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CLEAN GRID VISION:

A U.S. PERSPECTIVE

Executive Summary

CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

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CLEAN GRID VISION:
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Ella Zhou, Gregory Brinkman, Vahan Gevorgian,
Elaine Hale, David Hurlbut, Jeffrey Logan, Barry Mather,
Yingchen Zhang – National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
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Energy use is one of the main drivers of anthropogenic greenhouse gas emissions [1]. Transitioning the electric power system to high levels of renewable energy generation and substituting fossil fuel use in transportation, buildings, and industry with low- or zero-emission electricity are essential for decarbonizing the economy [2]. This transition entails fundamental changes with respect to technology, policy, market, and institutional dynamics, and must deliver as much economic efficiency, sustainability, reliability, resilience, and security as possible.

Integral to this transition is the rapid growth of renewable energy over the past decade. Spurred by initial policy support, economies of scale, technology improvements, and market competition, the price of wind and solar photovoltaic (PV) systems has seen dramatic reductions in many countries [3]. Global investment in renewable energy reached $282.2 billion in 2019, and U.S. investment reached $55.5 billion [4]. Consequently, the deployment of renewable energy—wind and solar PV in particular—has outpaced any other generation source in the United States and many other countries for years [5]. Generation from wind and solar PV increased from almost zero to 8% and 3%, respectively, in the United States over the past decade [6].

The United States has set a goal to reach 100% carbon-free electricity by 2035. Over 100 countries have set net-zero emission or carbon-neutral goals at different target years [7], as have many utilities and corporations [8], [9]. Renewable electricity generation is a fundamental part of the implementation approaches for many countries, and some regions are already experiencing periods of high variable renewable energy (VRE) penetration [10]–[12].

Future clean grids—in particular, power systems with high penetration of variable renewable energy—present multiple interlinked challenges and opportunities. How should key stakeholders analyze, plan, and operate the future power system while serving demand and maintaining system reliability and stability? How to bring a variety of resource types with considerably different characteristics into the system and provide reliable delivery at least cost? What types of regulation, market rules, or institutions need to be developed to enable nimble innovation in technology and business models that can respond quickly to system needs, market changes, or customer behavior? We seek to answer questions like these in the body of this report.

Clean Grid Vision: A U.S. Perspective aims to present a range of possible pathways for future grid development and call attention to some common trends. It focuses on the lessons learned through National Renewable Energy Laboratory's (NREL's) studies of the U.S. power sector that have measured the impacts of high-penetration VRE and have tested strategies for enhancing grid flexibility and reliability. As such, this report is limited in its scope and does not attempt to review or summarize all grid integration literature. While it refers to relevant external literature to provide context when needed, this report is primarily a summary of the NREL's research in the past 5 years on five key topics: grid planning and operation, grid reliability at the distribution level, grid reliability at the transmission level, demand-side evolution, and power markets—each corresponds to a chapter in this report. The main insights of the report are presented below.

1. What Are Possible Visions for the Future Grid?

The power sector may evolve in many different ways, but VRE is expected to grow in all scenarios. The steady future growth of wind and solar is observed in all major studies (**Figure ES- 1**), including NREL's Standard Scenarios 2019 [13], International Energy Agency's (IEA's) World Energy Outlook 2019 [14], U.S. Energy Information Administration's (EIA's) Annual Energy Outlook 2019 [15], and Bloomberg New Energy Finance's New Energy Outlook 2019 [16]. In the Standard Scenarios 2019, total wind and solar PV penetration reaches 53% nationally by 2050 under Mid-case assumptions, and ranges from to 17% to 74% under different fuel and technology cost assumptions [13].

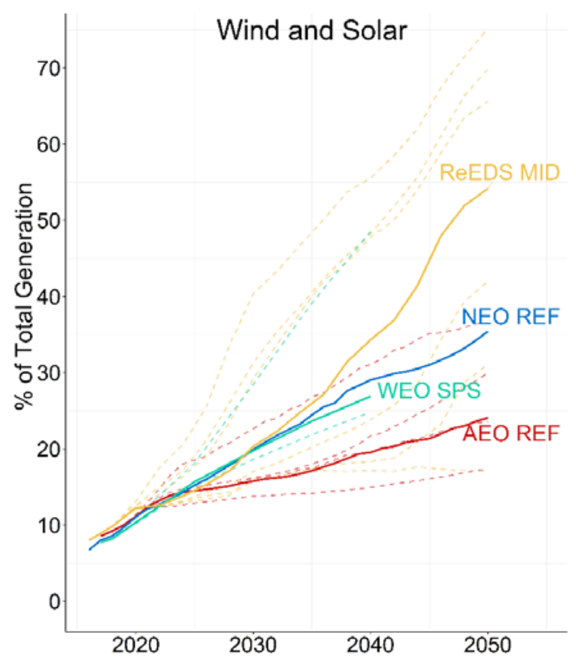

Figure ES- 1. Wind and solar generation as a percentage of total power generation in the long-term scenarios

ReEDS MID= ReEDS Standard Scenario 2019 Mid Case, NEO REF= New Energy Outlook 2019 Reference, WEO SPS=World Energy Outlook 2019 Stated Policy Scenario, AEO REF=Annual Energy Outlook 2019 Reference.

Many technologies can be part of the capacity mix in the future power system. On the supply side, multiple NREL studies showed that natural gas, wind, solar, hydropower, pumped storage, geothermal, battery storage, and many other technologies have high potential for growth in the future. Development of these technologies will depend on future fuel costs, technology costs, and policy and market conditions. For example, addressing the technical and nontechnical barriers to geothermal development could expand geothermal capacity to nearly 61 GW by 2050, which would account for 8.5% of total generation [17]. And with low battery costs, the total power capacity of deployed battery storage could reach 302 GW by 2050 [13]. The demand side can also provide capacity to the power system. In addition, energy efficiency, demand-side flexibility, and electrification have the potential to reshape future load and change system ramp needs.

The demand side may see transformative changes in the future. Demand-side evolution is driven by three main interrelated factors: energy efficiency, demand-side flexibility, and electrification. Successful energy efficiency can lower overall energy demand and peak load while reducing the need for grid infrastructure. Demand-side flexibility refers mainly to demands that can be shed during peak times or be shifted to a different time of consumption via scheduling or price responsiveness. Such flexibility can come from a variety of sources in the building, industrial, and transportation sectors, and it has the potential to defer generation, transmission and/or storage investment, reduce VRE curtailment, reduce system ramping needs, and contribute to system reliability. Electrification could lead to U.S. electricity demand in 2050 that is 80% higher than in 2018, reaching nearly electrification 7,000 TWh and a doubling of the generation capacity in the high electrification scenario modeled in [18] (**Figure ES- 2**).

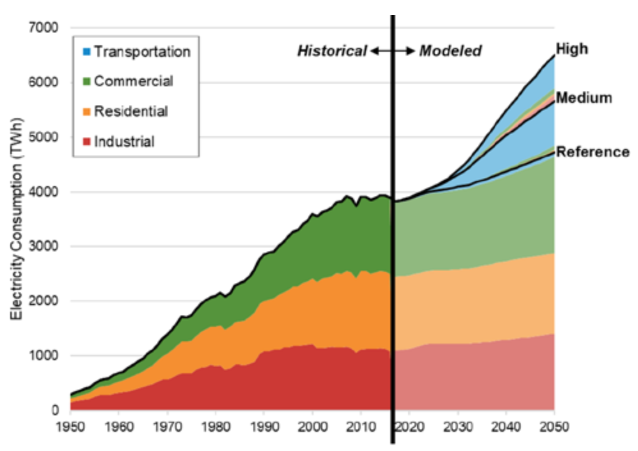

Figure ES- 2. Potential electricity demand changes in the U.S. under different electrification scenarios *Source: [18]*

2. How Can the Future Grid Be Operated Effectively?

Envisioned future power systems would have characteristics different from historical paradigms. While NREL's analysis showed that the bulk power system can be operated reliably and cost-effectively at very high levels of VRE penetration (88% in the Western Interconnection [19] and 73% in the Eastern Interconnection [20]), new operational challenges must be addressed:

1. Impacts on balancing at different timescales may lead to increase in operating reserves, ramping requirements, thermal plant cycling, and other issues [20], [21].
2. Reliability issues such as frequency response, regulation, active power control, reactive power and voltage control, disturbance ride-through tolerance, and others must be carefully evaluated [24].

Variable generation can address many of these reliability challenges by providing different types of essential grid services, including, but not limited to, load following, frequency regulation, reactive power, and voltage support. However, adequate market mechanisms and regulatory measures are needed to unleash and incentivize such participation. At the distribution level, integrating increasing distributed energy resources (DERs) could bring voltage range violations, protection coordination challenges, and power quality issues such as harmonics, voltage sags and swells, and flicker. As a result, new analytical tools and technologies have been developed to address these issues.

New analytical tools and methods have enabled us to gain a fuller picture of the impacts of high-penetration VRE. NREL has developed or used various models and tools for investigating different aspects of VRE impacts. These include planning tools such as the Regional Energy Deployment System (ReEDS) and RPM (Resource Planning Model); distributed resource adoption models such as dGen (distributed generation market demand model); production cost models such as PLEXOS; integrated transmission and distribution tools such as IGMS (the Integrated Grid Modeling System) that connects FESTIV (Flexible Energy Scheduling Tool for Integrating Variable Generation), a unit commitment, economic dispatch, and automatic generation control model, MATPOWER, a transmission power flow model, and GRIDLab-D, a distribution power flow model for integrated transmission and distribution simulation. Using these tools, NREL has conducted various transmission-level grid integration studies such as the E*astern Renewable Generation Integration Study* [25] and *Operational Analysis of the Western Interconnection at Very High Renewable Penetrations* [19]. NREL has also developed analytical methods and performed analyses of the impacts on the distribution system from DERs [26], [27]. These new methods and analytics results addressed the concerns over the current DER screening process currently used by industry and have provided comprehensive technology solutions (protection, power quality, forecasting, under-frequency load shedding) for planners and operators to adopt higher levels of DERs while maintaining and improving the reliability and stability of distribution and transmission grids.

Power system operators can utilize a wide variety of resources to address system flexibility and reliability challenges. While the challenges in the future power system mentioned previously may seem daunting, there are many resources and approaches that can address them. At the transmission level, resources that can balance the load, increase power system flexibility, and/or enhance system reliability include:

- Balancing area coordination
- Thermal power plant flexibility
- Battery storage to provide energy shifting, system ancillary services, grid frequency control, reactive power and voltage support, black start, etc.
- Transmission technologies such as flexible AC transmission to increase power transfer capability, stability, and controllability of the networks [28]
- VRE such as wind and solar PV to provide active power control, inertial response, droop-like response, secondary frequency response, fault ride-through, etc. [24], [29], [30]
- Demand-side flexibility, including shiftable and interruptible building, industrial, and electric vehicle demands [31], [32]
- Market solutions such as expanding market footprint, shortening market intervals, reducing energy trading barriers, and above all, building markets according to time-tested market principles (see Chapter 5).

3. What Are Approaches for Facilitating Power Sector Transformation?

Cost-optimized markets are replacing administrative reliability management and unit dispatch in many parts of the world. This trend appears to be correlated with the pace at which new technologies are entering the market. Wind, solar, and storage are expanding. Coal plants are retiring—in many cases, without being replaced by new ones. Some jurisdictions have adopted special financial tools to reduce the economic burden of stranded costs when they arise. Policy sometimes plays a role in this transition, but power sector economics are often the more powerful driver. Improvements in grid operations and market design have opened up a new source of value on the bulk power system: resource flexibility. These changing market dynamics are challenging old notions of resource adequacy (that is, how to sustain future investment in the most cost-effective technologies to meet peak demand). While the economic trends seen in many organized wholesale power markets have the potential to reduce costs and emissions, they can also lead to other social impacts such as displaced labor. Many areas are looking into workforce strategies to cushion the transition.

Multistakeholder participation helps build confidence and enhance outcomes. Through working with various countries and U.S. state and local governments, NREL finds that it is best practice to include not just engineers, but also policymakers, market operators, industry participants, and consumer advocates in conducting grid integration studies; all have key roles in planning for and operating the future power system. Because power sector decisions have long-lasting socio-economic and environmental impacts, governments and regulators have an important role in creating a level playing field for all technologies, safeguarding the integrity of the markets, and ensuring that reliability and other standards are met. Emerging technologies and solutions have given rise to new business models and market dynamics. In addition, with the increase of DERs such as rooftop solar PV, behind-the-meter storage, and electric vehicles, power sector development is becoming less centralized; therefore, end-use consumers have also evolved from passive consumers to potentially active participants. It is important to include stakeholders representing different interests when studying future clean grids.

Many possible paths exist for the power system transition, with various investment and socio-economic policy options. **A successful transition would not only contribute to mitigating climate change, but would also spawn innovation, create employment, and energize economic growth.** This report indicates that many aspects of the power system may need to evolve substantially to achieve a high-renewable clean grid future. Significant work is still needed to explore various technological, market, and policy aspects of the transition, such as the following:

- Integrated planning of power system with climate and water impacts, and social equity considerations
- Better understanding and demonstration of a wide range of low-carbon technologies, including renewable integration in the industry sector, carbon-capture and storage, advanced renewable fuels for shipping and aviation, advanced batteries and fuel cells, etc.
- Addressing barriers to expanding and modernizing the transmission and distribution grids.

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Chapter 1. Clean Grid Scenarios

Chapter 2. Distribution Issues and Tools

Chapter 3. Transmission Grid-Supporting Technologies

Chapter 4. Demand-Side Development

Chapter 5. Global Power Market Trends

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