Greening the Grid

Integrating Variable Renewable Energy Into the Grid: Key Issues

Introduction

To foster sustainable, low-emission development, many countries are establishing ambitious renewable energy targets for their electricity supply. Meeting these targets necessitates changes in power system planning and operations, due to the variable nature of solar and wind power as well as escalating electricity demand. Grid integration is the practice of developing efficient ways to deliver variable renewable energy (VRE), primarily wind and solar, to the grid. Good integration methods maximize the cost-effectiveness of incorporating VRE while maintaining or increasing system stability and reliability.

To inform decarbonization strategies, policymakers, regulators, and system operators consider a variety of costs and opportunities associated with VRE integration, which can be organized into five topics:

- New renewable energy generation and transmission
- Power system reliability
- Transmission and distribution coordination
- Cross-sectoral decarbonization opportunities
- Energy equity and justice.

Photo by Dennis Schroeder, NREL 58020

Investing in New Renewable Energy Generation and Transmission

Power system planners can secure and sustain investment in new VRE generation by aligning targets and incentives with grid integration considerations. Long-term aspirational renewable energy targets establish a vision that can drive policy and system operations innovation in support of clean energy. Also critical are "grid-aware" incentives (e.g., rewarding wind and solar generators that incorporate technologies contributing to grid stability), which both motivate investment in renewable energy and mitigate negative impacts of integrating these resources to the grid.

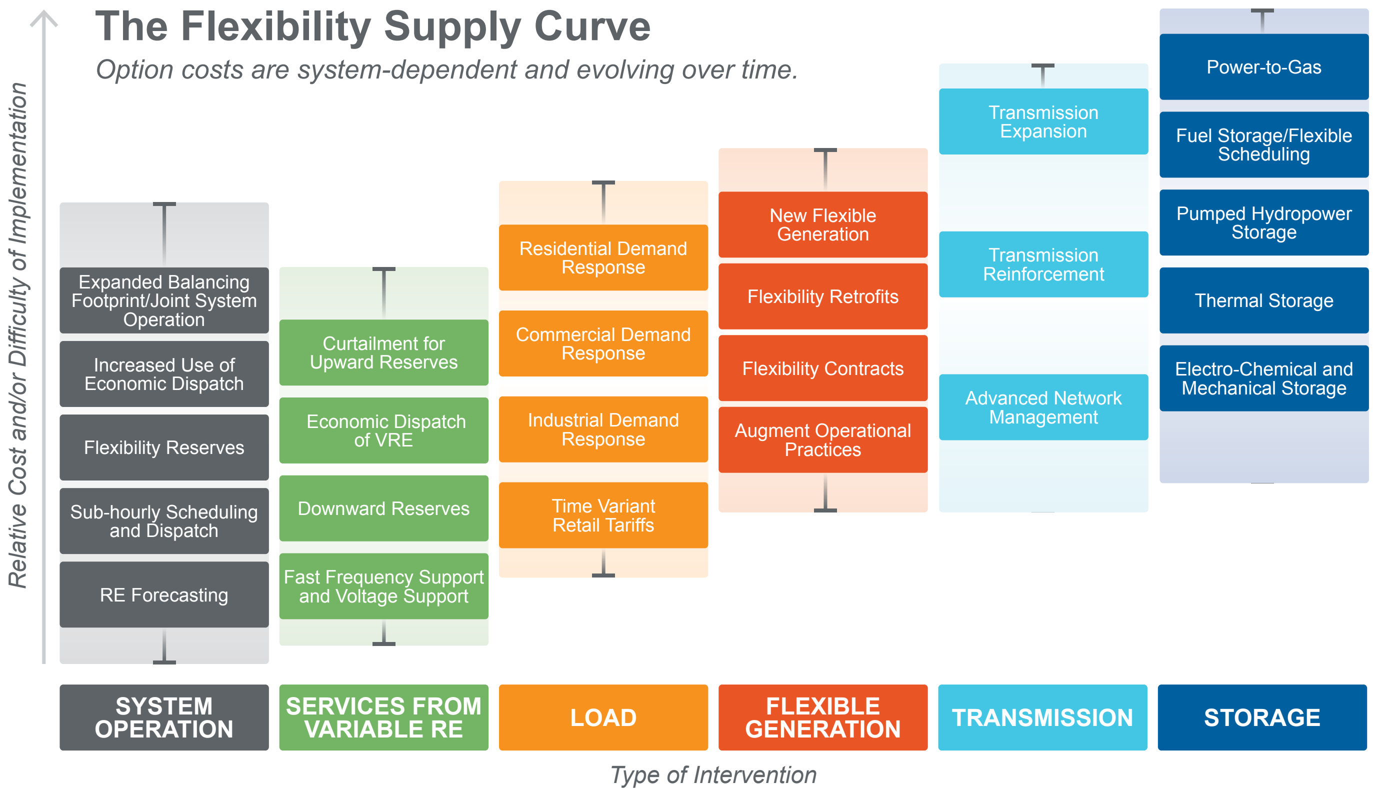
Scaling up VRE generation requires grid expansion and upgrades so that power systems can access high-quality solar and wind resources, which are often remote from existing transmission networks and demand centers. A well-crafted combination of policies, rules, and procedures encourages investment in large-scale transmission expansion. These measures not only improve the utilization of VRE, but also potentially defer the need for network refurbishment.

Related factsheets:

"Scaling Up Renewable Energy Generation: Aligning Targets and Incentives with Grid Integration Considerations": https://www.nrel.gov/docs/fy15osti/63034.pdf

Ensuring Power System Reliability

Power system reliability can be characterized by resource adequacy and operating reliability. Resource adequacy, or the requirement that power systems always have sufficient resources to meet demand, can be broken down into long-term capacity-planning and real-time flexibility strategies. Capacity planning, system flexibility, and operating reliability in the context of power systems with high penetrations of VRE are discussed below.



- **Capacity planning:** Scaling up VRE generation requires changes to how power systems are planned and operated to maintain reliability. As systems integrate more VRE, system planners often rely on existing fossil-based generation to serve net load, or the load remaining after accounting for VRE generation. To fully decarbonize electricity grids, energy storage and low-carbon dispatchable technologies are needed to replace fossil-based capacity.
- **System flexibility:** Long-term planning can ensure energy systems meet annual load requirements, while real-time strategies enhance system flexibility to address the short-term variability of wind and solar output. Low-cost methods like detailed forecasting, subhourly scheduling, and flexibility reserves boost flexibility without significant investments in new infrastructure. Demand response, including time-of-use rates, shifts consumer usage to non-peak times, increasing system adaptability. The power electronic devices, or inverters, that connect VRE resources to the grid may also offer greater flexibility than traditional mechanical generators. For vertically integrated utilities, contracts and policies can encourage flexibility adoption, whereas incentives and market designs like price-responsive demand and ancillary services motivate flexibility in restructured markets.
- **Operating reliability** describes the ability of power systems to withstand unexpected, sudden disturbances without load interruptions or equipment damage. Advanced inverter controls, including grid-forming capabilities and other technologies such as synchronous condensers, are being developed to effectively respond to these disturbances. More widespread analyses of power system stability are needed to inform the least-cost measures that maintain inverter-based power system reliability.

As power systems transition to 100% renewable generation, the strategies deployed to maintain reliability will vary according to the prevalence of inverter-based resources, the configuration of transmission and distribution networks, and demand profiles. Therefore, engineers can consider the unique characteristics of each power system to design reliable, sustainable, and affordable electricity grids.

Related factsheets

"NERC Reliability Terminology": https://www.nerc.com/AboutNERC/Documents/Terms%20AUG13.pdf

"Power System Planning: Advancements in Capacity Expansion Modeling": https://www.nrel.gov/docs/fy21osti/80192.pdf

"Using Wind and Solar to Reliability Meet Electricity Demand": https://www.nrel.gov/docs/fy15osti/63038.pdf

"Methods for Procuring Power System Flexibility": https://www.nrel.gov/docs/fy15osti/63040.pdf.

Photo by Werner Slocum, NREL 74116

Transmission-Distribution Coordination

Integrating distributed VRE resources is changing the interactions between transmission and distribution networks, necessitating greater cooperation between the two to support higher contributions of renewables. Traditionally, transmission networks enable power flows from large power plants to reach consumers on distribution networks. Significant localized growth in distributed photovoltaics (PV) can raise concerns such as voltage management and bi-directional flows of electricity in distribution networks. However, various studies have shown that positive impacts (e.g., reduced line losses and avoided generation costs) can also result from distributed PV. Different frameworks are being developed to coordinate capacity planning, congestion, connection requirements, and protection methods between transmission and distribution networks to realize these benefits and reduce the need for grid reinforcement. For example, integrated transmission-distribution flexibility markets enable distributed generation to participate in markets and provide ancillary services, helping reduce the strain on transmission networks. System planners can also undertake transmission planning and interconnection studies to identify specific areas prone to congestion and evaluate the cost-effectiveness of mitigation strategies including curtailment and the integration of storage technologies relative to the costs of expanding the transmission network.

Transmission and distribution system operators can also consider the electrification of heating, transportation, and other end uses that increase the demand for electricity and strain aging infrastructure. They can cooperate to increase their generation and power transfer capacities and optimize distribution to serve these loads. With sufficient updates to distribution network infrastructure, many of these new loads can be configured to support system flexibility, benefiting transmission and distribution systems alike.

Related factsheets

"Grid-Integrated Distributed Solar: Addressing Challenges for Operations and Planning": https://www.nrel.gov/docs/fy16osti/63042.pdf

"Cooperation Between Transmission and Distribution System Operators": https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_TSO-DSO_co-operation_2020.pdf.

"Transmission Planning Studies for the Renewable Energy Zone (REZ) Process": https://www.greeningthegrid.org/Renewable-Energy-Zones-Toolkit/quick-reads/copy_of_technical-potential-assessment-for-the-renewable-energy-zone-rez-process-a-gis-based-approach.

Cross-Sectoral Decarbonization Opportunities

Many opportunities exist for coordinating economy-wide decarbonization efforts and reducing costs as electricity grids transition to renewables. Electrifying the transportation sector could support VRE grids with upgrades to electric vehicle charging infrastructure that, in the future, may enable electric vehicle batteries to provide ancillary services. Hydrogen electrolyzers under development for grid-scale applications could leverage demand-response incentives to produce low-carbon hydrogen when electricity prices are low. This low-carbon hydrogen

Related resources:

"Cross-Sector Technologies": https://www.energy.gov/eere/iedo/cross-sector-technologies

"Declining System Inertia and Dynamic Reserve Requirements" course: https://globalpst.org/what-we-do/workforce-development/university-level-teaching-materials/#topics

Grid Integration of Electric Vehicles: https://iea.blob.core.windows.net/assets/21fe1dcb-c7ca-4e32-91d4-928715c9d14b/GridIntegrationofElectricVehicles.pdf

"Hydrogen 101": https://www.nrel.gov/docs/fy22osti/82554.pdf.

Photo by Dennis Schroeder, NREL 40481

could in turn be used to fuel long-haul hydrogen trucks, produce hydrogen derivatives to replace higher-carbon fuels in industrial processes, or provide grid-scale energy storage to offset the variability of renewable electricity generation. Low-carbon fuels, including biogas and hydrogen, could increasingly be used to generate electricity directly to provide clean dispatchable resources for power grids or to power industrial cogeneration systems.

Energy Equity and Justice

Transitioning to clean and decarbonized energy can present new opportunities and challenges to advance equity and justice within the design of future energy systems. Specific dimensions of equity and justice that could be relevant for power system planning and VRE integration might include (but are not limited to): energy access and affordability; job opportunities and workforce transitions; climate vulnerability and resilience; environmental quality and public health; infrastructure siting and land use change; and other intersecting or related social, economic, and/or environmental challenges and goals.

Actions to incorporate equity and justice in a transition to clean energy will look different across countries, reflective of the unique needs, priorities, and available resources within the relevant context, but might include:

- Engaging diverse stakeholder and community groups in the VRE planning and decision-making process
- Developing a context-specific understanding of the energy-related challenges and burdens faced by different consumer groups (including underserved and potentially under-invested communities)
- Using stakeholder and community input to identify specific objectives and metrics to achieve energy equity and justice goals
- Evaluating and communicating strategies for equitable sharing of the costs and benefits associated with a clean energy transition.

Related resources:

"Clean Energy Co-Benefits: Air Quality, Health, and Just Energy Transitions": https://www.nrel.gov/docs/fy23osti/85554.pdf

"LA100: The Los Angeles 100% Renewable Energy Study and Equity Strategies": https://maps.nrel.gov/la100/la100-study/report

"Strategies and Good Practices To Support Robust Stakeholder Engagement in Multi-Sector Energy Transition Planning": https://www.nrel.gov/docs/fy24osti/88389.pdf

"JEDI: Jobs & Economic Development Impact Models": https://www.nrel.gov/analysis/jedi/international.html.

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For more information about collaborating with the USAID-NREL Partnership or if you have any questions, please contact us at **USAID.NREL@nrel.gov**.

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