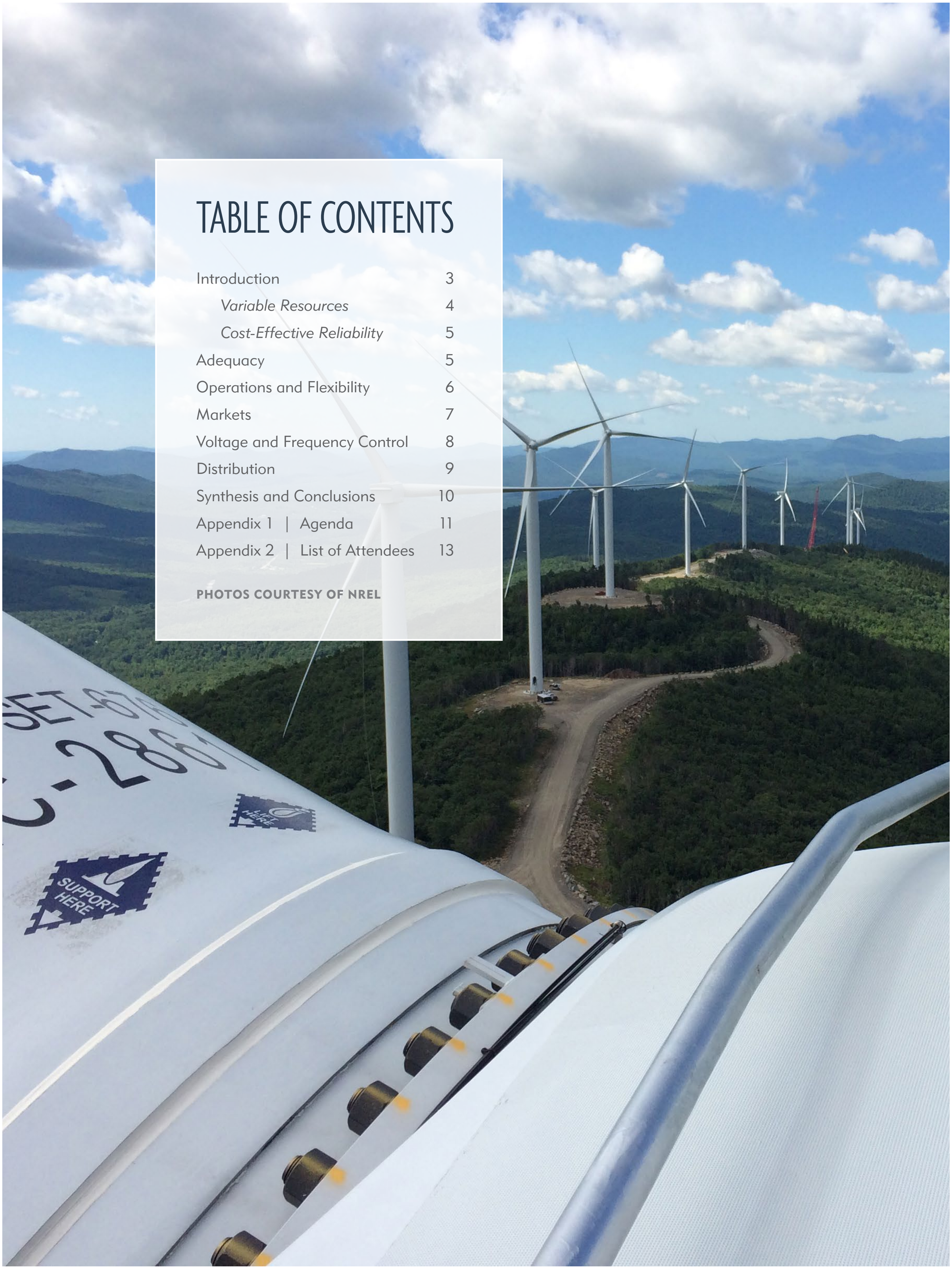
TOWARD 100% RENEWABLE ENERGY PATHWAYS:

KEY RESEARCH NEEDS

OCTOBER 2019

ESIG

ENERGY SYSTEMS INTEGRATION GROUP



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INTRODUCTION

Decarbonization of the energy system is fundamental to combating climate change. Several pathways could contribute to a decarbonized energy system including efficiency, nuclear energy, carbon capture, and renewable energy. Very likely pathways, based on technological and economic grounds, are renewable energy harnessed through the electricity system and the electrification of large parts of the economy, including transportation and heat. The combination of these two primary pathways is gaining traction with, for example, the growing electrification of transportation and the rapid deployment of variable renewable energy sources on electricity systems. It is likely that different pathways will evolve in different regions, but renewables and electrification will globally be a part of the solution.

It is important to understand the technological and economic challenges of transforming the electricity system to a high percentage of renewables. This will help in identifying what is known and is implemented, what is known but requires implementation (e.g., through knowledge transfer and education), and what is unknown and requires research and innovation ranging from technology development to business models to analysis. Such an understanding can indicate, from a decarbonization objective, what is best done using approaches other than renewables alone, such as a portfolio of renewables and nuclear power. Instantaneous renewable energy penetrations of 100% will be reached in a given region long before annual energy penetrations of half that amount. Proven technologies are likely to get us to 80% of annual energy from renewables, with the final margin toward 100% requiring additional technology and approaches that we will have some time to address. From a technical and engineering point of view, the goal is to help society achieve policy objectives in ways that are reliable, economic, and sustainable.

To this end, on May 14 and 15, 2019, the Energy Systems Integration Group (ESIG) held a workshop bringing together 56 experts from around the globe to identify the technological and economic integration challenges of transforming the electricity system toward 100% renewable. (See Appendix 1 for a list of attendees and Appendix 2 for the meeting agenda.) This report summarizes the outcome of the meeting. The workshop summarized here is seen as the first step of many to address the issue of going toward 100%, with the ultimate aim of producing a research roadmap for use by researchers, research organizations, and funders to help focus and prioritize their efforts and investments.

The starting point for the discussions was around existing electricity system operational and planning paradigms and market designs. The end state of the electricity system will evolve from the existing system and a set of competing influences, many of which are regional in nature. Every system is different, with different starting points and different characteristics–technically, socially, and economically–and different pathways will be adopted. For example, regions with abundant hydro resources with storage can more easily get to 100% renewables, while regions with a large amount of variable renewable resources may have to develop other storage or demand-side solutions. The workshop discussions assumed no technological or societal game-changing breakthroughs and focused on getting there with existing solutions. However, some enabling trends in the electricity system are evident today whose impacts will be highly influential; these are highlighted here.

- The **demand side** in electricity will be subject to substantial changes in the future. Workshop discussions assumed that the economy will be heavily electrified, which will both increase the demand for electricity and alter the demand profile. The electrification trend includes sector coupling and a more integrated energy system, with electricity playing a central role with the electrification of heat and transportation and coupling at scale to fuels (natural gas, hydrogen etc.). The societal trend toward digitalization is also enabling the growth of **demand side participation**, which can help demand follow the availability of variable renewable energy resources and provide other reliability services for the system. The new electrified loads can be designed with demand participation in mind–e.g., loads designed to be flexible–and will provide system integration opportunities. Aggressive **energy efficiency** will moderate the increase in demand due to electrification, although the reduced demand may also moderate the maximum potential for demand participation to some degree.

- **Battery storage** has recently experienced dramatic cost declines, which is beginning to impact the short-term (daily) operation of the electricity system today and is enabling more renewables. For longer, seasonal time scales, battery storage is not likely to be economically viable for the foreseeable future. Power-to-gas technologies are currently very costly, particularly if they are used in the classic storage mode of electricity in and electricity out; however, their costs are declining, and they have potential for seasonal storage. Thermal storage is also an option for longer-term storage needs.

- **Decentralization** is a growing trend, with energy production (typically renewable) being located closer to consumption. This is changing the characteristics of the centralized paradigm, where bulk electricity was transported by large-scale high voltage transmission across long distances in a unidirectional fashion to load centers. The advantages of aggregation of variable renewable resources over larger areas with large-scale transmission are well established. Therefore, while decentralization may result in higher contributions by renewables, when coordinated with the centralized paradigm it will produce a diverse electricity system that combines the best of the centralized and decentralized paradigms.

These trends toward demand-side participation, storage, and decentralization can have a synergistic influence on the pathways toward a 100% renewable electricity system. Their contributions are yet to be revealed, but together they present an enormous opportunity to enable a 100% renewable electricity system. The May 2019 workshop focused on identifying the research, education, and knowledge transfer needs for the integration of these synergistic trends into the electricity system in order to enable its cost-effective and reliable transformation into a variable renewables—based system.

VARIABLE RESOURCES

There exist today electricity systems operating at or very close to 100% renewable (for example, in Iceland, Norway, Austria, and Quebec). However, these systems tend to be based on less-variable renewables such as hydropower with storage, geothermal, biomass, or concentrating solar rather than on solar photovoltaics (PV) or wind power. The focus of the May 2019 meeting was variable renewables, primarily wind and solar PV, given the global abundance of wind and solar energy and their dramatic drop in cost in recent years that makes them a competitive, and often the lowest-cost, source of energy. Variable renewable resources differ from conventional generating resources (thermal, nuclear, and hydro plants) in two respects. Wind and solar PV are dependent on the weather and therefore

are, by definition, variable and somewhat difficult to predict. And they are connected to the electricity system via power electronic converters with different properties than the more traditional synchronous generators.

COST-EFFECTIVE RELIABILITY

The fundamental objective of an electricity system is to cost-effectively maintain supply-demand balance reliably at all locations and at all times. This reliability/cost tradeoff is enabled technically and economically by defining a set of services. Ideally, these services translate into having adequate generation and transmission capacity that is flexible enough to deal with the variability and uncertainty of demand and supply and can do so in a cost-effective manner, either through markets or equivalent mechanisms. Supporting this is the voltage and frequency that is controlled and can recover dynamically and protect the equipment during faults. These objectives apply at all locations; however, the distribution system needs special attention, as it has not traditionally had active generation and/or demand connected. Attention to the distribution system is particularly important in regions where the decentralization trend is significant.

ADEQUACY

Variable renewable generation resources contribute to resource adequacy, but, like nearly all types of resources, their contribution declines with their penetration level. These declines can be significant because of the correlated nature of the variable renewable resource, but are moderated by diversification and larger geographical footprints enabled by transmission. As the contribution of variable generation increases, there may be a need for more diverse and less correlated renewable energy generation sources, electricity storage, and/or demand participation. Although demand participation, in contrast to electricity storage, is unidirectional–i.e., electricity is converted into another form but is not converted back to electricity–it does contribute to adequacy. Adequacy requirements drive the need for investment, and in a 100% renewable electricity system the bulk of the costs is in capital expense. Therefore, from a cost perspective, adequacy is the main driver of cost.

Adequacy calculation methodologies are well established for wind and solar PV but are not widely applied. Many of the challenges identified at the May 2019 meeting shared this trait–solutions well known and understood but not widely applied–indicating that education and increased technology transfer are needed. As variable renewables' share increases, there will be a need for more rigorous use of the methodologies to ensure adequacy at least cost. This balancing act, to ensure that capacity is rewarded in a market setting or otherwise, without over investment, will require education of practitioners in existing state-of-the-art methodologies.

With more demand-side participation and increasingly flexible resources, the adequacy metrics need to be updated to properly reflect the needs of society. For example, the most common metrics (e.g., loss of load probability) are arbitrarily employed with respect to the societal requirements. Other metrics exist (e.g., expected unserved energy) that may be more meaningful if the energy, as opposed to capacity, limitations become more dominant. Metrics for loss of load probability and expected unserved energy make sense if there is a fraction of the demand that is totally inflexible, that is, that "must" be served. If there is enough flexible or responsive demand, the classical adequacy problem recedes and is replaced by a cost minimization problem, where the investment cost is balanced against the expected cost of compensating consumers for reducing or shifting their demand.

As we go toward 100%, adapting and enhancing the adequacy calculation methodologies is needed because traditionally they do a poor job of representing the impact of important enablers of moving toward 100%: transmission, generation embedded in the distribution system, storage, demand participation, and sector coupling. This suggests a number of modeling and data challenges, in particular:

- Research is needed on how to model transmission–a major contributor to adequacy–and its operation in order to correctly capture adequacy benefits that occur when a larger geographical area is connected by limited capacity transmission.
- On the other end of the spectrum are distribution-connected resources that are limited by the distribution network and their operational characteristics. These distributed resources need to be correctly modeled in adequacy calculations.
- Demand is also largely connected to the distribution system, and its contribution to adequacy requires modeling its physical characteristics and its responsiveness to price.

- Similarly, the operational characteristics of storage devices, if deployed at scale, will need to be better modeled in order to account for their adequacy contribution. This is also true of other resources with highly flexible response characteristics.
- Wider sector coupling between electricity, transportation, heating, and fuels highlights the need for improved models to fully capture the impacts of sector coupling on adequacy.
- The dimensionality and underlying correlations between demand and supply (through weather) indicate that more high-quality, long time-frame data are needed to make the adequacy calculations robust.

To a large extent, these modeling and data needs are related to more effectively capturing the potential flexibility contributions of these resources, and this is an active area of research and implementation. There are also operational challenges that need to be resolved in order to fully take advantage of this flexibility.

OPERATIONS AND FLEXIBILITY

An inflexible but capacity-adequate system with high contributions from wind and solar PV will need to curtail significant amounts of these energy sources, thereby increasing costs compared to a more flexible system; there may also be challenges managing the variability and uncertainty in a reliable fashion. There is thus a need to ensure that the system can provide enough flexibility, as well as other services, to maintain a desired level of reliability. Operators will need tools and methods to ensure reliability from the operational planning stages down through scheduling and into real time. This includes visibility and control at sufficient levels of detail.

As with adequacy, flexibility can be tackled on both the supply and the demand side, and it has both operational and planning aspects. Traditionally, flexibility and the provision of services are mainly an operational challenge, while adequacy is mainly a planning challenge. As we go toward 100%, adequacy and flexibility will increasingly need to be considered simultaneously. The operation of the electricity system to maintain reliability in a cost-effective manner will require that system needs for flexibility and other grid services are minimized and that the provision of grid services, including flexibility, is maximized across all

available resources. These operational flexibility needs include:

- Because wind and solar PV are variable and somewhat difficult to predict, there is an increasing need for improved forecasting, tools, and data sets that allow for the best use of existing flexibility. With weather driving both the demand (e.g., heating and cooling) and supply, integrated forecasting is required. Forecasting not only of supply and demand, but also their characteristics and uncertainty, becomes increasingly important; for example, how much of the demand is flexible? What is the synchronous inertia online? These forecasts then need to be integrated into the various operational tools–operational planning and outage scheduling, contingency assessment, unit commitment and dispatch, and real-time operations and control–with data and models shared across different domains and applications in a standardized fashion.
- New operating tools that ensure stability of the system may be needed and existing tools improved upon. Much of this is already in practice in electricity systems with high contributions of variable renewables, and as levels increase, there is continual need for education, implementation, and improvement.
- With the supply-demand balance becoming more dynamic and the levels of uncertainty increasing, this will require a change in the deterministic mindset of the industry participants to a more probabilistic one. In order to minimize the need for flexibility while maximizing its availability–with the associated benefits for cost and reliability–better, more user-friendly, probabilistic tools need to be developed through research and leveraging improved computational power and better data sets.
- Going toward 100% renewables, new sources of flexibility will need to be unlocked. These include storage options via sector coupling, such as electric vehicles and thermal storage. The incentives across sectors will need to be transparent and functional. The ability of different resources to contribute will need to be quantified and understood, and well-designed system architecture established around providing flexibility and other services from these new or expanded sources.
- Data gathering and visibility will become increasingly complex, and system operators need to be fully aware of the situation in order to maintain reliability in operations.
- Sources of flexibility may be within the distribution system, which will require working across the transmission and distribution interface and developing the tools, architecture, and protocols that allow an understanding of the ability of aggregate sets of distributed resources to provide services (including when they can do so, how long they can sustain the services, and how quickly they are able to respond, etc.). Similarly, for accessing flexibility at another scale across regions and borders, greater coordination is needed between system operators.

In all these instances of operational flexibility, it is important to define system needs and communicate a consistent set of well-designed services to all actors across all spatial and temporal domains in order to ensure efficient and reliable operation of the electricity system now and in the future. The provision of many of these services becomes the role of markets, tariffs, or interconnection requirements.

MARKETS

Competitive electricity markets operate reasonably well in many parts of the world. While formal electricity markets are one way of organizing the electricity industry and ensuring good economic outcomes, others include regulated vertically integrated utilities or a hybrid approach. The principles should be the same: to ensure cost-effective and reliable operation of the electricity system.

Thus far, markets have absorbed a significant amount of renewable generation. Several of these markets have substantial hydro electricity generation that has been in place for decades and is globally the largest renewable electricity resource. However, increasing amounts of variable renewable generation, coupled with the inflexibility of many conventional resources, are causing longer and more numerous periods of very low, zero, or negative energy prices at times of excess energy supply. Similarly, variability and inflexibility can result in periods of high prices during times of limited supply of energy or other services (as they should in any well-designed market system). This price volatility is encouraging investment in needed flexibility, but it is unclear whether the current market structures will support investments as we go toward 100%. A perennial problem with electricity markets regardless of increasing variable renewable resources has been the difficulty of getting the investment signals correct.

Some system operators have begun experimenting with various services and design changes aimed at meeting this need for flexibility. Other regions have introduced forward markets for capacity, with mixed success, to provide revenue for resources that are needed for resource adequacy but do not earn enough revenue for fixed costs in the energy market due to price caps or other reasons. Market designs globally have several common characteristics but can vary substantially in the details, driven by a number of factors including energy resources and historical, social, and political considerations. This leads to a set of fundamental market design questions:

- What are appropriate market designs that will incentivize investment toward the optimal mix of resources by accurately determining their value, as well as the attributes that may be beneficial or required in a future electricity system with 100% renewables? And, is this even the proper role of the organized markets, or are there other approaches to support long-term investment?
- Will these market designs or other approaches be enough to incentivize the resources that underpin the balance between cost and reliability that are aligned with the needs of society and can they discriminate between differing customer valuations of the reliability?
- With the increase in demand-side participation potentially being critical to getting to 100%, how can the market and regulatory framework be enhanced to allow for demand to become responsive to price in a manner that can help resolve potential market design challenges, including price setting, revenue adequacy, resource adequacy, and flexibility needs?

With an adequate system that has the required level of flexibility that is fully enabled in a cost-effective manner, supply-demand balance can be met in a reliable manner. However, the underlying engineering reliability of supply demand balance is characterized by voltage and frequency control, an area with a number of needs, outlined below.

VOLTAGE AND FREQUENCY CONTROL

Wind and solar PV generation (and many modern loads) are electrically connected non-synchronously to the electricity system via power electronic converters. This stands in contrast to the synchronous generator that has dominated electrical generation technology from the beginning. There are some fundamental issues due to this underlying change in the nature of the electricity system, which may be moving from a synchronous system toward a non-synchronous system, that require a significant research agenda.

If the alternating current (AC) paradigm is maintained, which is likely at least in the short to medium term, then several important research questions need to be addressed, including:

- The design of an AC electricity system with little or no synchronous generation will require grid-forming power electronic converters. What are the most robust and best designs and functionality for these components? For example, in these circumstances, is frequency the right parameter to indicate system load-generation balance? How should system frequency be set?
- A more conservative solution might be to maintain the synchronous machines in the form of synchronous condensers and maintain a synchronous electricity system or one that varies its operation from synchronous to non-synchronous depending on the current resource mix. How would we ensure seamless operation of such an electricity system while maintaining reliability?

The outcomes of these research challenges have potentially very significant implications for the electricity system in the future. In the interim, with increasing levels of variable generation that are connected with power electronics, there are novel challenges and opportunities.

Power electronics mechanically decouple the inertial response of wind turbines from the electricity system, and there is no inherent inertial response in solar PV. Lower inertia/higher rate of change of frequency issues and available solutions have been studied and known about for decades (in ERCOT, Ireland, and Hydro Quebec in particular because of their "island" nature), but are not globally recognized and applied.

Today's power electronics have a limited ability to provide large transient currents, which is fundamental to conventional protection technologies during faults. This limited fault current and inertial response can have major impacts on voltage and frequency control, dynamic behavior during faults, harmonics, and black start capabilities. At the same time, non-synchronous resources are, by their nature, highly programmable devices that can emulate many behaviors. Many of these challenges are about understanding the exact behaviors that we want them to have, particularly when some behaviors are different from and superior to the inherent, largely unprogrammable behaviors of synchronous resources to which we are accustomed.

Specific research needs include the following:

- Simulation tools and models that have the fidelity to support system planning and interconnection studies are needed. Understanding the limitations of existing tools should be followed by the development of new tools and models for the power electronic converters.
- Protection systems that work well as the synchronous generators are replaced by power electronic—interfaced generation are needed.
- New designs are needed for bulk power system restoration and black start with high levels of power electronic converter—connected variable generation.
- The impact of system harmonics and resonance on power electronic converters and design of mitigation measures must be better understood (e.g., shaping harmonic impedance of inverters to provide damping and attenuation at specific frequencies).
- Control and physical stability with high contributions of power electronic converter—connected generation changes the game and requires a heightened awareness and deployment of new technologies to resolve.
- How to most effectively unlock the advanced capabilities of power electronic resources? What is the role of standards to require a minimum performance vs. policy and markets to incentivize them? Either way, a transformation of how all assets behave is needed to achieve 100%.
- What is the role of synchronous generation and transmission and distribution infrastructure in adapting to the increased flexibility, stability, and control needs of our future grid with high levels of non-synchronous resources? A critical part of achieving 100% is getting there, and the adaptability and coordination of all grid assets is paramount.
- Direct current (DC) solutions within an AC-dominated system are becoming more common. What is the appropriate balance between the AC and DC solutions, and how should they be best planned and operated together?

These voltage and frequency control challenges apply throughout the electricity system at both transmission and distribution levels. However, there are additional needs regarding the distribution system if the decentralized trend is significant.

DISTRIBUTION

Many of the distribution system needs are similar to those on the broader electricity system: adequacy, flexibility, markets, frequency, and voltage. If decentralization happens at scale, and demand becomes more responsive, then planning and management of the distribution system will need to change. Even with only modest decentralization, attention must be given to the distribution system in order to provide the functionality to handle demand flexibility and the increased electrification of all sectors.

With substantial amounts of variable renewable generation and storage on the distribution system, new approaches are needed to manage voltage and congestion on the distribution system as well as new ways for markets and operations to reach distributed energy resources. These needs include the following:

- A new architecture and communication strategy will be required given the potential for billions of distributed energy resources. System operators and planners must resist the urge to implement a "command and control" approach for these new resources. Decentralization and digitization mean at least an order of magnitude more participants in the energy system, which becomes intractable to a centralized control paradigm.
- With a more active distribution system (more demand participation and distributed generation), the coordination with the transmission system will become increasingly important. For example, how will these systems interact such that efficiency is gained and users on both systems have the right price signals to provide reliable and affordable energy?

- How do the non-monetary values that some customers assign to distributed energy resources influence investment decisions and the evolution of the demand and supply portfolio?

- How do we accomplish a transformation of the distribution planning process that accounts for the impact of inverter-based resources in a way that is equivalent to how the transmission planning process has evolved?

These distribution system needs are at the boundary of the scope of the workshop and open up another set of questions related to the demand side and how it will evolve, in particular the detailed impact of electrification, energy efficiency, distributed storage, deployment of electric vehicles, and other positive trends.

SYNTHESIS AND CONCLUSIONS

At its core, the objective of an electricity system is simply to cost effectively maintain supply-demand balance reliably at all locations and at every point in time. This cost-reliability tradeoff is central to any endeavor to go toward 100% renewables. It is easily achieved at a high cost and/or a low level of reliability. However, we must achieve a balance where the correct level of reliability is achieved at an acceptable cost.

The needs detailed above range from education to fundamental research questions that could profoundly change the electricity system as we go toward 100%, to less profound issues that could degrade reliability and/or increase costs. The scale of what needs to be done is evident and all aspects need to progress in parallel. The dependencies between the needs identified above are striking and make it difficult to identify "no regret" investments in time and resources to address the needs.

The most urgent need is to address the fundamental research questions, as they may have profound impacts across the electricity system. Two examples mentioned above stand out:

- The question of the potential change in the synchronous nature of the electricity system will have a profound impact on the core technologies that make up the electricity system and its control and protection.

- The nature of the societal need for reliability in the electricity system and the role of the demand side may change, and this would have a profound impact on adequacy, flexibility and the nature of maintaining supply-demand balance.

These two research questions and their potential impacts span the entire range from the technological to the economic to the societal and underscore the dimensionality and complexity of going toward 100%.

As noted above, every electricity system is different, and this will drive regional solutions as is the case in the system today. Renewable resources are by their nature regional, and this is likely to drive a much more diverse set of solutions. However, even with this regionality, there will be many opportunities to deploy a given solution in multiple regions. A global coordinated effort therefore has great potential. The dependencies between the needs also mean that coordination between the different modalities of effort (i.e., education, implementation, and research) is highly desirable.

In conclusion, there are a large number of diverse needs when moving toward 100% renewable electricity systems, but these are all potentially solvable in the near future. A coordinated global approach connecting the research, education, and implementation of the solutions outlined in this summary can enable this pathway, leading to the successful implementation of the reliable, economic, low-carbon electricity system we need in the decades ahead.

APPENDIX 1 | AGENDA

TOWARDS 100% RENEWABLE ENERGY PATHWAYS: A RESEARCH ROADMAP

MAY 14-15, 2019 | DENVER, COLORADO

WORKSHOP PURPOSE

All deep decarbonization scenarios involve increasing electrification of energy end-use and increasing utilization of renewable resources.

The purpose of this workshop is to develop a coordinated international research roadmap to address the technical challenges associated with incorporating very large amounts of variable generation (wind and solar) into the energy supply mix, recognizing the accompanying electrification of the economy and its social science dimension. In particular, the workshop will focus on the issues of operating a power system with 100% instantaneous penetration of inverter-based resources in a reliable and economic manner. The ultimate goal of the energy systems integration effort is the decarbonization of the complete energy system, through the integration of electrical, thermal and gas systems with application to the transportation, buildings and industry sectors. The bookend scenario of 100% annual energy from renewables will also be considered as a limiting case for illustrative purposes.

The roadmap will provide a research framework to allow cooperation among multiple independent parties. It is recognized that not all regions will follow the same pathways at the same time, but the chosen pathways must lead to a common destination. The pathways will identify major technology development needs, analytical efforts, and decision points needed to support the selected path. The vision is that the resulting roadmap will allow parties, using their available resources and working in a loosely coordinated fashion, to make progress toward common goals while identifying and taking advantage of advances in other international efforts.

TUESDAY, MAY 14, 2019

Opening Session (9:00 – 10:00 am)

Chair: Mark Ahlstrom, *President, ESIG Board of Directors*

A Word from our Sponsor
Ric O'Connell, *GridLab*

A Sense of Urgency
Michael O'Boyle, *Energy Innovations*

Workshop and Agenda Overview
Charlie Smith, Executive Director, ESIG
- Introductions of group leaders and rapporteurs
- Review agenda and topic content
- Expectations for the work product of each group

Research Roadmap
Mark O'Malley, *Chief Scientist, NREL; Chair, ESIG Research & Education Working Group*
- Process for putting a final report together with Research & Education WG
- How the report will be used

Workshop Background (10:15 am – 12:00 pm)

WHERE ARE WE AT, WHERE ARE WE GOING, AND HOW WILL WE GET THERE

Chair: Ric O'Connell, *GridLab*

This session will set the stage for the workshop participants regarding the workshop scope, possible pathways and expected outcomes. We recognize that different regions may follow different pathways at different times, but there must be a common destination at the end.

Where Are We At
Vera Silva, CTO, *GE Renewables and Grid Business*

Where Are We Going
Nick Miller, *Consultant*

Possible Pathways Toward 100% RE: How Will We Get There
Mark Ahlstrom, *President, ESIG Board of Directors*

Group Discussion

Session 1 (1:00 – 5:30 pm)

TOPIC SCOPES AND ISSUES: PARALLEL TRACKS

Each group will start with a detailed presentation for orientation on the session topic. The groups will discuss their individual scopes and come to consensus on what is known and what are the major unknowns that must be dealt with in each area for the purpose of developing the research roadmap. The fact that different pathways may be followed at different times in different regions will be recognized, while identifying the basic engineering physics which will govern any pathways selected, and the resulting choices which must be made in order to reach the common destination.

TRACK 1: Adequacy

Chair: Aaron Bloom, *NextEra Analytics*
Rapporteur: Hannele Holttinen, *VTT*

- Adequacy Issue Orientation: Aaron Bloom, Next*Era Analytics*

TRACK 2: Volts and Amps

Chair: Jason MacDowell, *GE*
Rapporteur: Abraham Ellis, *Sandia National Lab*

- Volts and Amps Issue Orientation: *Jason MacDowell, GE*

TRACK 3: Distribution Systems, Microgrids, and Customers

Chair: Debbie Lew, *GE*
Rapporteur: Ben Kroposki, *NREL*

- Distribution Systems, Microgrids and Customers Issue Orientation: Debbie Lew, *GE*

TRACK 4: Flexibility, Operations and Balancing

Chair: Aidan Tuohy, *EPRI*
Rapporteur: Chris Greig, *University of Queensland; Visiting Professor, Princeton*

- Flexibility, Operations and Balancing Issue Orientation: Aidan Tuohy, *EPRI*

TRACK 5: Markets

Chair: Erik Ela, EPRI
Rapporteur: Daniel Kirschen, *University of Washington*

- Markets Issue Orientation: Erik Ela, *EPRI*

Report-out to full group

WEDNESDAY, MAY 15, 2019

Session 2 (8:30 – 12:30)

TOPIC RESEARCH ROADMAP OUTLINES: PARALLEL TRACKS

Each group will outline a research roadmap to tackle the issues identified and develop the information base necessary to answer the related questions and resolve the issues. The research framework will acknowledge the differing pathways possible at different times in different areas; the technology development, analysis work, and major decision points which the chosen pathways will require; the consequences of delaying or not making the important decisions; and the need for the selected pathways to reach a common destination.

Report-out to full group

Session 3 (1:15 – 4:30 pm)

TOPIC ELEMENTS OF THE RESEARCH FRAMEWORK: PARALLEL TRACKS

The beginning assumption for each track will be that the tasks can proceed in parallel relatively independently. For each of the identified tasks, we will provide a research framework, including technology development, analytical studies and major decision points to allow multiple independent parties to work in a coordinated fashion across national boundaries. At the end, all of the pathways and task roadmaps should lead us to a common destination where grid following converters, grid forming converters and synchronous machines (generators or condensers) can operate seamlessly with one another as the state of the system resource mix continually changes from very low to very high IBR penetration.

Report-out to full group

Wrap-up Session (4:30 – 5:30 pm)

PROGRESS REVIEW AND NEXT STEPS

We will summarize what has been accomplished, what remains to be done, and lay out the steps to complete the roadmap, followed by a moderated discussion. It is proposed that ESIG will serve as the platform to coordinate the work of the parties, report on progress and update the roadmap. This is envisioned as the first step in a coordination process which will unfold over a long period of time.

Moderator: Jonathan O'Sullivan, *Eirgrid*

ACCOMPLISHMENTS AND NEXT STEPS

Mark O'Malley, *NREL/ESIG*

CLOSING REMARKS

Mark Ahlstrom, *ESIG*

Adjourn (5:30 pm)

APPENDIX 2 | LIST OF ATTENDEES

ADEQUACY TRACK

Moderator: Aaron Bloom, *NextEra Analytics*
Rapporteur: Hannele Holttinen, *IEA WIND Task 25*

Steve Beuning, *Holy Cross Energy*
Paul Denholm, *NREL*
Brandon Heath, *MISO*
Tim Heidel, *Breakthrough Energy*
Bri-Mathias *Hodge, NREL*
Jim McCalley, *Iowa State University*
Michael Milligan, *Consultant*
Rodrigo Moreno, *U. of Chile*
Mark O'Malley, *NREL*
Kevin Pera, *Xcel Energy*

VOLTS AND AMPS TRACK

Moderator: Jason MacDowell, *GE*
Rapporteur: Abraham Ellis, *Sandia National Lab*

Thorsten Bülo, *SMA Solar Technology AG*
Julia Matevosyan, *ERCOT*
Nick Miller, *HickoryLedge*
Mahesh Morjaria, *First Solar*
Ryan Quint, *NERC*
Goran Strbac, *Imperial College*

DISTRIBUTION SYSTEMS, MICROGRIDS AND CUSTOMERS TRACK

Moderator: Debbie Lew, *GE*
Rapporteur: Ben Kroposki, *NREL*

Miroslav Begovich, *Texas A&M*
William D'haeseleer, *KU Leuven*
Xiaoming Feng, *ABB*
Andy Hoke, *NREL*
Barry Mather, *NREL*
Ric O'Connell, *GridLab*
Kazuhiko Ogimoto, *University of Tokyo*
Charlie Smith, *ESIG*

FLEXIBILITY, OPERATIONS, AND BALANCING TRACK

Moderator: Aidan Tuohy, *EPRI*
Rapporteur: Chris Greig, *Princeton University*

Francisco De La Rosa, *CENACE*
sShuanglei Feng, *China Electric Power Research Institute*
Alain Forcione, *Hydro-Québec*
Andrew Groom, *AEMO*
Michael O'Boyle, *Energy Innovation*
David Schweizer, *PJM*
Vera Silva, *GE*
Ramteen Sioshansi, *The Ohio State University*
Sonya Twohig, *ENTSO-E*
Wesley Yeomans, *NYISO*
Ning Zhang, *Tsinghua University*

MARKETS TRACK

Moderator: Erik Ela, *EPRI*
Rapporteur: Daniel Kirschen, *University of Washington*

Mark Ahlstrom, *NextEra Energy Resources*
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