performance is also continuously improving despite a growing share of variable generation resources and reduction in Regulation requirements (Du et al. 2017). The Control Performance Standard 1 (a measurement of how well a Balancing Authority maintains grid frequency within acceptable parameters) has improved over the years (Wattles 2017) for ERCOT. This can be due to continuous fine-tuning of the procured ancillary service amounts, based on historical data; requiring renewable energy generators to include primary frequency response through governor or governor like action; continuous monitoring by ERCOT after each significant frequency event and implementing new standards that narrow governor dead band settings from 0.036 to 0.017 Hz (Du et al. 2017). Through establishing new operational standards and modifying market mechanisms ERCOT has been able to maintain reliability performance even with increasing shares of wind.

However, the increasing penetration of non-synchronous generation (wind) still poses future reliability and power system stability concerns for ERCOT. The displacement of synchronous generators in the power system is resulting in a decrease of the system's overall synchronous inertia. The overall system inertia is expected to further decrease as the wind generation continues to grow (Du et al. 2017). As a result, ERCOT is expected to face challenges maintaining its frequency control performance. A study was conducted by ERCOT in 2014 examining the minimum primary frequency response requirement to prevent the frequency from dropping below 59.4 Hz (0.1 Hz above the prevailing first step of involuntary under-frequency load shedding) after the loss of two largest generation units (2750 MW) for thirteen different low inertia scenarios (ERCOT 2014). The study found that more Responsive Reserve Service (reserve used to reduce frequency decline after a disturbance, and as a replacement reserve to restore the depleted Responsive Reserves) is needed for low-inertia situations to maintain the security and reliability of the grid (ERCOT 2014). The study showed that with increasing system inertia more and more primary frequency response reserve is required. The study also showed that in low inertia scenarios when two largest generation units are lost, voltage oscillations and voltage control issues occur. It recommended increasing the frequency response reserve requirement and changing the ancillary service procurement methodology as mitigation strategies. As part of the process to modify the ancillary service procurement methodology, load resources are now able to provide the Responsive Reserve Service since they are 2.35 times more effective at primary frequency response than generators due to the speed of the response (ERCOT 2014).

Looking forward, ERCOT has been considering a myriad of strategies to accommodate more and more non-synchronous generation including: installing synchronous condensers, increasing the monthly Responsive Reserve Service requirement, increasing Fast Frequency Response Reserve requirements, and introducing synthetic inertia. ERCOT continues to develop new tools to allow operators to better analyze and visualize wind output (Du et al. 2017). ERCOT's overall 7-day wind forecast performance has steadily improved over the years and an experimental dashboard has been set up to monitor real-time inertia (Wattles 2017). Thus, ERCOT is making a concerted effort to innovate and keep fine-tuning their operations as more and more wind enters the system.

Denmark Wind Power Integration

The Danish government seeks to supply 100% of Denmark's energy demands with renewable energy by 2050 with wind turbines supplying 50% of electricity demand by 2020. Today, the Danish wind power production meets approximately 39% of the electricity demand. The transmission network in Denmark is divided into two separate transmissions grids; Western and Eastern. The Western Danish grid is connected to the European continental grid, whereas the Eastern Danish grid is connected to the Nordic grid. A larger portion of the wind power is located in the Western part of Denmark, where the wind share reached 51 percent in 2014, compared to 21 percent in Eastern Denmark (Sorknæs et al. 2013). On several occasions in 2014 instantaneous wind penetration levels exceeded 100% in Western Denmark. There were 1,230 of these hours in 2014 (Anders et al. 2015). Denmark maintained a reliable grid and avoided curtailment during these high penetration levels using the following strategies:

Interconnectors: Being part of a larger Nordic grid is one of the most important strategies of reducing wind power curtailment for Denmark. On a July 2015 summer day when electricity demand in Denmark dropped, and wind generation exceeded load by 40%, interconnectors allowed 80% of the power surplus to be shared equally between Germany and Norway. Sweden took the remaining 20% of excess power (Nelson 2015). The interconnector has a 6.4 GW net transfer capacity which is 0.4 GW higher than Danish peak demand (Sorknæs et al. 2013). Denmark is able to sell surplus wind power to its neighbors and import power in times of low wind production. Nordic pumped storage hydro power stations are able to act as effective energy storage facilities and store the excess wind power for use during low generation periods.

Flexible Coal/ Thermal Power: Danish coal plants have been transformed into the most flexible power plants in Europe (Anders 2015). Denmark's administrative limit for must run capacity of conventional power plants has been reduced over the years. Coal power plants have been retrofitted to deal with steep ramp rates, shorter peaks, deep turndowns. Different flexibility measures have been taken for each thermal/coal plant (Anders 2015). For instance, in the case of a coal-fired plant commissioned in 1998, ramp rates were improved by replacing the old, rigid, non-programmable control software with new software that allows for the flexible modification of start-up criteria (Anders 2015).

Integrated Heating: Almost all power plants in Denmark can cogenerate district heat and electricity. Combined heat and power plants (CHP) can be switched from producing just heat to producing just electricity using steam bypass systems (Anders 2015). This adds flexibility to the system and provides opportunity for greater integration of VRE resources. During periods of high wind generation CHPs can stop generating electricity while continuing to provide heat without completely shutting down.. When needed, they can switch back to producing electricity, balancing any mismatch between wind production and load within very short time horizons (Anders 2015). CHP plants can also accommodate heat storage units which act as energy storage devices and further improve the flexibility of the power system.

Despite the above measures, the country does struggle with wind integration challenges. Mainly, the challenge of keeping wind power valuable during high wind production (Anderes 2015). As wind penetration grows, larger fractions of wind power get sold at low or negative prices. Thus, it becomes uneconomical for wind operators to invest in new wind turbines and continue to participate in the market. Currently, the dominant support scheme in Denmark for onshore wind energy is a price premium paid on top of the wholesale market price for electricity (Anders 2015). For continued wind development into the future it is essential to ensure that the economic value of wind remains preserved. The power sector also faces the challenge of balancing supply and demand and ensuring there is sufficient base load power available when there is no wind. With increasing wind power deployment, it has become economically less attractive to build base load plants (Anders 2015). The Danish Transmission System Operator (TSO), Energinet is meeting these challenges with further demand side flexibilization measures. Energinet, has made a clear list of priorities with short term and long-term goals of expanding interconnectors, electrification of heating sector, smart grids, compressed air energy storage etc. (SEDC 2017).

In accordance with its 2020 renewable energy goals, Denmark is poised to add an additional 9.2 GW of wind capacity to its power sector. However, renewable energy policy beyond 2020 is still unknown (Steel 2015). Wind industry experts remain optimistic regarding wind power's role in future energy policies (Steel 2015). In 2014, the Danish Energy Agency released a white paper outlining four energy scenarios for Denmark's energy sector from 2020 to 2030 (DEA 2014). The study concluded that scenarios with high wind shares in the system would require fast-regulating gas engines/gas turbines, and more electrical interconnectors to neighboring countries. Almost all the scenarios extensively included heat storage facilities and the report showed a trend towards incorporating large scale electrification of the consumptions and transportation sector. Thus, the future of Denmark's power sector could continue to see the expansion of wind capacity meeting while meeting reliability challenges with a holistic set of solutions.

California Solar Integration

California has been a leader in the United States in integrating VRE, specifically solar. The California grid is operated by the California Independent System Operator. The three-main investor owned utilities in California are Pacific Gas and Electric, San Diego Gas and Electric and Southern California Edison and they collectively serve around three quarters of the state's electricity demand (Ewing 2017). The total installed generation capacity in 2016 was 79,025 MW of which 8,619 MW comes from commercial-scale solar facilities larger than 1 MW and 5,644MW comes from wind. Thus, variable renewable energy generation accounts for approximately 18% of the installed capacity in California. In 2016, solar and wind accounted for 49895 GWh of electricity generation or 17.17% of total generation (CaliforniaDGStats). Distributed renewable resources also have a strong presence in the California grid with a 5900 MW interconnected solar PV net energy metering (NEM) capacity (CaliforniaDGStats). State laws, regulatory structures and falling system prices have played a significant role in making California a leader in solar installation. The state Renewable Portfolio Standard (RPS) sets renewable energy procurement targets for the state's load serving entities, requiring both retail sellers and local publicly owned electric utilities to increase their procurement of eligible renewable energy resources to 33 percent of retail sales by 2020 and 50 percent by 2030. The adoption of distributed renewable resources has been also been a key focus of state laws. The state has a goal of installing solar energy systems on 50 percent of new homes by 2020. State incentive programs have included utility feed-in tariffs for the investor owned utilities' (IOUs), procurement of small-scale renewables, and state-mandated self-generation incentive programs.

Falling costs of solar and wind technologies have helped maintain a fast pace of growth for variable renewables in California. For projects completed in 2016, the cost of installing utility-scale PV (systems greater than 5 MW) has fallen by two-thirds since 2007–2009 (CEC 2017).

Flexibility from baseload power sources have so far allowed for the integration of wind and solar without need for any significant changes in the system operation. However, as California moves towards its 50% renewable goal new technical challenges are expected to emerge. The California Public Utilities Commission 2015 (CPUC 2015) and CAISO (Liu 2016) have lists several reliability challenges including, over generation and curtailment, steep evening ramps and decreasing supply of frequency response.

Evening Ramp: Dispatchable resources need to change their output to match net-load as variable resources such as solar become unavailable. As distributed solar resources become more prominent in the grid net load can change more quickly and more system flexibility is required, Net load, is defined as the remaining demand that must be served after subtracting the energy provided by wind and solar generation. CAISO identifies four distinct ramps in the net load curve that base load generation would have to follow on a January study day. The first ramp in the upward direction occurs early in the morning when people start waking up. The second, in the downward direction, occurs after the sun comes up and on-line conventional generation is replaced by supply from solar generation resources. As the sun sets the third upward ramp occurs and the conventional generation must come online again to follow the steepest net load. Immediately after this as demand on the system decreases into the evening hours, the fourth downward ramp occurs. To ensure reliability under these conditions, CAISO needs resources with ramping flexibility and the ability to start and stop multiple times per day.

Over-generation: When all anticipated generation exceeds the real-time demand over supply occurs. If the CAISO market does not automatically correct for oversupply it can lead to over-generation and risk reliability of the grid. Over-generation becomes more and more of an issue in high VRE systems since VRE output is harder to accurately forecast and schedule. These events can be managed through manual curtailment of renewable generation, which incurs economic costs.. In 2014, 2.2 GWh of renewable energy were curtailed due to oversupply, relative to the 44,000 GWh of renewable energy supplied to the grid. Currently, congestion events cause more curtailment in the grid than oversupply. However, the problem is expected to get worse as more wind and solar enter the market.

Declining Frequency Response: The 2020 CAISO grid integration study shows that in times of low load and high renewable generation, as much as 60% of the energy production would come fromVRE resources. As explained earlier, variable renewable generators do not have the same frequency response capabilities as synchronous generators. In the CAISO market variable renewable generators are not currently required to include automated frequency response capability. Without this capability, if there is high share of variable renewable generation in the grid and a frequency imbalance occurs due to loss of generator or transmission line, the system could be exposed to blackouts.

Some of the solutions enacted by CAISO and CPUC are as follows:

The Long-Term Procurement Plan (LTPP) proceeding under the review of the CPUC is currently where the analysis and planning to tackle grid integration challenges is being addressed. The LTPP framework is looking at supply side flexibility by increasing flexible capacity; reviewing market mechanisms; regionalization of energy markets; renewables procurement and valuation; and procuring energy storage.

Market Mechanism: CAISO has been developing a flexible ramping product to help address the steep evening ramps. The product would allow CAISO to pay generators for some of their capacity to remain on standby during low-ramp periods, so that the generator is then available to turn on during high-ramp periods at the request (dispatch) of CAISO.

Energy Storage Procurement: California has enacted policy setting storage procurement targets for utilities. The targets total 1.325 GW of storage procurement by the end of 2020 across three grid domains: transmission, distribution, and customer-side.

Energy Imbalance Market: In 2014 CAISO began implementing a regional Energy Imbalance Market (EIM) that allows other neighboring balancing authorities to participate in their market as a way to share reserves and integrate renewable resources across a larger geographic region. EIM is expected to mitigate over-generation events and potentially reduce curtailments in California and neighboring balancing areas.

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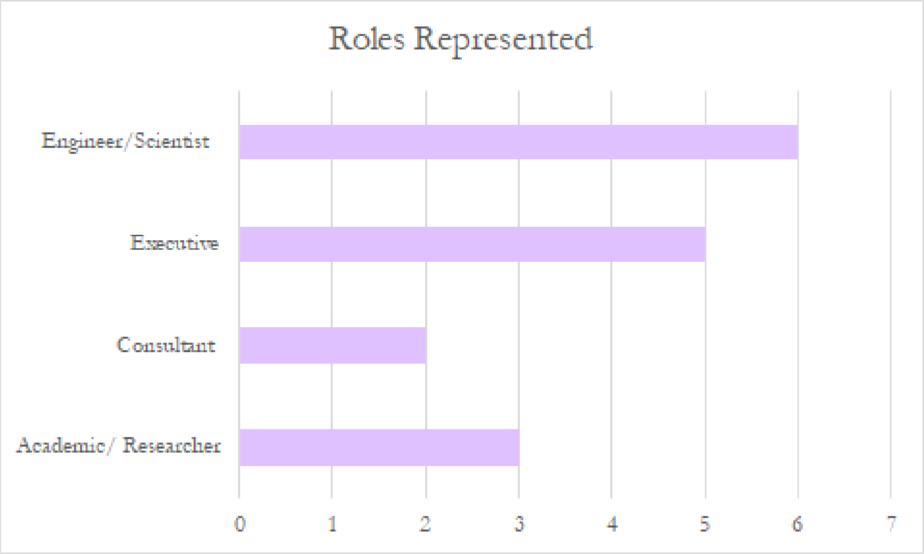
Appendix A

Institutions Represented

Argonne National Laboratory
University of Michigan
Argonne National Laboratory
NC State University
University College Cork
Hydro Tasmania
Enernet global
IEA
Lawrence Berkeley National Laboratory
Independent Consultant
Energynautics GmbH
VTT Finland / IEAWIND Task 25
Energinet
ERCOT
MPE
Utility Variable Generation Integration Group

Current Role

Research Scientist
Asst Prof
Computational Engineer
Assoc Prof
Research Fellow
Implementation Manager
Head of Engineering
Head of Unit - System Integration of RE
Senior Scientific Engineering Associate
Principal Scientist / Operating Agent
Vice President, Associated Activities
Lead Engineer - Renewable Integration
Managing Director / Consultant
Executive Director



Survey Sent out to Experts

Name:

Institution/ Organization/ Company: **Current Role:**

General Questions

According to you what are the main drivers of integration of VRE sources in current power systems? (public policy, technological evolution, climate change mitigation markets, research, cost of technology etc)

What factors do you think current researchers have not explored enough when envisioning grids with high shares of VRE (>75% of annual electricity generation)?

Integration Challenges

How would long term power system planning change for grids operating with high share of VRE sources?

Could you discuss some of the day to day needs for the operation of a power system with high shares of VRE in the grid? (e.g. frequency control strategies to respond to power imbalances, short term load forecasting etc.)

A research project in Europe, Project Migrate 2020 is currently investigating ways to securely operate systems with low or no synchronous machines. According to you, what are the most pertinent power system stability challenges brought by increased penetration of VRE sources in the grid? List them in order of relevance.

Are there issues related to grid integration challenges that were not brought up in this section that you would like to discuss?

Integration Solutions

According to you, what are some of the long-term planning solutions power system operators would need to adopt to enable high penetration of VRE?

What are some of the strategies power system operators could use to deal with the day to day operational challenges of a high share VRE grid?

In your opinion, how would energy storage technologies need to evolve to complement future power systems with high shares of VRE? (e.g. increasing capacities and/or efficiency of existing technologies, development of new technology for decentralized or large scale centralized application etc).

Are there any emerging technologies or practices enabling very high or even 100% shares of VRE that were not brought up in this section that you would like to discuss?

Future Grid Scenarios

According to you. is there a technical limit to the amount of instantaneous VRE penetration that a grid can handle without affecting reliability? What are the factors that govern the technical limit?

How will future power systems need to evolve (in terms of rules of operation, technologies that are utilized to control and maintain reliable operation) in order to accommodate 100% instantaneous share of VRE?

What boundaries of technological innovation would need to be pushed to operate a power system with 100% of annual demand being met by VRE sources?

How do you envision power systems that operate with 30-50% instantaneous VRE penetration today evolving over the next 50 years? What is your vision for the grid of the future?