NATIONAL RENEWABLE ENERGY LABORATORY

ANALYSIS INSIGHTS | APRIL 2015

# RENEWABLE ENERGY ON THE GRID

## Redefining What's Possible

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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# ELECTRIC POWER SYSTEMS ARE PROFOUNDLY CHANGING

Environmental regulations, state-level portfolio standards, new methods for accessing natural gas reserves and aging power plants are opening opportunities for new electricity generation from renewable resources and natural gas. Advances in efficiency and smart grid technologies also have the potential to change historical demand curves. New renewable generation technology costs, including solar and wind, continue to fall, and installations are increasing. NREL works within these currents of change, and helps shape them to enhance our energy and environmental security. We help utilities, policymakers, investors, regulators, and industrial leaders around the world understand and navigate these currents. Our analysis, data sets, and tools illuminate choices and future impacts of choices on power system reliability, greenhouse gas emissions, economics, and energy security. Our work is redefining what's possible for renewable energy on the grid and supporting the transition to power systems that are cleaner and more reliable than ever before.

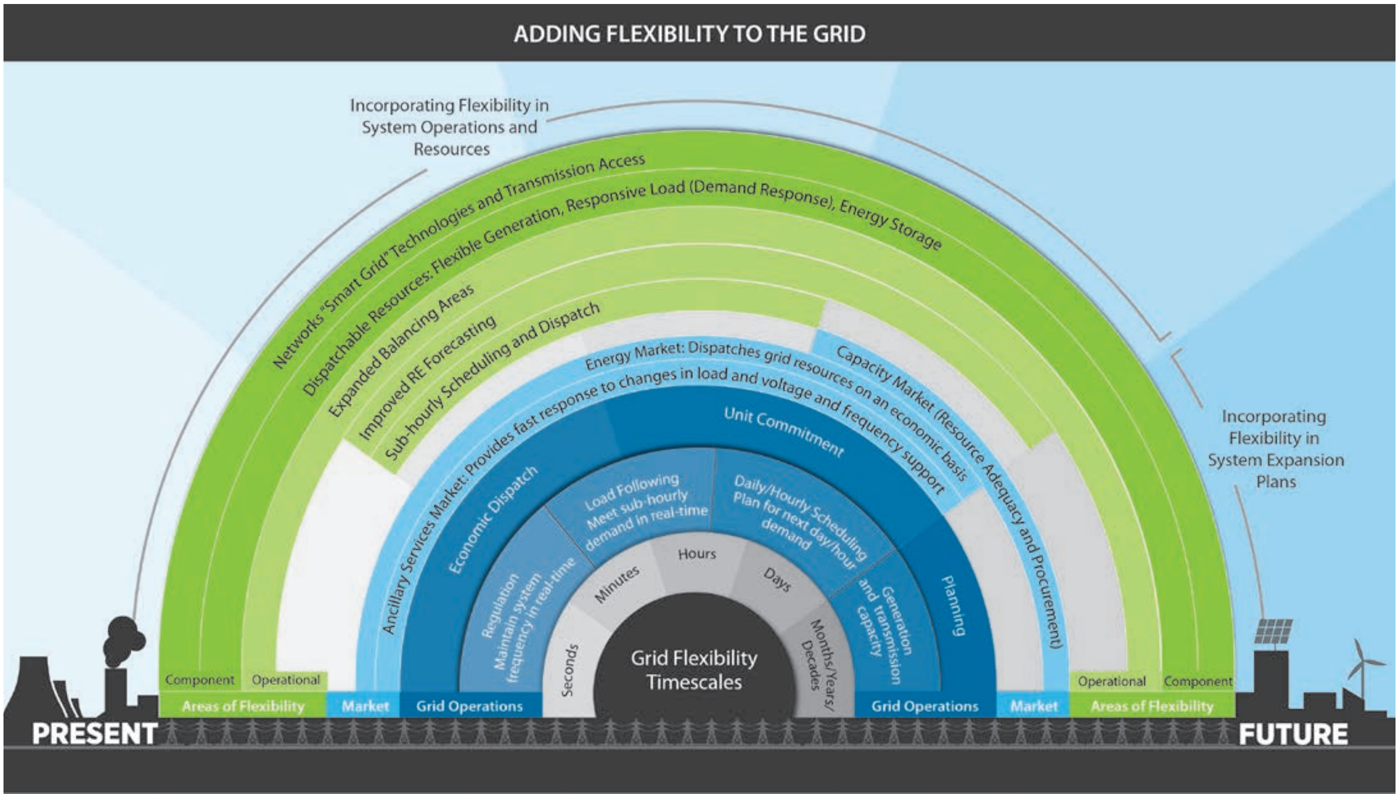


**Figure 1.** Flexibility can help accommodate higher levels of variable renewable generation on the grid. Sources of additional system flexibility can be organized around the three main domains of power markets—capacity, energy, and ancillary services—that support balancing the electricity grid at multiple timescales—through regulation, load-following, daily/hourly scheduling, and planning.

## Leveraging Our Expertise to Inform International RE Roadmaps

Mexico is expanding renewable energy as a key strategy to reduce greenhouse gas emissions from its electricity sector. One of the key challenges to meeting the renewable goal—35% renewable energy by 2024—is integrating variable wind and solar resources into the existing grid. Through the U.S. government's Enhancing Capacity for Low Emission Development Strategies (EC-LEDS) program, NREL is collaborating with Mexico's ministry of energy, power system operators, research institutions, and policymakers to set and meet technically achievable annual renewable energy targets to support Mexico's renewable energy goal. NREL and its Mexico partners developed the *Renewable Electricity Grid Integration Road Map for Mexico*, which outlines technical priorities and recommendations for the integration of renewable energy technologies at large scale, and the steps energy institutions need to take to determine how the electricity infrastructure and systems must change to accommodate high levels of renewables. The roadmap focuses on analysis methodologies—including grid expansion modeling, resource characterization, forecasting, and grid operational practices—to evaluate the infrastructure and operational impacts of increasing levels of renewables. The roadmap gives policymakers a basis for assessing potential challenges, solutions, and economic impacts of increasing the level of variable RE penetration on the grid and gives system operators confidence that reliability concerns can be met.

### COMPUTING CENTER ENABLES FASTER, MORE DETAILED ANALYSIS

Thanks to the High Performance Computing Center in the Energy Systems Integration Facility, DOE's newest user facility at NREL, NREL is modeling the impacts of increased penetration of variable generation on grid system operations, emissions, and reliability in ways that are faster and more detailed than previously possible. The complex models supporting NREL's Eastern Renewable Generation Integration Study now need just 3 days to run, down from 67. Learn more at www.nrel.gov/esi.

## Regional and National Grid Integration Studies Consistently Show Higher Levels of Renewables are Possible

Through groundbreaking modeling and analysis of the operational, economic, and environmental impacts of increasing renewables on the nation's electricity grid, NREL has shown that a more flexible electric grid can achieve much higher levels of renewable penetration than we have today. Operational changes and improved transmission access can help increase overall flexibility of the power system. Flexibility helps balance the increased variability and uncertainty associated with wind and solar generation. Some physical solutions to accommodate increase power system flexibility are already underway. The institutional, legislative, and market options to increase flexibility are relatively more complex, but are essential to allow power systems to develop and integrate technology advances, new operating procedures, evolved business models, and new market rules.

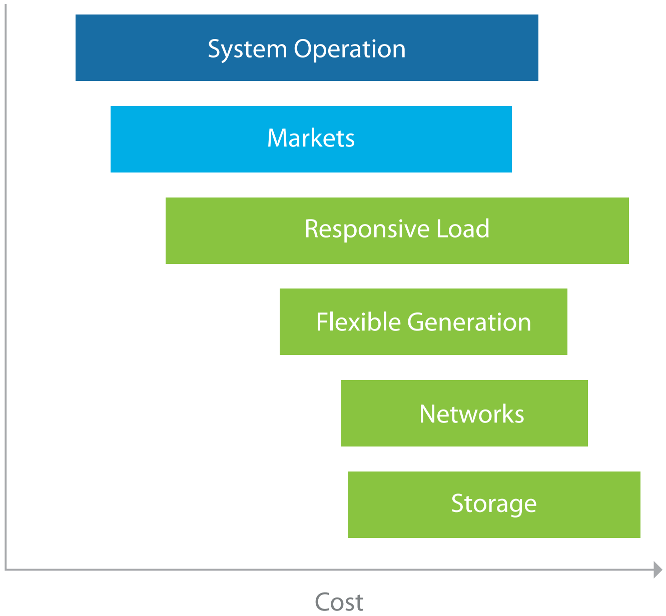


**Figure 2.** Relative Economics of Integration Options. Today, storage is a relatively expensive integration option. Actual option costs are system-dependent and evolving over time.

Adapted from: *Flexibility in 21st Century Power Systems*
http://www.nrel.gov/docs/fy14osti/61721.pdf

# Operational Changes are Enhancing System Flexibility

## Sub-hourly Scheduling and Dispatch

Grid integration studies show that sub-hourly scheduling and dispatch of generators (5- or 15-minute intervals) improves system efficiency, reduces the amount of reserves required to balance the system, and enables systems to integrate higher penetrations of variable renewable energy generation. Faster dispatch can enable the system to access reserves from existing units at little or no extra cost. It can also reduce the need for regulation reserves, which are the most expensive types of reserves, because there are fewer minute-to-minute deviations between load and generation when the system is re-dispatched frequently. For example, the *Western Wind and Solar Integration Study*, indicates that sub-hourly scheduling is important for minimizing regulation requirements on the system. Scheduling resources every 5 or 15 minutes, rather than every hour, reduces the need to ramp units that provide load following. The study also found that wind and solar variability has a lesser impact on regulation requirements than hourly scheduling of generating units.

## Expanded Balancing Footprint

Our studies have shown that increasing cooperation between balancing areas can reduce fluctuations in supply and demand and make it easier to maintain system balance. In addition, expanded balancing footprints can enhance the benefits of faster dispatch, reducing required regulation reserves and associated costs. The benefits of sub-hourly scheduling between balancing areas are greater with higher levels of variable renewable generation. Particularly where transmission constraints exist, faster scheduling across areas can allow variable generation to be more efficiently integrated through faster and coordinated dispatch with a neighboring market.

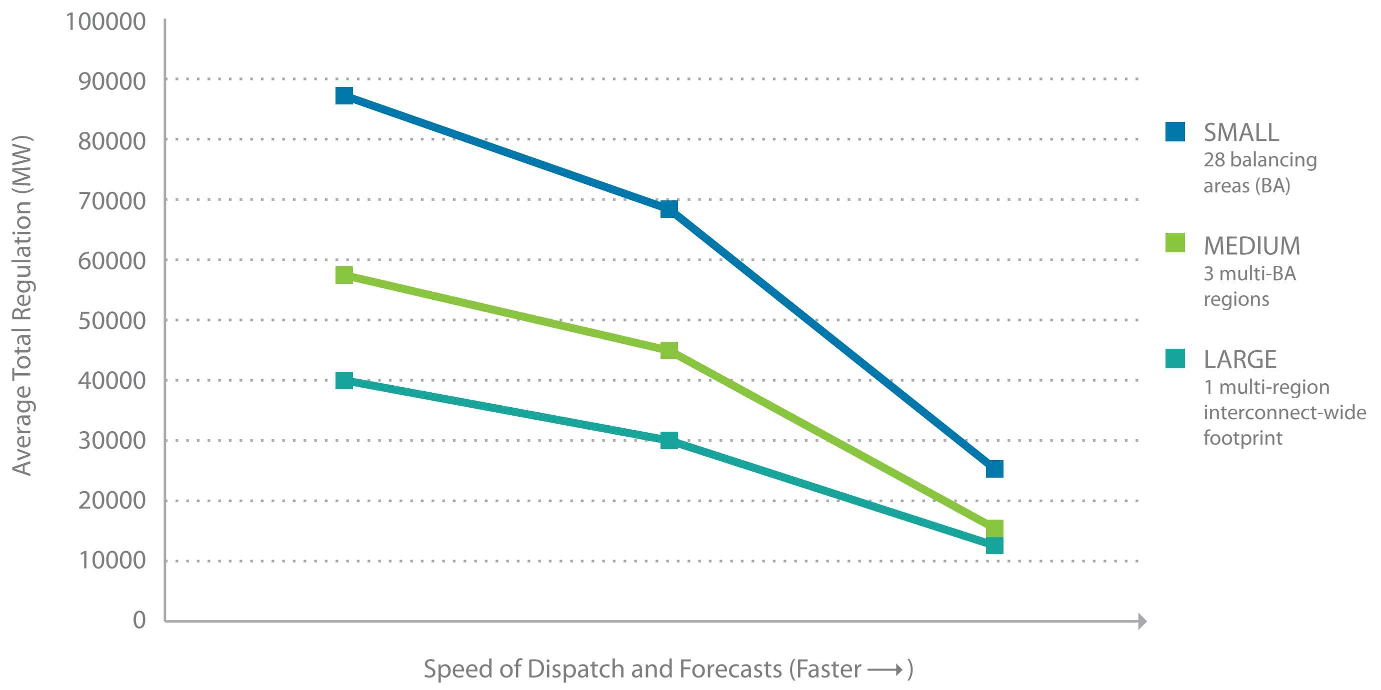


**Figure 3.** NREL has found that increased dispatch frequency and shorter forecast horizons reduce the amount of required regulation reserves. Larger balancing areas enhance these benefits, further reducing regulation reserve requirements.

For source data and analysis, see *Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection* http://www.nrel.gov/docs/fy12osti/52330.pdf

SHARING DATA, ADVANCING SCIENCE

Electric sector stakeholders use NREL's high-resolution wind and solar datasets to model and plan for operating power systems with more variable resources.

**Learn More:** http://maps.nrel.gov/wind_prospector http://www.nrel.gov/electricity/transmission/solar_integration_methodology.html

### Advanced Variable Generation Forecasting

Improved forecasting is considered to be a key means of integrating wind and solar power efficiently and reliably. VG forecasts are more accurate the closer they are to real time, and many utilities have adopted practices that allow forecasts to be updated on a 5-minute basis. VG forecast costs are dropping and system operators are becoming more confident in the forecasts, according to a 2014 survey of system operators in the Western Interconnection. Other survey highlights include:

- **Many system operators now regard VG forecasting as a cost effective mechanism for maintaining electric reliability and scheduling resources efficiently. Several said the system savings are so great and the cost minimal enough that formal cost-benefit analysis is not needed.**
- **Nearly all system operators surveyed—regardless of size, proportion of renewables, or average monthly load—use their wind forecasts for day-ahead unit commitment. Intra-day unit commitment and reserves planning are the next most common uses.**
- **Wind forecasting accuracy continues to improve thanks to advanced forecasting techniques and models, seasoned vendors, and growing portfolio size. Wind forecast errors typically range from 3% to 6% of rated capacity one hour ahead and 6% to 8% a day ahead on a regional basis. For comparison, load forecast errors typically range from 1% to 3% day-ahead.[1]**
- **Solar forecasting is still in its infancy, but several system operators have recently begun working on in-house solar forecasts and at least one company is beginning to track solar forecast accuracy.**

## Increased Coal Plant Flexibility Can Improve Renewables Integration

### Flexible Generation

Increasing wind and solar penetration also increases opportunity for savings associated with improved coal flexibility. Using a commercial production cost model, NREL estimated the impact of generator flexibility on the integration of wind and solar generators, at penetrations between 15% and 60%. Increased flexibility was simulated by reducing the minimum generation level of the coal fleet from 60% to 40% of nameplate capacity. Minimizing generation levels can allow plants to stay online during periods of low energy prices, such as at night, and minimize the need for and impacts of cycling. In the more flexible system, fuel costs and $CO_2$ emissions are lower, as are variable operations and maintenance costs.

Coal plant flexibility can be increased through retrofits and operational practices that enable lower turndowns, faster starts and stops, and faster ramping between load set-points. One North American coal generating station accommodates significant cycling thanks to key hardware modifications and operational changes—e.g. monitoring and managing temperature ramp rates, implementing inspection programs for affected equipment, and continual operator training. These changes have minimized potential damage and minimized the cycling-related cost of maintenance at the plant.

System-wide flexibility can be enhanced by retrofitting just a portion of conventional generators within a power system. NREL investigated the costs and benefits of retrofitting ~25% of coal and natural gas plant fleet capacity for improved operational flexibility. The study showed that retrofits that improve the turndown level of gas-fueled and coal-fueled power plants have a net-benefit to the system, although there may or may not be a benefit at plant level. Additional analysis could help determine the system-level costs and benefits of faster ramp rates and faster and less expensive starts.

1. [Source: http://www.nrel.gov/docs/fy13osti/60451.pdf ]

## Flexible Load – Demand Response Resources

Demand response (DR) is a load management practice of deliberately reducing or adding load to balance the system during periods of peak demand or high market prices. DR resources represent a potentially large and relatively untapped resource for supplying flexibility to the grid systems. NREL is working with other national laboratories to estimate the economic value of DR resources—including water heating, space heating and cooling, and water and wastewater pumping—for the Western United States. The value is calculated in terms of reduced system production costs and potential revenue streams. Because some DR resources are more flexible or better correlated with system requirements, revenue from energy or grid services provided can vary significantly.

## Flexible Storage

Electricity storage technologies—such as pumped hydro, batteries, flywheels, and compressed air—have had limited deployment in the U.S. power grid, but could potentially allow greater use of variable renewables by matching energy dispatch to periods of high demand, providing flexible load during periods of high RE output, and providing a variety of high-value ancillary services. One of the challenges faced by storage developers is quantifying the value of storage, particularly benefits that may not be fully captured within U.S. electricity markets.

The operational value of storage is expected to increase with increasing penetration of variable wind and solar generation. For storage applications involving time-shifting of generation (i.e., load-leveling), variable generation tends to suppress off-peak prices more than on-peak prices, increasing price differentials for energy storage. Additional operating reserves required with higher levels of variable generation, also increase the potential value of storage when providing these reserves. Significant charging from renewables, and the associated net reduction in carbon emissions, does not occur until VG penetration is in the range of 40%-50%. Other sources of storage value, such as the ability to replace or defer generation, transmission, and distribution investments may also be impacted by the deployment of VG resources.

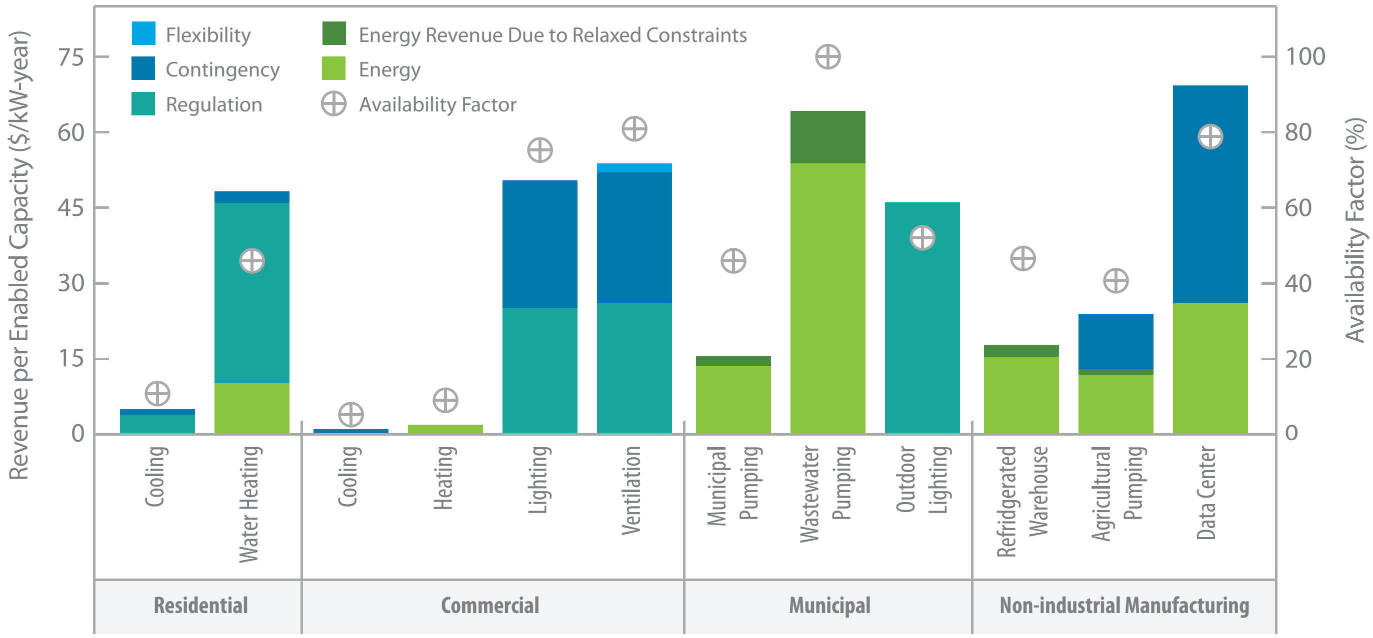


**Figure 4.** Value of Demand Response Resources for Energy and Grid Services. This chart shows the average annual revenue (left axis) from the day-ahead market per annual availability factor (right axis) for each type of demand response resource. Across all DR resources evaluated, 80% of revenue came from grid services, primarily from the regulation reserve market. Only 20% of the revenue came from the energy market.

Source: DR Resources for Energy and Ancillary Services in the West

## Well-designed Wholesale Electricity Markets Support System Flexibility

Market design largely determines the operational mechanisms available to maintain long-term and short-term power system reliability. For systems with high levels of variable generation, well-designed electricity markets drive efficient solutions to meet reliability needs in a least-cost manner, and they can facilitate access to a range of options that increase system flexibility. Table 1 summarizes current and emerging market design approaches and best practices for incentivizing and accessing flexibility. In collaboration with the electric power community, NREL continues to lead analysis on best practices in market design.

**Table 1.** Market Approaches and Best Practices for Incentivizing and Accessing Flexibility.

| Ancillary Services Market | Energy Market | Capacity Adequacy Market |
|---|---|---|
| **Dynamic system reserve requirements**, which vary by time of day and system conditions on an hourly basis, could better target high-risk periods of significant change in the wind resource and reduce integration costs. Market participants would plan ahead to understand what the ancillary services demand might be, similarly to how they anticipate the load demand.<br><br>**Co-optimization of energy and ancillary service markets** has improved the efficiency of scheduling and dispatching resources.<br><br>**Primary frequency response** is an autonomous generator response that stabilizes the system frequency. Explicit compensation for this service (which is typically provided by conventional generators as a part of interconnection) through cost-based measures or market designs could help ensure system reliability with high VG. | **Dispatch resolution** of 5- to 15-minutes improves system flexibility by more closely matching the changes in variable generation and load (net load) economically and reducing use of regulating reserves—cost-effectively optimizing generation.<br><br>**Integrating Advanced, Centralized Forecasts** into market operations could increase market efficiency and provide additional opportunities for wind and solar resources to participate in electricity markets.<br><br>**More frequent (Intraday) markets** could enable participation from power plants with intermediate lead/start-up times and help reduce the relatively high cost of balancing resources on the minutes timescale. The current two-step market with unit commitment in the day-ahead timescale leaves significant forecast errors to be resolved during real-time balancing.<br><br>**Flexible ramp products** could help address operational needs in real-time by maintaining dispatchable flexibility in terms of ramping capability. | **Scarcity pricing** sends price signals in the real-time market when there is a system wide shortage of power to meet demand and provide sufficient backup reserves. Scarcity pricing can be designed to encourage investments in flexible response, such as storage and price-responsive load, because these resources can respond quickly to brief periods of scarcity.<br><br>**Capacity markets** ensure that new generation is developed on time to meet resource adequacy targets and help these resources recover their capital costs. Capacity markets can help address concerns about declining wholesale electricity prices and ensure system flexibility with increased VG.<br><br>**Capabilities markets** have been proposed as a mechanism to create investment incentives for the right mix of generation, demand-side resources, storage and other grid resources to deliver flexibility and other attributes necessary to cost-efficiently balance systems where there is an increasing proportion of renewable power. |

# Moving Toward Cleaner, More Reliable, and More Resilient Power Systems

NREL is leading a worldwide conversation about energy systems integration and spearheading innovations that optimize our entire energy system. Our energy analysis capabilities complement our science and technology work in this area. NREL works with utilities, policymakers, and investors to explore options and future impacts of today's energy choices—on grid reliability, GHG emissions, economics, and energy security. See how NREL research and analysis are redefining what's possible for renewable energy on the grid at http://youtu.be/XtV574KBEbU.

# Learn More

## National and Regional Grid Integration Studies

**Western Wind and Solar Integration Study**

- **Phase 3**. (2014) Examined the large-scale stability and frequency response with high wind and solar penetration in the Western United States. http://www.nrel.gov/electricity/transmission/western_wind.html
- **Phase 2**. (2013 ) Assessed impacts of cycling fossil-fueled power plants on emission and wear-and-tear costs. http://www.nrel.gov/electricity/transmission/western_wind.html
- **Phase 1**. (2010) Investigated integration of large amounts of wind and solar energy into the electric power system of the Western Interconnection. http://www.nrel.gov/electricity/transmission/western_wind.html

**Renewable Electricity Futures Study** (2012) Explored implications and challenges of very high renewable electricity generation levels—from 30% up to 90% of all U.S. electricity generation—in 2050. http://www.nrel.gov/analysis/re_futures/

**Eastern Wind Integration and Transmission Study** (2010) Examined the operational impact of 20%–30% wind energy penetration on the power system of the Eastern Interconnect of the United States. http://www.nrel.gov/electricity/transmission/eastern_renewable.html#ewits

**20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply** (2008) Examined costs, challenges, and key impacts of generating 20% of the nation's electricity from wind energy in 2030. http://www.nrel.gov/docs/fy08osti/41869.pdf

## System Flexibility

**A Review of Variable Generation Forecasting in the West: July 2013 – March 2014** (2014) Industry survey on VG forecasting practices, lessons learned, and priorities. http://www.nrel.gov/docs/fy14osti/61035.pdf

**Integrating Variable Renewable Energy: Challenges and Solutions** (2013) Explored renewable energy integration mitigation strategies that have been implemented in the United States and internationally. http://www.nrel.gov/docs/fy13osti/60451.pdf

## Resource Flexibility

**Impact of Generator Flexibility on Electric System Costs and Integration of Renewable Energy** (2014) Estimated the impact of generator flexibility on the integration of wind and solar generators for wind and solar penetrations between 15% and 60%. http://www.nrel.gov/docs/fy14osti/62275.pdf

**Flexible Coal: Evolution from Baseload to Peaking Plant** (2013) 21st Century Power Partnership. Looked at a coal plant that cost-effectively operates as a flexible resource. http://www.nrel.gov/docs/fy14osti/60575.pdf

**Cost-Benefit Analysis of Flexibility Retrofits for Coal and Gas-Fueled Power Plants: August 2012 – December 2013** (2014) Studied the costs and benefits of retrofitting fossil units for improved operational flexibility. http://www.nrel.gov/docs/fy14osti/60862.pdf

**Value of Demand Response: Quantities from Production Cost Modeling (Presentation)** (2014) Discussed the value of co-optimized DR resources to provide energy and ancillary services. http://www.nrel.gov/docs/fy14osti/61815.pdf

**Impact of Wind and Solar on the Value of Energy Storage** (2013) Evaluated how the value of energy storage changes when adding variable renewable generation to the grid. http://www.nrel.gov/docs/fy14osti/60568.pdf

## Market Design

**Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation** (2014) Reviewed market design approaches focused on revenue sufficiency for long-term reliability. http://www.nrel.gov/docs/fy14osti/61765.pdf

**Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience** (2012) Documented diverse approaches to effective integration of variable renewable energy among six countries. http://www.nrel.gov/docs/fy12osti/53732.pdf

**Market Evolution: Wholesale Electricity Market Design for 21st Century Power Systems** (2013) Reviewed wholesale power market designs that help ensure adequacy, security, and flexibility. http://www.nrel.gov/docs/fy14osti/57477.pdf

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