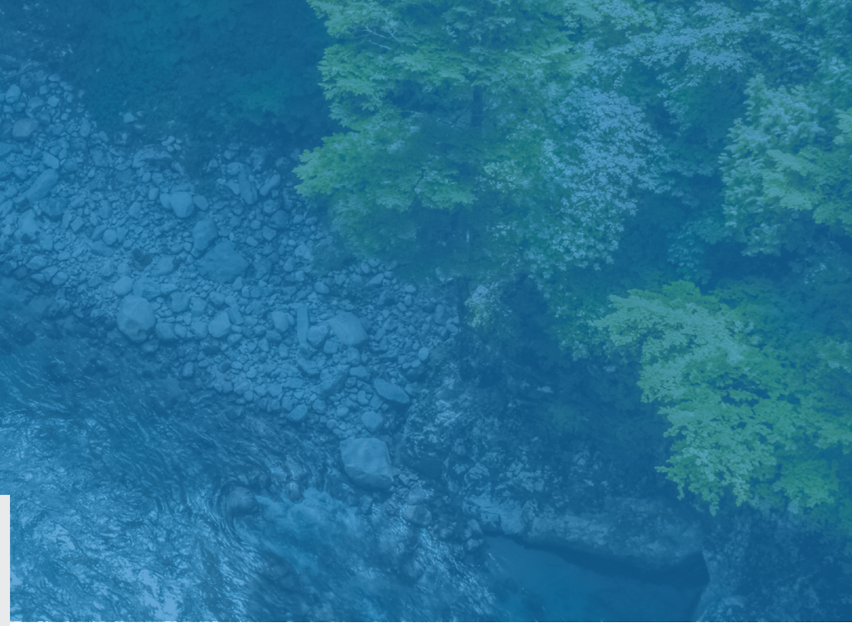

PLANNING

# for Ultra-High Levels of **Renewables**

A GUIDE FROM ESIG

## What's **happening?**

The power sector has evolved considerably in the last 10 years. Natural gas has become the dominant fossil-fuel generating resource in the US in particular, and clean energy technologies such as wind and solar are growing rapidly[1]. At the same time, public policy at the state and local levels is driving municipal utilities, electric cooperatives, and investor-owned utilities to ask new questions about how much renewable electricity can be economically and reliably integrated into the grid to decarbonize the electricity sector. Although hydro-rich systems like Quebec and Iceland have been operating for years with close to 100% renewable power, no major power systems have reached these levels with wind and solar. A decade ago, the boldest of these system planners and policymakers were evaluating 10% to 30% of energy from wind and solar on their systems[2]. Now, however, their sights are set higher, with some areas such as Hawaii (Hawaiian Electric Company 2016), Los Angeles (LADWP n.d.), New York, Denmark[3], and Sweden[4] pushing for 100% renewable electricity systems.

## What does **100% renewable** even mean?

There is not a consistent definition of what it means to be a 100% renewable electricity system. Jurisdictions have taken a variety of approaches to achieving a common goal of decreasing carbon emissions from the electricity sector. In some regions, renewable electricity resources can include all carbon-free technologies; in other regions, only wind, solar, hydro, and biomass are eligible resources. Most regions are looking to a mix of physical and financial approaches (e.g., renewable electricity credits) to reach their targets. In Hawaii and Los Angeles, regulators and system planners are being asked to plan a system that physically meets the 100% goal with renewable technologies, while in Denmark and Sweden, the goal is more broadly focused on achieving a carbon-free energy system.

## What research has been done on **100% renewable?**

There has been limited research on the technical and institutional feasibility of obtaining 100% of a system's electricity needs from renewable generation resources such as wind, solar, hydro, and biomass. The literature contains some limited explorations of ultra-high penetrations, defined here as penetration levels between 80% and 100%, of renewables (e.g., NREL 2012; Becker et al. 2014; Elliston et al. 2014; Frew et al. 2016; Lenzen et al. 2016).

## What **research and development** needs should we plan for?

At the 2017 Fall Meeting of the Energy Systems Integration Group (ESIG), a working group on system planning began to identify and discuss some of the challenges associated with (1) conducting rigorous analyses to support a transition to a 100% renewable electricity system and (2) actually transitioning to such a system. True 100% cases by their nature push the modelling, analysis, and data requirements to a limit that makes studying them challenging. However, a challenge in analyzing them does not necessarily mean they are challenging to physically achieve. The working group sought to understand the challenges and opportunities by focusing on a few key topics: defining resource adequacy, market design, and modeling tools and data. The working group assembled the following list of the top 9 research and development needs to address these challenges of analyzing and/or physically transitioning systems to a limit of 100% renewable electricity.

1 In 2016, natural gas was the dominant fuel source for U.S. electricity generation at 34% ("Frequently Asked Questions: What is U.S. Electricity Generation by Energy Source?" U.S. Energy Information Administration, last updated April 18, 2017, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3). Consumption of energy generated by solar and wind resources in 2016 has increased by over a factor of 7 relative to 2006 values (EIA n.d.)

2 Key past integration studies are listed in MISO (n.d.).

3 Comprehensive power systems analysis includes long-term planning, operations, and stability timescales.

4 https://www.government.se/articles/2016/06/agreement-on-swedish-energy-policy/

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# Analysis of up to 100% Renewable Electricity Systems

## 1 DATA:

Understanding ultra-high penetrations of renewables requires the gathering and creation of new data. Regions that are committed to integrating higher levels of renewables should collect and validate more detailed and higher quality data about their system, and they may also need to create new data to help them study the potential challenges and opportunities of ultra-high renewables. Examples of improved and new data sets include time-synchronous load and renewable time-series data at four-second resolution (or finer) to capture regulation timescales; data on the physical capabilities/limitations of thermal generators, such as outage rates, minimum generation levels, ramp rates, and cycling capabilities; and data on the transmission and distribution (T&D) system, such as line ratings, max flow limits, and distribution feeder topologies needed for power flow simulations. Since each system characterized by this data is unique to the underlying network topology, generator fleet composition, resource availability, load profile, and other data, all data gathered and created must be specific and congruent to the system under study.

## 2 TOOLS:

Some of the tools used to study power systems to date will continue to be useful as the potential for 100% renewable electricity systems, and the transition this requires, is carefully evaluated. However, it is also necessary to create new tools that can better identify system challenges and opportunities, as well as increase coordination between existing tools that span multiple timescales, such as planning models, operations models, and power flow or stability tools. One area in need of research is capacity valuation of variable renewable resources; this valuation impacts capacity-based market participation and system planning efforts. Traditional approximation-based metrics used by some of these system planners for long-term resource adequacy, such as planning reserve margins, are not suitable for systems that rely predominately on weather-driven resources such as wind, solar, and hydro (Pfeifenberger et al. 2013; Milligan et al. 2016a). Instead, probabilistic-based methods, such as loss of load expectation, are more robust and are the preferred approach (NERC 2011; Keane et al. 2011; Milligan et al. 2016b). In addition, there is a need for tools that properly represent interconnection of systems, as well as the coordinated operation of systems when this impacts resource adequacy. For example, T&D co-simulation tools are needed to understand the increased interdependency on generation flowing from the distribution system to the transmission system, which will continue to take place at increasing levels as distributed PV is added to the system.

## 3 UNCERTAINTY QUANTIFICATION AND ANALYSIS:

There is some uncertainty in technologies that can help reach the goal of 100% renewable electricity as well as in future weather conditions (NERC 2014). New work in uncertainty analysis over multiple timescales for power systems is critical for developing a more robust understanding of the impacts of this uncertainty across the full range of planning and operating issues. Previous work has shown that one key impact of higher penetration levels of renewables is an increase in reserve requirements that is due in part to the uncertainty of these resources at shorter timescales (Lew et al. 2013). More analysis is needed to better quantify the impact of ultra-high renewable penetration levels on reserve requirements and the economic ways of providing such reserves from loads, storage, and generation.

# **Realization** of up to 100% Renewable Electricity Systems

## 4 MARKET EVOLUTION:

Markets offer a decentralized approach to incentivizing the behavior and investments for achieving economic and public policy goals. Many aspects of current market designs will need to evolve to properly value and incentivize the capital investments and operational services required to ensure reliability and revenue sufficiency in highly renewable systems. Market design challenges include issues related to price formation, the effectiveness of certain capacity and ancillary service products, and rules for participation in various markets. Market design modifications that enable greater robustness against future uncertainties, such as fuel prices and load growth, are of particular importance in light of recent revenue sufficiency concerns (e.g., U.S. Department of Energy 2017).

## 5 END-USER BEHAVIOR:

Policymakers and system planners should work to develop mechanisms that allow resources and end-users, including residential, commercial, and industrial consumers, to respond to price signals and thereby exercise their preferences for electricity and their desired levels of reliability. Economically achieving the goals of policymakers may depend on unlocking the vast potential of responsive demand. In addition, as end-user consumption patterns evolve within this transition to ultra-high renewables, the role of regional transmission organizations and utilities may need to be re-evaluated to better accommodate different consumer preferences, such as reliability preferences and to understand and adapt to their opposition to some infrastructure.

## 6 INERTIA-LESS POWER SYSTEM OPERATION:

As conventional synchronous generators are replaced by inverter-based wind, solar, and battery storage resources, the synchronous inertial response (i.e., the stored kinetic energy of the rotating mass across all synchronized machines being released in synchrony) of the interconnection declines (Kroposki et al. 2017). This can alter the system's response to unexpected fluctuations in load and generation and require faster automated response for other resources. However, advances in power electronic controls are now making it possible for wind, solar, and storage resources, if the controls are designed properly, to provide the full range of ancillary services, as well as very fast frequency response. In addition, with future change to inverter technology, these resources could also provide emulated inertial response if the power grid maintains a synchronous design. These solutions are not equivalent to synchronous inertial response, but are complementary and could be used to provide equivalent or superior frequency support to the system. This will require research on redesigned inverter-based systems, grid-forming inverters, and inertia-less power systems. One alternative option for providing true synchronous inertial response is through synchronous condensers.

## 7 STORAGE (SEASONAL):

As wind and solar penetration levels increase in today's power systems, curtailment also increases, diluting the environmental and economic value of wind and solar resources. Previous work has indicated that shorter-duration storage (generally up to 8–12 hours) is sufficient for reducing curtailment for wind and solar penetrations up to 55% (Denholm and Mai 2017). However, as penetration levels approach 100%, very-long-duration or seasonal storage may be needed to address the seasonal mismatch of low load with high wind and solar production in the spring and fall in the contiguous United States (Blanco and Faaij 2018). Research is needed on the best ways to provide long-duration or seasonal storage using both new and existing technologies or other alternatives, e.g., seasonal demand response, particularly from the industrial sector.

# **Analysis and Realization** of up to 100% Renewable Electricity Systems

## 8 TRANSMISSION:

A 100% renewable system will require greater regional coordination, including physical interconnectedness through an enhanced transmission network (NREL 2012; Bloom et al. 2016). Because of the relatively long development timelines and complex stakeholder coordination required for transmission projects, analysis should begin now to strategically plan how to develop an enhanced network, including both AC and DC options and the interactions with the distribution network, that best supports the physical transition to a future 100% renewable system. This process also requires identifying any potential regulatory, manufacturing, or other bottlenecks that would prevent or limit the amount of transmission buildout needed for the physical realization of such a transition.

## 9 IT'S NOT JUST ELECTRICITY—IT'S THE ENTIRE ENERGY ECONOMY:

The consensus from the working group at the ESIG Fall 2017 Meeting was that reaching 100% renewable electricity systems at a continental scale will involve many possible technical, political, and social challenges. For example, previous research has shown that the last 10%–20% of renewable deployment will result in two times the cost and three times the curtailment (Frew et al. 2016; Jenkins and Thernstrom 2017). Within a social context, a fundamental shift in how consumers view, use, and value energy services will be necessary, and the feasibility of this transition is unclear. Achieving this last 10% will require a holistic approach, leveraging other aspects of the energy sector to help with the transition to clean energy. Transportation and heating/cooling are logical places for collaboration and coordination. Electrification of mass transit and personal transportation represent an opportunity to increase load that could help accommodate the generation profiles from renewables while reducing economy-wide carbon emissions. Industrial, commercial, and residential heating/cooling offer significant opportunities for the substitution of electricity for fossil fuels and the beneficial use of otherwise curtailed energy. This suggests exciting possibilities for a highly clean and economic economy for both developed and developing countries. Therefore, research is needed on the interplay between the timing for achieving the dual goals of broader electrification of other energy sectors (i.e, Energy Systems Integration) and 100% renewable electricity.

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*This document was produced by the ESIG System Planning Working Group, which is chaired by NREL's Aaron Bloom. Topics examined by this working group include generation and transmission planning studies; both technical and economic aspects of integration studies of electrical, thermal, gas and transportation systems; capacity adequacy and flexibility; and alternative sources of system flexibility services. For more information, contact Aaron Bloom at aaron.bloom@nrel.gov or (303) 384-7032.*

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