Review and Status of Wind Integration and Transmission in the United States: Key Issues and Lessons Learned

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List of Acronyms

BAA	balancing authority area
DOE	U.S. Department of Energy
ERCOT	Electric Reliability Council of Texas
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IVGTF	Integration of Variable Generation Task Force
NERC	North American Electric Reliability Corporation
WWSIS	Western Wind Solar and Integration Study

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1 Introduction and Key Issues

In the years since the U.S. Department of Energy's (DOE's) *20% Wind Energy by 2030* study was published (2008), a great deal has been learned about the impacts that wind generation can have on electric power systems and how to efficiently integrate wind power into the bulk power system. This report adds to DOE's Wind Vision discussion about how to integrate wind energy into the bulk power system.[1] It explores what has been learned from both actual operating practices and integration studies, which have become increasingly sophisticated during the past few years.

Wind Vision

DOE's Wind and Water Power Technologies Office leads the Wind Vision analysis, a broad-based collaborative that has four principal components:

1. Document the current state of wind power in the United States and identify key technology accomplishments and trends during the past decade.
2. Explore the potential for wind power to contribute to the future electricity needs of the nation, including objectives such as reduced carbon emissions, improved air quality, and reduced water use.
3. Quantify costs, benefits, and other impacts associated with the continued deployment and growth of U.S. wind power.
4. Document actions and future achievements that could support the continued growth in the use and application of wind-generated electricity.

The objective in electric power system operation is to use generation and transmission resources within organizational constraints and operational rules and regulations to reliably and cost-effectively balance load and generation. To meet this objective, system operational practices have been created to accommodate the innate variability and uncertainty that comes from a variety of sources, such as uncertainty of demand forecasts, whether a specific generating unit will be available when called upon, the variability of demand from many different types of customers, and others. As more wind power is connected to the power system, operating experiences acquired during the past several years have generally confirmed the findings of wind integration studies: wind energy increases the level of variability and uncertainty that a system operator must manage.

The DOE Wind Vision examines what would need to happen if wind energy contributes 20% of annual electricity demand in 2030 and 35% of demand in 2050. Practical experience and studies so far have not identified any insurmountable obstacles to integrating in excess of 20% annual

[1] See http://www.energy.gov/windvision.

wind energy, the wind penetration target proposed by DOE in the 2008 wind vision. Although this statement may be generally true, it does not imply that all possible ways of integrating 20% wind energy will be successful. For example, small balancing authority areas (BAAs)[2] and regions with inflexible generation scheduling will have a more difficult time integrating wind than large ones or those that have subhourly energy scheduling. Additionally, the impact of transmission network limitations can vary considerably at different locations and times and therefore may also pose challenges.

The past 15 years of wind integration experience has demonstrated that flexibility is the key to successfully and efficiently integrating wind energy. Large penetrations of wind energy will necessitate steeper ramp requirements from dispatchable generators and demand-response sources, require lower minimum generation operating levels than are required today, and increase the amount of reserves necessary to maintain reliability levels. Thus, a “flexible” electric power system implies one in which the operator has some combination of agile generators that are physically able and equipped to respond quickly to load changes or an operational environment (scheduling interval, demand response, robustness of electric market, proper institutional structures) that allows quick adjustments to be made to load, or both. Understanding and providing this flexibility, especially at high levels of wind penetration, may be the most critical wind integration issue. Possessing physical flexibility without the institutional ability to access this flexibility may be insufficient. Conversely, possessing institutional flexibility without physical flexibility will also generally be insufficient.

To address these operational issues, advanced wind turbine controls can aid the operation of the grid if proper incentives are provided. For example, wind turbines can now provide synthetic inertia, governor response, and regulation service. Dispatching wind generation below the maximum power wind conditions currently enables wind generators to provide fast and accurate responses, which can be economically attractive when other options are limited.

This report summarizes the lessons learned from some of the most relevant and comprehensive wind integration studies conducted during the past several years. Following is a discussion about lessons from operating practices, especially as related to reserves, efficient operating practices, and wind power forecasting. The concluding sections of the report describe the main industry organizations involved in wind integration and transmission, briefly discuss transmission expansion related to wind energy, and include a summary.

[2] A BAA is a predefined area within an interconnected transmission grid in which an entity such as a utility, an independent system operator, or a transmission system operator has the responsibility to balance load and generation while maintaining system reliability and interchanges with adjoining BAAs. An interconnected grid can have numerous BAAs or a single BAA. For example, the Western Interconnection covers much of the western United States and western Canada and has 35 BAAs; whereas the Texas Interconnection has a single BAA, the Electric Reliability Council of Texas (ERCOT).

2 Lessons Learned from Wind Integration Studies

When *20% Wind Energy by 2030* was published, experience integrating wind energy into power systems was limited—wind energy penetration was more than 7% in some states and 1.1% nationally (Wiser and Bolinger 2008). Since that time, however, wind energy penetration has increased substantially—to more than 20% in some states and 4.2% nationally (Wiser et al. 2013). With respect to wind integration studies, although the basic methodology had been established by 2008, the techniques and tools employed to conduct these types of analyses were, and still are, very much in development. At that time, wind power was essentially "tacked on" to conventional power systems, and thus integration studies focused on determining the impacts of wind power on operations and estimating a "wind integration cost." Integration costs refer to a hypothetical cost of operating a power system with wind energy compared to some other "ideal" power source that does not possess wind power's natural variability and which is perfectly predictable. Most early studies estimated these costs below $5/MWh of wind energy, although one study approached $9/MWh of wind energy (Wiser and Bolinger 2008). Subsequent studies that had similar objectives confirmed these findings: most predicted costs below $5/MWh of wind energy, and all studies predicted less than $12/MWh of wind energy (Wiser et al. 2013).

During the past several years, however, wind power has transformed from being an add-on to power systems to a fully integrated part of the generation fleet. As a consequence, wind integration studies have moved away from devising proxy "ideal" resources needed to determine an integration cost and have evolved to capture the impacts on system operations and the overall cost and emissions savings due to displaced thermal generation. At the same time, there has been recognition that other generation sources also produce integration costs and that individual loads differ dramatically in their variability and uncertainty. Regulators are concerned that it may not be appropriate to allocate specific costs to one set of entities (wind) if costs are not appropriately allocated to all (other individual generators and individual loads). Thus, state-of-the-art integration studies typically determine electric power system/reliability impacts and seek to establish an overall system operating cost. These impacts and operating costs can be compared and contrasted to other configurations for serving system load.

The material presented in this section describes recent experiences, lessons learned, and best practices in integrating wind power.

2.1 Wind Integration Studies: Questions to Answer

Favorable economic and political conditions for much of the past decade, along with improvements in cost and performance of wind turbines, have caused the rapid expansion of wind energy in our electric power system. Wind energy brings many positive benefits to the electric power system—such as cost-effective energy, long-term price stability, some generation capacity, and improved emissions of the generation fleet—but it also has generation characteristics that are different than those of conventional generation resources. In particular, because wind is driven by meteorological processes it is intrinsically *variable*. This variability occurs on all time frames of utility operation from real-time minute-to-minute fluctuations to yearly variations that affect long-term planning. In addition to being variable, wind power production is a challenge to accurately predict on the timescales of interest to power system planners and operators, and therefore its production is inherently *uncertain*. This uncertainty is more prevalent during longer time periods than during shorter time periods. Combined, these effects impact the cost of power system operations, and thus they require changes in system operational practices and allocations of reserves.

To understand these impacts, utilities and transmission system operators have conducted integration studies about electric power system operations and planning that include low (a few percent) to high (well in excess of 20%) penetrations of wind power. The first wind integration studies were conducted in the late 1990s and were primarily statistical analyses of the potential influences of wind power. However, low wind power prices and subsequent policies promoting its use caused a rapid expansion of wind power, motivating planners and operators to conduct more detailed, realistic studies of wind power integration. These studies produced a wealth of information concerning the expected impacts of wind integration as well as useful insights into strategies for managing them. Several reports summarize the results and lessons learned from many of these studies (Smith et al. 2007, Ackerman and Kuwahata 2011, Exeter and GE Energy 2012), which typically focused on answering some or all of the following questions:

- How will wind power affect the reliability of an electric power system BAA? What grid reinforcements will be needed, if any?
- Can specific amounts of wind power be incorporated into the existing system operational practices of a given BAA or independent system operator? How should these practices be modified to cost-effectively and reliably accommodate wind power?
- At what levels of wind integration do existing practices need to be modified? Are there any limits to the amount of wind energy that can be incorporated?
- How does integrating wind energy influence system operational costs and the provision of operating reserves?

Through much debate among various stakeholders, these questions have led to a consistent yet continuously improving method of analysis. Good references describing the methodology, assumptions, and data requirements for a quality integration study are provided in the International Energy Agency (IEA) wind Implementing Agreement reports by Holtinnen et al. (2009)[3] and Acker (2011a and 2011b), Milligan (2011) and Milligan (2012a and 2012c), and as suggested by the North American Electric Reliability Corporation (NERC) (2011). In addition, the IEA Task 25 recently issued a report on recommended best practices for integration studies (2013).

2.2 Power System Balancing and Ancillary Services

Utility generation resources are dispatched to meet varying load. Wind energy has a very low marginal cost and is frequently incorporated into utility systems via “take or pay” contracts. When wind power is viewed as “must take” and not dispatchable in the traditional sense, it essentially appears as negative load to the rest of the system. As a consequence, conventional dispatchable generators are tasked with balancing the net load of the system—that is, the load minus the wind generation. As the penetration of wind energy increases, the character of the net load changes, sometimes dramatically, from the load-only profiles.

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[3] See http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf.

Figure 1 shows an excellent example of how the net load profile can change and lead to changes in the deployment of conventional generation resources. Taken from the first phase of the *Western Wind and Solar Integration Study*, the top plot shows how the aggregate load is met in the study's "Westconnect" region using conventional generation resources; whereas the plot on the bottom shows how generation is utilized when 35% wind and solar penetration is employed. Note that at times the instantaneous penetration of wind power is quite high, near 75%. The changes in generation shown are striking; they represent the most challenging week identified in this study (a relatively low-load period combined with high wind generation). Despite the changes shown, the study demonstrated that even with this sometimes large influence of renewables, it was still feasible to balance the system. Also evident from this figure is that accommodating high levels of wind power may require changes in the normal planning and operating paradigms, and at a minimum careful study is warranted to assess impacts and devise efficient and effective operating strategies.

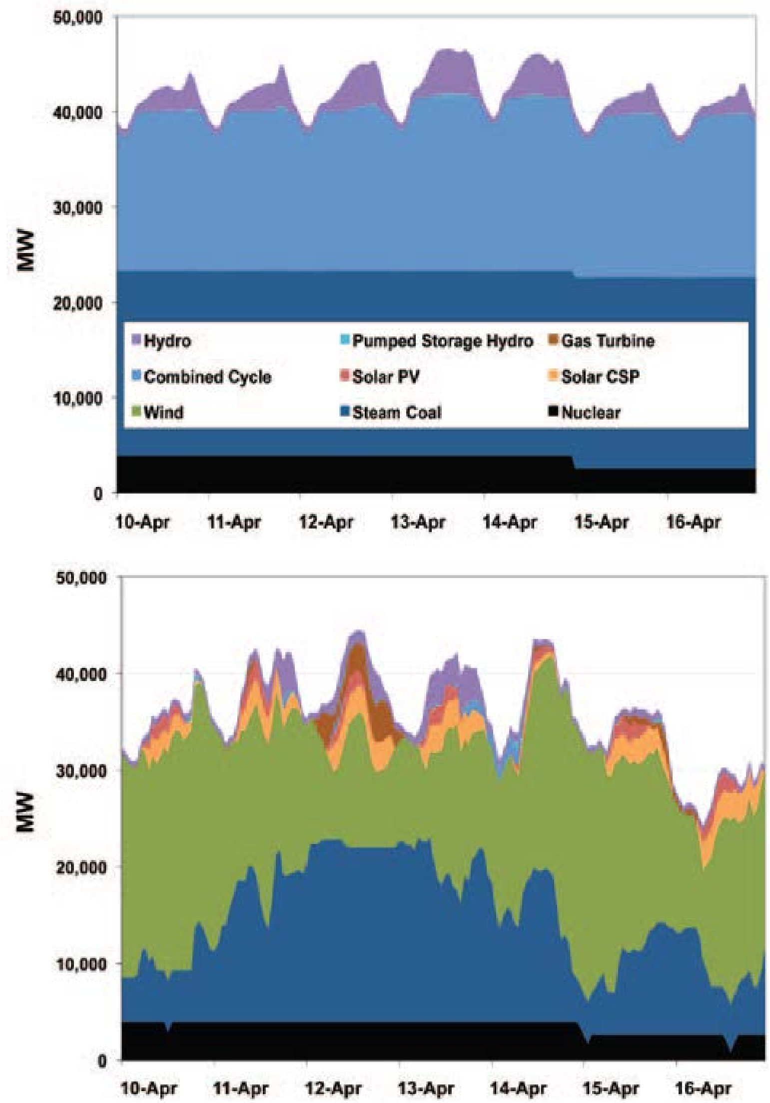

Figure 1. (Top) The dispatch of conventional generation resources for a typical week in April and (bottom) during this same week showing the effect of 35% renewables (30% wind and 5% solar) (NREL 2010b)

Operational impacts of variable resources can occur in each of the timescales managed by power system operators. Figure 2 illustrates these timescales, which range from seconds to days. Regulation is a service that rapid-response maneuverable generators deliver on short timescales to allow operators to maintain system balance. This typically occurs over a few minutes, and it is provided by generators using automatic generation control, which can be supplied by several types of generation including combined cycle, hydro, and even coal and wind plants if equipped with appropriate controls. Load following includes both capacity and energy services, such as spinning reserves, and generally varies from 10 minutes up to several hours. This timescale incorporates the morning load pick-up, the evening load drop-off, and inter-hour swings in net load, and it can employ combined-cycle, hydropower, gas turbine, and sometimes coal-powered steam generation. The scheduling and unit-commitment processes are devised to ensure that sufficient generation will be available when needed over several hours or days ahead of the real time schedule and that sufficient *flexible* generation will be available. This last point is increasingly important with larger penetrations of variable renewable generators like wind, because these processes require forecasts of the net load that rely upon load and wind power forecasts.

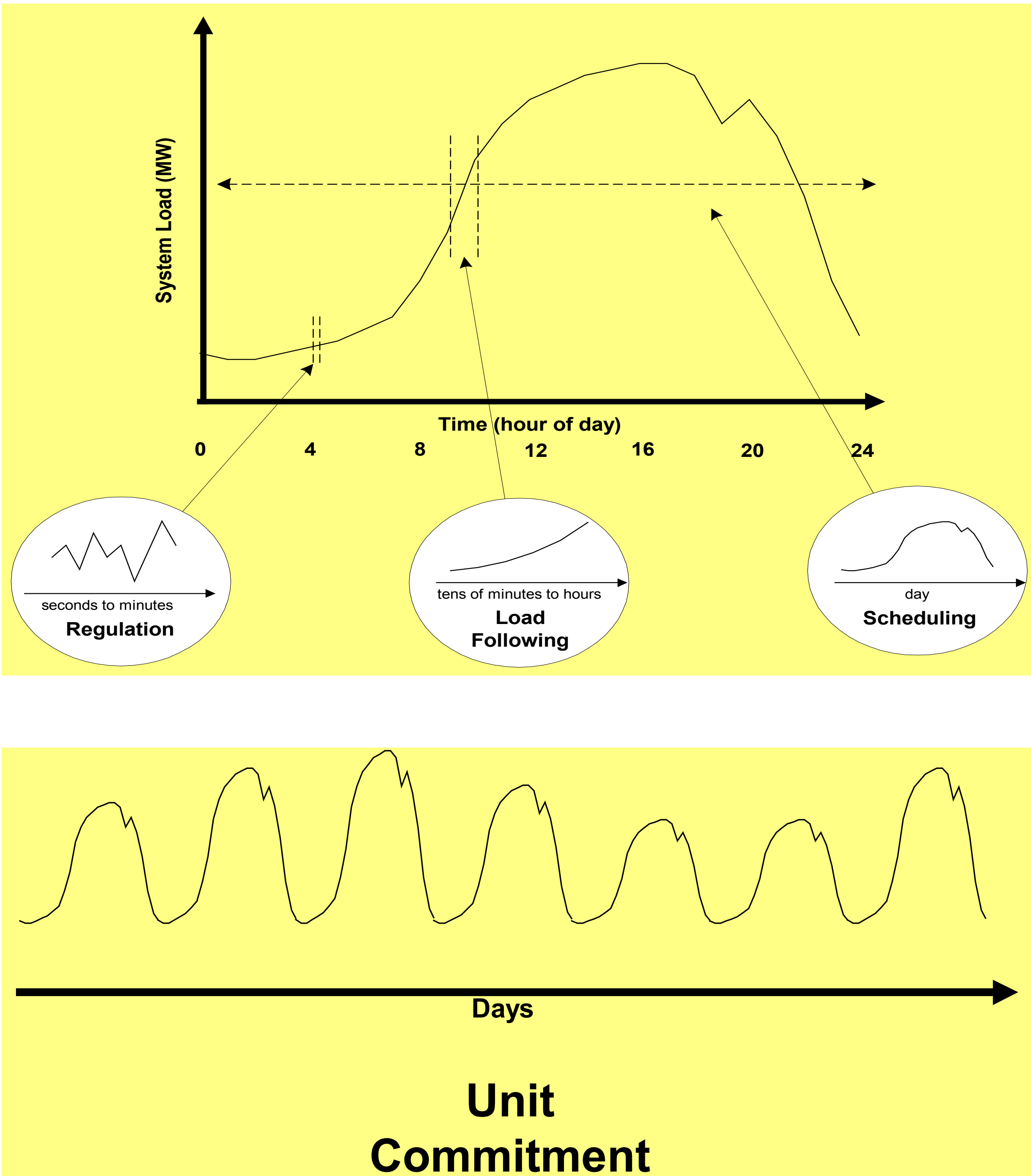

Figure 2. Typical load shape showing the various timescales relevant for system operations (Ela, Milligan, and Kirby 2011)

The overall result of the additional variability and uncertainty introduced into system operations and planning across these time frames is the need for additional generation reserves, additional flexible generation or load, and possibly grid reinforcements. The specific technical terms used to describe the generator and load portion of these services vary among different power systems and BAAs but are generally referred to as "ancillary services." Ultimately, supplying these ancillary services boils down to allocating additional operating reserves or in some way acquiring the generation or load flexibility needed to balance the system. Indeed, the purpose of many current and future integration studies is to assess the BAA system *flexibility* and consequent ability for the provision of ancillary services through mechanisms that do not artificially limit but rather encourage the incorporation of variable renewable generation.

2.3 Wind Integration Study Methodology

The methods used in wind integration studies aim to simulate actual power system operations, including the decision processes made in committing system resources through detailed, transmission-constrained production-cost models and statistical analyses of hourly and subhourly net load variations. Dynamic system modeling is also performed to determine transmission system reliability impacts. A list of best practices for wind integration studies includes the following (NERC 2010a, Holttinen et al. 2009):

- Include time-coincident, realistic wind power and load time-series data as input data. Both wind and load are dependent upon weather, and thus time-synchronized data is necessary.
- Analyze the balancing of the system *net load* and not wind power in isolation from load.
- Employ an accurate production-cost model with a sufficiently detailed time resolution to simulate system operations, characteristics, and responses, which includes transmission modeling and accurate models of the generation fleet's capabilities, emissions, and constraints.
- Ensure that the smoothing effects of geographic diversity on wind power variability are accurately characterized.
- Use realistic, state-of-the-art wind power forecasts in production-cost model simulations along with load forecasts.
- Conduct detailed statistical analyses of the hourly and subhourly wind power output and net load data to ensure that production-cost models correctly capture ramping events and to properly identify reserve requirements.
- Determine the capacity value of wind using industry-accepted resource-adequacy models, such as loss-of-load probability and effective load-carrying capability.
- Apply dynamic models to understand the wind integration reliability impacts on the transmission system.
- Focus on determining the total system operating costs for realistic generation and operating scenarios. Comparing these costs will lead to the most accurate view of the impacts of wind integration, including increased balancing costs, decreased fuel costs, and so on.
- Include expert review of the study methods and results by forming a technical review committee composed of experts in the field who can provide objective feedback.

Statistical analyses are employed in integration studies. Stochastic methods may offer more optimal and effective solutions in certain circumstances, particularly in characterizing the operational uncertainty of variable generators, although these methods have not yet been widely adopted by industry. As discussed in a recent Integration of Variable Generation Task Force (IVGTF) report, more work is needed to improve these probabilistic techniques as well as the understanding and benefits of such methods (NERC 2014b).

2.4 Key Integration Study Results

Dozens of wind integration studies have been conducted during the past several years, some limited in scope and others very expansive and detailed. It would be difficult to review them all here, so the approach below summarizes results from a subset of these studies that represents some of the more-detailed, higher penetration studies, all of which implemented the best practices described above and led to the key lessons learned. Studies of higher penetration levels are important, because larger amounts of wind energy stress system operational practices and reliability, and therefore the results offer more insight into grid integration impacts and costs. Several good studies of lower penetration levels demonstrated results consistent with those presented below, such as those by Xcel energy (2006), Acker et al. (2008), and New York Independent System Operator (2010). However, some of the studies of higher penetration levels, as well as other regional studies such as those by California Independent System Operator (2010) and Exeter and GE Energy (2012), are representative of what has become the norm in integration studies: studies of incorporating substantial penetrations of more than one renewable energy technology—often wind with solar—to meet system load. This section summarizes results and conclusions from several key studies performed by the following organizations:

- NREL—Large-scale integration studies in the western and eastern interconnections (Western Wind and Solar Integration Study [WWSIS] Phase 1 and Phase 2 and Eastern Wind Integration and Transmission Study) and contiguous United States (Renewable Electricity Futures). WWSIS-1, WWSIS-2, and the Eastern Wind Integration and Transmission Study examined up to 30% wind energy penetration, and Renewable Electricity Futures examined up to 90% renewable (including nearly 50% from variable renewable generators) energy penetration.
- Independent System Operator–New England—up to 24% wind energy penetration
- Electric Reliability Council of Texas (ERCOT)—9% wind energy penetration[4]
- IEA Task 25—up to 25% wind energy penetration

2.4.1 WWSIS-1

WWSIS-1 was conducted to investigate the operational impacts of integrating up to 35% wind, photovoltaics, and concentrating solar power on the power system operated by the WestConnect group of utilities in Arizona, Colorado, Nevada, New Mexico, and Wyoming (NREL 2010b). The study year selected was 2017, with system load and generation data scaled from 2007. Of

[4] ERCOT had a 9% annual wind energy share of total demand, with installed wind capacity of 23% of peak load at the time the study was performed. Since that time, additional wind capacity has been added to the system.

this renewable energy penetration level, up to 30% was from wind power and 5% was from solar photovoltaics or concentrating solar power. Key results from this study include:

- Renewable energy penetration of 35% (30% wind and 5% solar) is operationally feasible provided extensive BAA cooperation or consolidation is implemented, real or virtual.
- The 30% wind, 5% solar case reduced fuel and emissions costs by 40% and CO_2 emissions by 25% to 45% across the Western Electricity Coordinating Council. Incorporating these renewables resulted in operating cost savings for the Western Electricity Coordinating Council of $20 billion/yr[5] ($17 billion/yr in 2009 $U.S.) because of the wind and solar generation resources. These values equate to $80/MWh ($60/MWh in 2009 $U.S.) of wind and solar energy produced. This savings does not account for the capital or operating costs associated with wind and solar, although some of these savings would presumably be used to cover the costs of wind and solar generators.
- Subhourly scheduling may be required to successfully operate the system at high penetration levels without significantly increasing regulating reserves or curtailing renewables.
- Using state-of-the-art wind and solar forecasts in day-ahead unit commitment is essential and would reduce annual Western Electricity Coordinating Council operating costs by up to $5 billion ($4 billion in 2009 $U.S.) or $12/MWh to $20/MWh ($10/MWh to $17/MWh in 2009 $U.S.) of renewable energy, compared to the cost of ignoring renewables in the unit commitment process.
- Demand response may be a cost-effective method of providing operating reserves during the most critical 100 hours of the year. New or existing demand-response programs (load participation) should be targeted to help accommodate increased variability and uncertainty.
- Although the need for variability reserves doubles in the 30% wind case, backing down conventional units results in more available up-reserves. Therefore, committing additional reserves is not needed to cover the increased variability.
- Wind power plants can be curtailed to provide down regulating reserves instead of moving regulating units. Even so, curtailment is estimated to be on the order of 1% or less of total wind energy in the 30% case.
- Up to 20% renewable penetration could be achieved with little or no new long-distance, interstate transmission additions, assuming full utilization of existing transmission capacity.
- Wind was found to have capacity values of 10% to 15%, photovoltaics was 25% to 30%, and concentrating solar power with 6 hours of thermal energy storage was 90% to 95%.

2.4.2 WWSIS-2

Although WWSIS-1 demonstrated the feasibility of operating the Western Interconnect with significant amounts of wind and solar energy, it also raised some interesting questions. As demonstrated in Figure 1, thermal generating units that heretofore were run at near constant output would need to cycle more frequently at high penetrations of wind power. (*Cycling* implies

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[5] For this study, values are reported in 2017 $U.S., because that was the target year of the study. Values are also reported in 2009 $U.S., because that was the year in which the study results were actually calculated.

shutting down and restarting generating units, ramping them up and down, or operating them at part load.) Utilities were concerned about this new mode of operating thermal units and the consequent impacts on repair and maintenance costs and component lifetimes; thus, they suggested that these additional costs could significantly reduce the operational cost savings reported above and that part-load operation would cause substantially reduced emissions savings. The goal of WWSIS-2 was to investigate these concerns, and the results are listed below (Lew et al. 2013):

- High penetrations of wind and solar increase annual wear-and-tear costs from cycling by \$35 million to \$157 million (2011 nominal dollars).[6] This represents an additional \$0.47/MWh to \$1.28/MWh of cycling costs for an average fossil-fueled generator. Cycling diminishes the production-cost reduction of wind and solar by \$0.14/MWh to \$0.67/MWh, based on the specific system and generator characteristics modeled. These costs are a small percentage of annual fuel displaced across the Western Interconnection (approximately \$7 billion) and the reduction in fuel costs (\$28/MW/h to \$29/MWh of wind and solar generated), as illustrated in Figure 3.

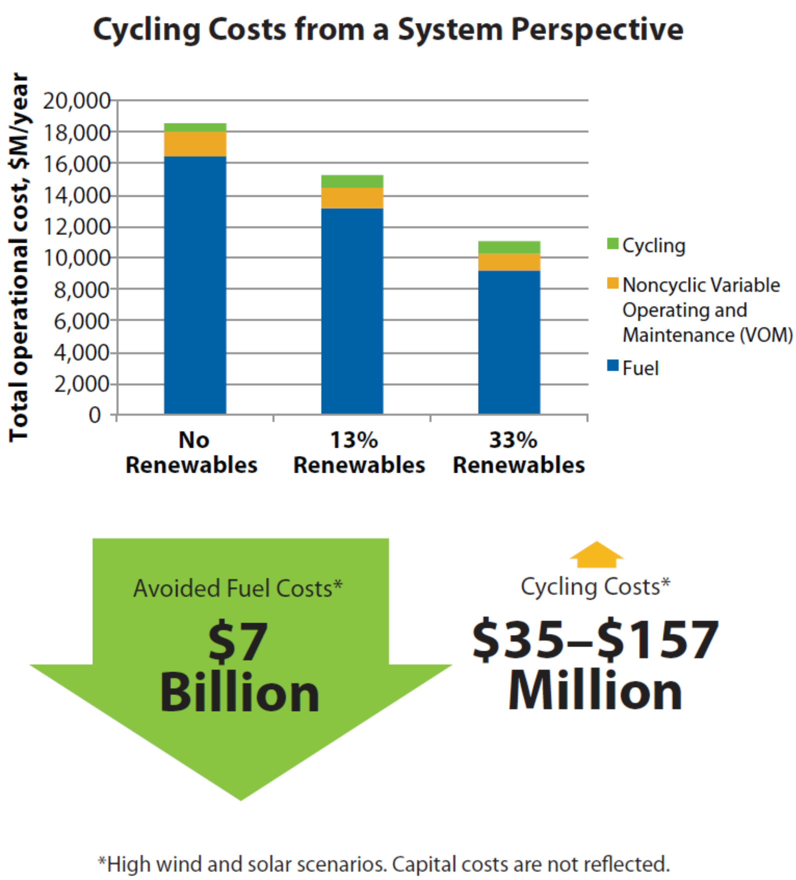

Figure 3. Cycling costs, though significant, have a small impact on the overall system operating cost savings due to the integration of renewables (NREL 2013).

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[6] The low and high ends of this range give an uncertainty range for cycling costs and represent an application of the lower-bound and upper-bound cycling costs, respectively. The high end of the uncertainty range is an overestimate because of the method used.

- CO_2, NO_x, and SO_2 emissions impacts resulting from wind- and solar-induced cycling of fossil-fueled generators are a small percentage of emissions avoided by wind and solar generation (see Figure 4). Wind- and solar-induced cycling has a negligible impact on avoided CO_2 emissions. Wind- and solar-induced cycling will cause SO_2 emissions reductions from wind and solar to be 2% to 5% less than expected and NO_x emissions reductions to be 1% to 2% larger than expected. From the perspective of a fossil-fueled generator, this cycling can have a positive or negative impact on CO_2, NO_x, and SO_2 emissions rates.

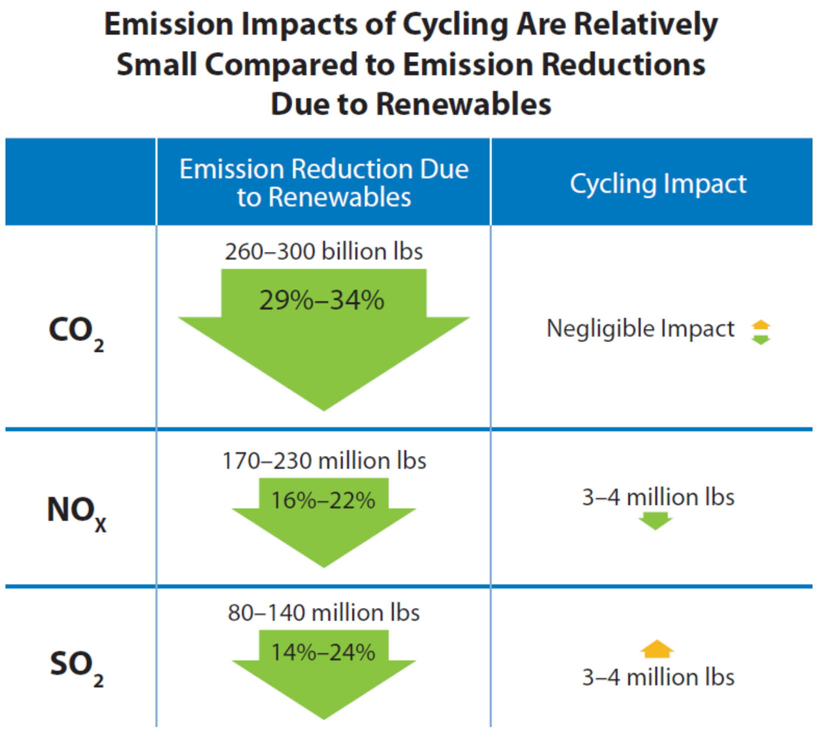

Figure 4. The impact of cycling on emission reductions due to fuel savings is very small (NREL 2013).

2.4.3 Eastern Wind Integration and Transmission Study

The Eastern Wind Integration and Transmission Study was conceived to examine the operational impacts of integrating up to 20% to 30% wind energy on the bulk power system in the Eastern Interconnection of the United States (NREL 2010a). The study considered scenarios in the Eastern Interconnection in which approximately 225,000 MW of wind was added (20% scenario) up to approximately 400,000 MW (30% case), along with substantial amounts of transmission to transport the wind energy to serve the load centers. Important findings of the study are provided below:

- High penetrations of wind generation—20% to 30% of the electrical energy requirements of the Eastern Interconnection—are technically feasible with significant expansion of the transmission infrastructure.
- New transmission will be required for all future wind scenarios considered in the Eastern Interconnection, though it occupies a small fraction (generally less than 10%) of the total

annual system cost in all scenarios. Thus, planning for this transmission is imperative, because it takes longer to build new transmission capacity than it does to build new wind power plants. Transmission helps reduce the impacts of the variability of wind, which reduces wind integration costs, increases reliability of the electric grid, and helps make more efficient use of the available generation resources.

- Without transmission enhancements, substantial curtailment of wind generation would be required for all of the 20% scenarios.
- Interconnection-wide costs for integrating large amounts of wind generation are manageable with large regional operating pools and significant market, tariff, and operational changes.
- With large BAAs and fully developed regional markets, the cost of integration for all scenarios is less than $6/MWh of wind (relative to a reference case in which wind energy was presumed to be perfectly forecasted and not require any additional regulation reserves—i.e., no effect of uncertainty and reduced impact of variability). This equates to less than $0.002/kWh of electricity used by customers.
- The capacity value of wind generation for the scenarios considered and as determined by the effective load-carrying capability ranges from 24.1% to 32.8% of the rated installed capacity of wind power.

2.4.4 New England Wind Integration Study

The goals of the New England Wind Integration Study were to determine the operational, planning, and market impacts of integrating up to 12 GW of wind generation resources in the New England BAA (Independent System Operator–New England). Wind energy penetrations of 2.5%, 9%, 14%, 20%, and 24% were evaluated. Key findings of the study are given below (Independent System Operator–New England 2010):

- New England could potentially integrate wind resources to meet up to 24% of the region's total annual electric energy needs in 2020 if the system includes transmission upgrades, and this may reduce average system-wide variable operating costs (i.e., fuel and variable operations and maintenance costs) in Independent System Operator–New England by $50 to $54 per megawatt-hour of wind energy.
- Wind generation would primarily displace natural-gas-fired generation, because the price of gas-fired generation is most often on the margin in the Independent System Operator–New England market.
- The average regulation requirement increased from 82 MW to 161 MW in the 9% wind energy scenario (4 GW installed wind capacity), and up to 313 MW for 20% wind energy (8 GW to 10 GW installed wind capacity).
- The 10-minute spinning reserve and the non-spinning reserve would both need to increase as wind energy penetration increases. As a consequence, the total operating reserve increased in all wind energy scenarios. Compared to the no-wind energy scenario baseline, the average required total operating reserve increased from 2,250 MW to 2,270 MW in the 2.5% wind energy scenario, up to approximately 2,600 MW in the 14% wind scenario, and up to approximately 2,750 MW with 20% penetration.

- As wind penetrations were increased up to 24%, under-forecasting wind energy led to periods when there were increasing amounts of ramp-down insufficiencies, with up to approximately 540 hours when there may potentially be insufficient regulation down capability. There were no instances in which shortages occurred in the regulation up. A transmission system with a 4-GW overlay could handle 20% wind energy without significant congestion, and one with an 8-GW overlay could handle 24% wind energy without significant congestion.
- Results demonstrated that there was only a relatively small increase in the use of existing pumped-storage hydropower for large wind penetrations, largely because the flexible natural-gas-fired generation fleet provided most of the system balancing.
- Introducing large amounts of low-marginal-cost wind generation tended to depress the spot price and reduce the price differential for bulk power between day and night, as indicated in Figure 5. System-wide locational marginal prices in Independent System Operator–New England dropped by $5/MWh to $11/MWh as wind penetration increased. Because of this decrease, revenue reductions for units not displaced by wind energy were approximately 5% to 10%. For units that were displaced by wind energy, revenue losses were even greater. To maintain viability of the generation fleet, the correct market signals must be in place to ensure that an adequate fleet of flexible resources is maintained.
- At 20% penetration of wind energy, NO_x emissions were reduced by approximately 6,000 t/yr, a 26% reduction compared to no wind; SO_x emissions were reduced by approximately 4,000 t/yr, a 6% reduction compared to no wind; and, CO_2 emissions were reduced by approximately 12,000,000 t/yr, a 25% reduction compared to no wind.
- The capacity value of wind power, as determined via effective load-carrying capability calculations, varied from 20% to 36% across the various scenarios, with an average value of 32%.

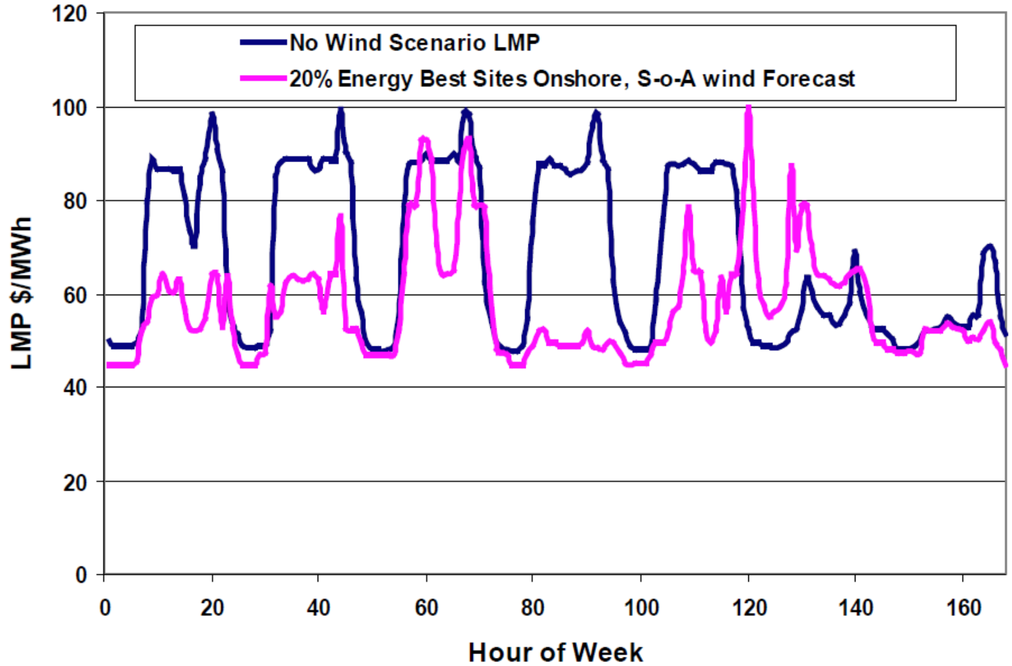

Figure 5. Locational marginal pricing in the New England Wind Integration Study for one of the study weeks, demonstrating wind power's effect in depressing the locational marginal price and reducing price differentials between day and night (Independent System Operator–New England 2010).

2.4.5 Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements

In this project, ERCOT commissioned GE Energy to perform an intensive study of the ancillary services required for the ERCOT system to accommodate the large-scale expansion of wind generation capacity: up to 15,000 MW of wind generation, equivalent to a 23% penetration of ERCOT's 2008 peak load (GE Energy 2008). Time-synchronous 1-minute wind and load data were analyzed in a production-cost simulation that employed day-ahead wind generation and day-ahead system load forecasts with hourly time resolutions. The purpose of the simulation was to determine the amount of ancillary services required to balance the net load, the ability of the system to provide these services, and an estimate of their costs. The following results were obtained:

- Net variability, as measured by an increase in the standard deviation of changes in the net load, increased by 6% (5,000 MW of wind) to nearly 19% (15,000 MW of wind) across time frames from 1 minute to 1 hour.
- The instantaneous wind penetration reached as high as 57% of served load during low-load periods.
- The study was able to identify periods when extreme net-load forecast errors may occur, and it suggested mitigation strategies.

- The net operating cost savings[7] with wind power were between \$53/MWh and \$55/MWh for all scenarios from 5,000 MW to 15,000 MW of wind. Wind power tended to displace gas combined-cycle generation.
- The effect of zero marginal cost wind power was to decrease the overall spot price of energy. Wind energy forecasts had a significant effect on spot prices; neglecting a wind forecast would cause a large drop in spot prices because of overcommitment of thermal generation.
- Required amounts of down-regulation and up-regulation increased linearly with wind power. There appears to be sufficient up-regulation available currently in the system, and only a small number of hours without adequate down-regulation (which would lead to curtailment). The cost of regulation per MWh of wind generation was shown to be very small, ranging from -\$0.18/MWh to +\$0.27/MWh, depending on the wind capacity scenario and wind forecast accuracy assumptions.
- In general, the impact of wind generation on system operation and ancillary service requirements are limited at 5,000 MW of wind, noticeable at 10,000 MW, and require attention at 15,000 MW of wind.

2.4.6 IEA Task 25: Design and Operation of Power Systems with Large Amounts of Wind Power

The objective of the IEA wind Implementing Agreement Task 25 report titled *Design and Operation of Power Systems with Large Amounts of Wind Power* was to provide information to facilitate the highest economically feasible wind energy penetration within power systems by analyzing and further developing the methodology to assess the impact of wind power and producing information about the range of impacts and best practices to assess the impacts. The task also reports on evolving experience with wind integration. Fifteen countries participated in the task and contributed information from country-based case studies to inform the task. Some central results are presented below (Holtinnen et al. 2009):

- Inertial response and frequency control (timescale of seconds) are not critical problems when integrating wind power into large systems, but they can be a challenge for small systems and may become so in the future for large systems with high penetration levels.
- The variability of wind power poses a significant challenge within the 1- to 6-hour time frame of system operation. The impact of wind power is mostly experienced in the 10-minute to several hours timescale and very little in the second-to-second automatic frequency control timescale.
- Increases in short-term reserve requirements exhibit a large range, and they are somewhat dependent upon the system being studied: 1% to 15% of installed wind power capacity at 10% penetration (of gross demand) and 4% to 18% of installed wind power capacity at 20% penetration.

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[7] In this study, as is common in all integration studies conducted by GE Energy, the capital and operating costs of wind power were not included in the operating costs. Thus, the cost savings presented represent an estimate of the per-MWh cost of wind energy that would result in no change in system operating costs compared to the no-wind scenario.

- The increase in reserve requirements does not necessarily imply new investment: the amount of wind-caused reserves is highest at times when wind power production is high, thus other power stations are operated at a low level and may be able to supply reserves.
- For wind penetrations of up to 20% of gross energy demand, the increase in system operating cost because of wind variability and uncertainty ranged from 1 €/MWh to 4 €/MWh ($1.30/MWh to $5.20/MWh) of wind energy, as presented in Figure 6. This equates to 10% or less of the wholesale value of the wind energy.
- Wind generation provides some reliable system generation capacity, between 5% and 40% for the case studies considered. Aggregating wind and load throughout larger areas tends to increase the capacity credit of wind power. Calculating the system capacity should be conducted using the most rigorous methodology available.
- For wind penetration levels of 10% to 20 % of gross electrical energy demand, the cost-effectiveness of building new electricity storage is still low, with the exception of hydropower with large reservoirs or pumped hydropower.

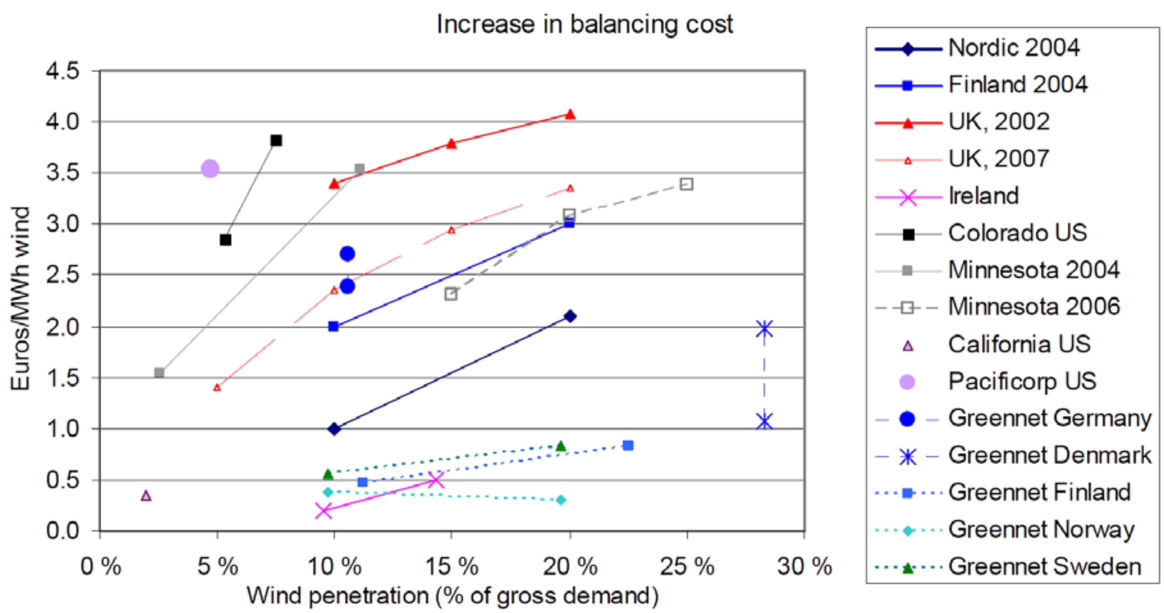

Figure 6. Estimates for the increase in system balancing and operating costs because of wind power as reported from IEA Task 25. Currency conversion was 1€ = 0.7 £ and 1€ = $U.S. 1.3 (Holtinnen et al. 2009).

2.4.7 REF

With all previously summarized wind power studies indicating that up to 30% of the electrical energy demand in the various study footprints could be served by wind energy, the logical question that follows is what is the limit of wind energy penetration that could be used to serve system load? The aim of REF was to characterize U.S. electricity grid operations in 2050 with much higher levels of renewable generation (NREL 2012). There were two central themes to the study: (1) employ the NREL Regional Energy Deployment System (ReEDS) model to assess the adequacy of geographically diverse U.S. renewable resources to meet electricity demand in future decades; and (2) investigate hourly operation of the U.S. grid with high levels of variable photovoltaics and wind generation using the production-cost model GridView. The Regional Energy Deployment System was employed to provide estimates of the type and location of conventional and renewable resource development; the transmission expansion required to enable the development of those resources; and the composition and location of generation, storage, and demand-side technologies needed to balance supply and demand. GridView was used to model the hourly operation of the power system in 2050 to provide a more detailed exploration of the operational impacts of a system with high levels of renewable electricity penetration. Key results of the study are provided below:

- Renewable energy resources, accessed with commercially available renewable generation technologies, could adequately supply 80% (with nearly 50% from variable wind and solar photovoltaic generation) of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level. Figure 7 presents estimated 2050 capacity, by technology, for scenarios with increasing levels of renewable energy penetration. Annual renewable capacity additions required to enable high penetrations of renewable electricity are feasible and consistent with current global production capacities for the technologies considered.
- Managing low-demand periods and curtailment of excess electricity generation will challenge power system planning and operation in the high renewable energy cases. More system flexibility, via supply- and demand-side options and market arrangements, will be needed to accommodate increasing levels of renewable generation.
- As renewable energy penetration increases, the use of storage was found to be a valuable option to increase electric system flexibility because of the ability of storage to shift load to better correlate to output from variable generators, reduce curtailments by storing excess generation in times of low demand, and provide firm capacity for a variety of reserve services.
- High renewable penetration requires additional transmission infrastructure to deliver electricity generated from cost-effective remote renewable resources to load centers and enable reserve sharing throughout greater distances.
- The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Further, high renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use.

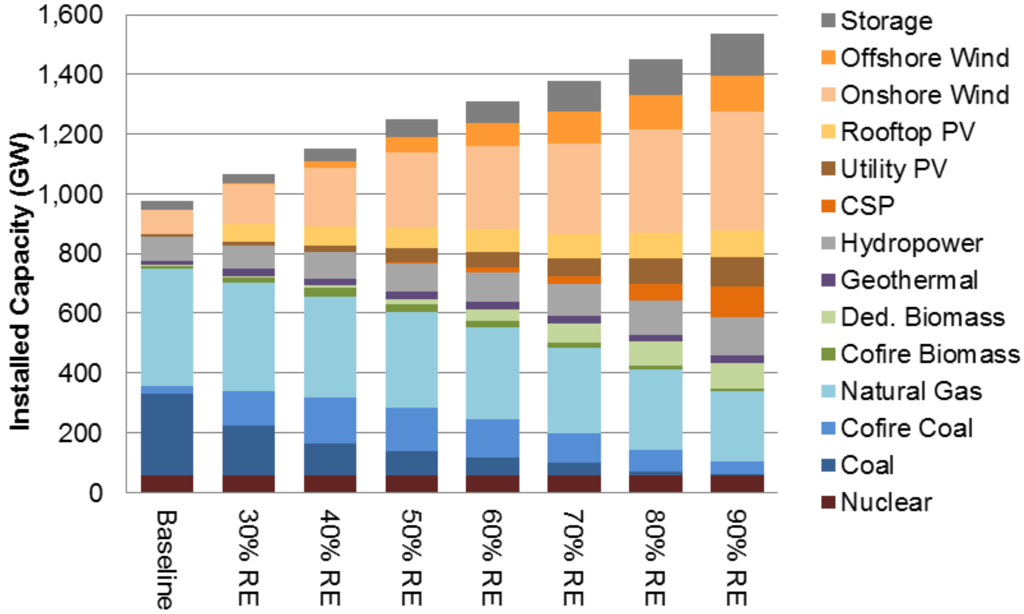

Figure 7. Illustration from the Renewable Electricity Futures Study of the installed capacity required to meet the 2050 load as the percentage of renewable electricity desired to serve the load is increased (NREL 2012)

2.5 Lessons Learned from System Integration Studies

The subset of the wind integration studies reviewed above demonstrates that even though many aspects of the electric system need to evolve substantially to deploy high levels of renewable electricity, integrating significant levels of wind energy generation, on the order of 30%, is not only technically possible, but economically feasible. How the variability and uncertainty of wind power increases the reserves required to balance the electric power system is now understood (see Ela et al. [2011] and results from selected studies in Section 2.4). Further, the magnitude of electricity production cost associated with this increase is less than 10% of the energy value of wind energy, and typically substantially less. The studies all point toward the benefit of system flexibility when incorporating wind power.[8] Wind penetrations up to 10% or 20% of the load served can often be accommodated with little or no changes to system operational practices. However, operational coordination among BAAs—especially small ones—can improve integration effectiveness. Further, at wind penetration levels in excess of 20%, it is likely that changes will be required to the standard practices of system balancing (e.g., increased frequency of scheduling and BAA coordination).

Moving forward, it will be necessary to gain a better understanding of the economic and environmental implications of potential high-renewable electricity futures, as well as the cost benefit relative to other expansions of the electric power system. An evolution of our electric

[8] The contribution to system flexibility of hydropower was not highlighted in the studies summarized here. Hydropower is an inherently flexible generation resource, and although it is often an important contributor to system flexibility and efficiency, it can be quite constrained and thus has reduced flexibility in nonobvious and often non-generalizable and system-specific ways. More details about wind integration in systems with hydropower can be found in several resources (Acker 2011a, Acker 2011b, NREL 2010b, Acker and Pete 2012).

power system will occur during the upcoming decades. If that evolution is to accommodate significant renewables, the experience gained during the past decade of incorporating wind power and studying its impacts, both positive and negative, suggest the following directions (Exeter and GE Energy 2012, Bird and Lew 2012, NERC 2011a, NERC 2011b, California Independent System Operator 2010):

- ***Learn from actual operations of BAAs that have integrated wind power.*** Collect, analyze, and archive system operational and generation data, especially during periods when large wind events occur, when the system is at high risk, or during low loads and high winds. Improve and utilize communication of wind turbine availability and production data, including turbine outage conditions and plans.
- ***Encourage geographically diverse wind resources***, and consequently "smooth" the variability of the resource to reduce the magnitude of aggregate wind forecast errors.
- ***Employ state-of-the-art wind power forecasting***, and integrate it into the day-ahead and hour-ahead commitment processes. Include the degree of uncertainty in each hour's forecast and a forecast of the expected wind variability on a subhourly basis. Use forecasts to define the ancillary service requirements, such as hour-to-hour regulation needs, and to predict wind ramps and the consequential impacts on intra-hour load-following requirements.
- ***Aggregate loads and generation into larger BAAs***, allowing for more generation resources to address net load variation and for the provision of reserves while simultaneously reducing the wind resource variability due to the smoothing effect of geographic diversity, ultimately facilitating more efficient and cost-effective operation of the electric power system. Increased BAA collaboration reduces cost overall, and it is valuable for integrating variable generation.
- ***Enhance system flexibility by increasing the frequency of commitment and dispatch intervals***, permitting the power system to be operated closer to the delivery hour of energy and including intra-day and intra-hour trading. Devise a commitment process in the 1- to 6-hour time frame to ensure sufficient unit commitment during periods when the uncertainty of wind forecasts may cause operational problems. For example, thermal units can respond to a 4-hour-ahead schedule adjustment based on revised wind and load forecasts.
- ***Enhance system flexibility by enabling the use of existing system flexibility***, including storage technologies, demand-side options, ramping of conventional generation, more flexible dispatch of conventional generators, energy curtailment, and transmission.
- ***Enhance system flexibility via market and operational mechanisms*** to improve the utilization of existing generation fleet operational flexibility, and create new categories of reserves appropriate for renewable energy resources that are, by their nature, variable and uncertain to forecast. For example, create a new, intermediate reserve, such as a non-spinning reserve with a 15-minute start-up to accommodate wind ramps, or allocate regulation and load-following reserves on an hour-to-hour basis. Each region or reserve-sharing group should permit contingency reserve deployment under imbalance energy circumstances made more likely with the increasing penetration of renewables.

- ***Enhance system flexibility through continual review of the rules and definitions of ancillary services*** to encourage and include a broad range of participants in a competitive ancillary service market. All capable technologies should be given an opportunity to participate in such a market and prove their economic value.
- ***Expand the transmission system.*** High penetrations of wind energy will require significant transmission additions that will allow remote, high-quality wind resources to reach electricity markets; enable the aggregation of BAAs and/or cooperation among BAAs—for example, in reserve sharing and intra-BAA trading; and facilitate a larger spatial range for the deployment of renewable generation, and thus allow for more geographic diversity and less resource variability.
- ***Improve understanding of the institutional challenges associated with integrating high levels of renewable electricity***, including the development of market mechanisms that enable the emergence of flexible technology solutions and mitigate market risks for a range of stakeholders, including project developers.
- ***Ensure that long-term generation planning and expansion are appropriately valued for flexible resources and their contribution to system capacity and balancing***. For example, integrating high penetrations of wind energy leads to low system spot prices and decreased use of gas combined-cycle generation. Markets must be devised to send proper price signals that encourage the development of flexible generation resources that will not occur in the existing energy markets.
- ***Establish the organizational and market mechanisms to account for the appropriate contribution to planning and operating reserves*** from conventional generators, dispatchable renewable generators, storage, and demand-side technologies. Additional flexible resources such as demand response, plug-in hybrid electric vehicles, and storage capacity may help balance the steep ramps associated with variable generation.
- ***Perform cost-benefit analyses designed to better understand the economic and environmental implications of alternative concepts for electric power system evolution and expansion***. Studies of integrating high penetrations of wind and renewable energy should include comprehensive comparisons of reliability, economic, and environmental impacts and influences to other alternative expansion scenarios.

The availability of flexible generation/load resources and flexible institutional practices and market mechanisms is not uniform throughout the United States. Figure 8 shows a simplified example of how flexibility characteristics are influenced by the structure of the local power grid. The numbers shown in cells shaded with green, yellow, or red indicate the ease of integration—green and higher numbers indicate greater ease, yellow cells indicate intermediate ease, and red cells and low numbers indicate more difficulty and cost. For instance, the most effective characteristics to facilitate reliable wind integration are shown in the figure; these include increasing the BAA size and implementing subhourly energy markets. Although the metrics used in the figure are somewhat basic, they are accurate illustrations of the power system properties that have a significant influence on the ease, or difficulty, of integrating wind energy into the bulk power system.

Accommodating Wind and Solar Integration

Example Utility Structures	Large BA	Geographically Dispersed Wind and Solar	Wind/Solar Forecasting Effectively Integrated Into System Operations	Sub-Hourly Energy Markets	Fast Access to Neighboring Markets	NonSpinning and 30 Minute Reserves for Wind/Solar Event Response	Regional Transmission Planning For Economics and Reliability	Robust Electrical Grid	More Flexible Transmission Service	Flexibility in Generation	Responsive Load	Overall
Large RTO with spot markets	10	8	7	10	7	2	7	6	7	7	3	7
Smaller ISO	6	6	6	3	3	2	6	4	7	2	2	4
Interior west & upper Midwest (non-MISO)	1	3	2	1	2	1	2	3	2	2	2	2
Large vertically integrated utility	7	6	6	2	2	2	5	4	2	5	2	4
Smaller Vertically Integrated Local Utility	1	3	2	1	2	1	2	4	2	2	2	2
Unconstrained hydro system										8		
Heavily fish constrained hydro system										3		
Weightings Factors	1	1	1	1	1	1	1	1	1	1	1	11

Figure 8. Characteristics that help integrate wind energy, adapted from Milligan et al. (2009)

3 Lessons Learned from Operating Practice

There is now significant operating experience with wind energy from growing levels of wind development not only in the United States but around the world. European countries lead the world both with the share of total energy generation from wind and instantaneous wind production. As shown in Figure 9 (Wiser et al. 2013), Denmark and Portugal receive approximately 28% and 19%, respectively, of their annual energy from wind. Spain and Ireland are not far behind, and these countries are still experiencing growth in wind energy development. With regard to instantaneous wind energy penetrations, Portugal has reached as high as 93% at one point in time,[9] Spain has tied Xcel's Colorado record of 60.5%,[10] and Ireland has regularly reached 50%. Ireland has limited its wind penetration to this level until further study confirms that a higher wind penetration will not undermine system inertia and frequency response and pose a reliability concern on this relatively small island system.

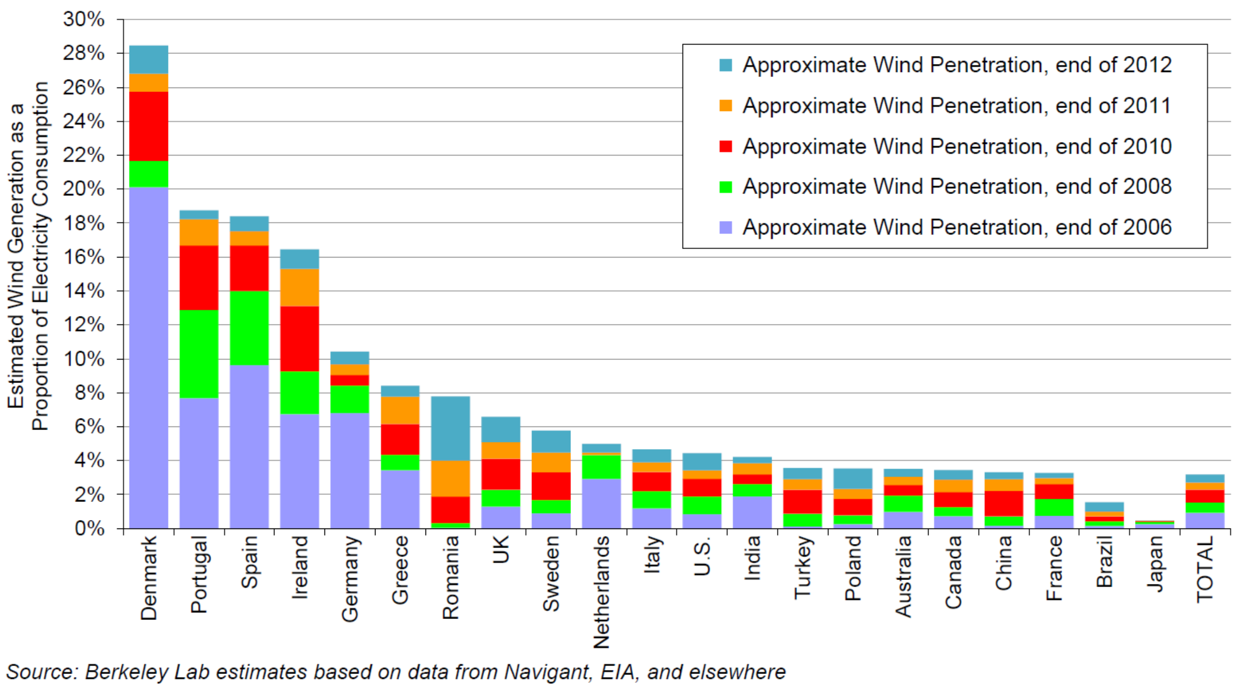

Figure 9. Wind energy penetration levels as a share of total electricity demand by country (Wiser et al. 2013)

In the United States, wind energy contributes to a much smaller share of annual energy needs—slightly more than 4%. However, as previously mentioned, there are areas of the country that have experienced high instantaneous penetrations. Two states—South Dakota and Iowa—generate more than 20% of their annual electricity demand from wind energy. Note that all of that wind energy is not necessarily consumed in the host state because of the nature of the interconnected power system. As shown in Figure 10, Public Service Company of Colorado, a

[9] See http://novasenergias.org/energia-eolica/portugal-bateu-recorde-de-producao-de-energia-eolica/.

[10] See http://www.bloomberg.com/news/2012-04-16/spanish-wind-power-reaches-record-as-north-suffers-weather-alert.html.

subsidiary of Xcel Energy, achieved a 60% instantaneous penetration in 2013, other areas have experienced values ranging from 6.9% in PJM to nearly 40% in several areas including ERCOT, which is similar to an island system because it is not synchronous with the rest of the United States.

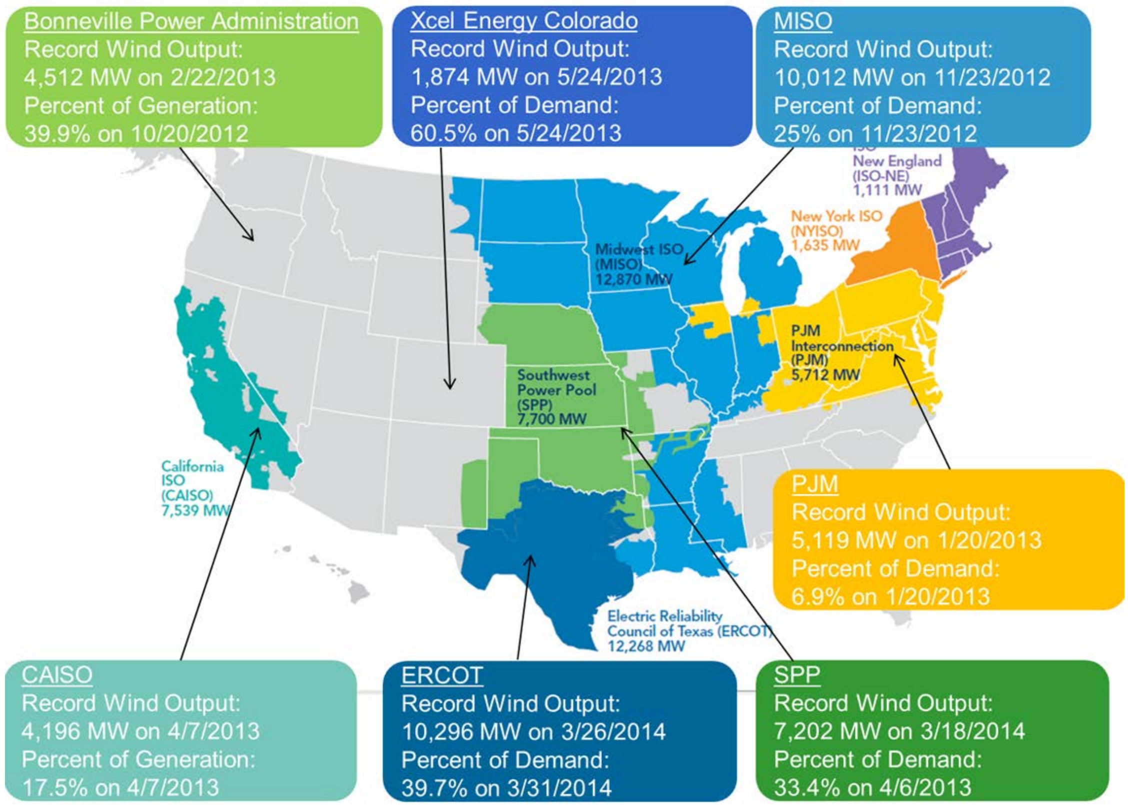

Figure 10. Instantaneous wind penetration records for U.S. grid operating areas shown overlaid on a map of currently installed wind capacity by independent system operator ("Wind Generation Records & Turbine Productivity" 2014)

Much experience has been gained from these growing wind levels. The IEA Task 25 is one source of such aggregated knowledge. As previously mentioned, this task provides a forum for researchers in wind energy integration from the 15 member countries to compare research methods and results as well as lessons learned regarding best practices. As a result, various IEA Task 25 reports document a combination of study results, actual operating experiences, actual impacts, and best practices for performing integration analyses.[11] This framework, coupled with the accumulating experience with wind power in the power system, provides an effective iteration between operating practices that inform the next round of integration studies and the studies that suggest new approaches to effectively integrate wind energy.

Operating experiences, such as those summarized by the IEA Task 25, have largely confirmed the findings of wind integration studies that (1) large amounts of wind energy can be reliably

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[11] See www.iea.org/task_25.html.

integrated at low cost, and (2) efficient grid operating procedures—such as large or coordinated BAAs, fast-interval generation scheduling and dispatch, setting wind generator schedules as close as possible to the dispatch time to minimize persistence forecast errors, and using wind energy forecasting—can greatly facilitate wind integration and reduce costs. This section highlights the lessons learned from the grid operators' experiences with integrating large amounts of wind energy.

3.1 Wind Integration Reserve Needs and Costs Based on Operating Experiences

Some grid operators now have enough wind energy on their power system that they are able to empirically determine the impact wind energy has had on their need for operating reserves. Data shows that for modest wind penetration levels, the increase in reserve requirements and associated costs due to additional wind are small. For example, ERCOT has calculated that the incremental regulating reserve needs are very modest for approximately 10,000 MW of wind (corresponding to approximately 11% of ERCOT's energy needs) on its system (Maggio 2012). When assigned a dollar value, these reserve needs account for an additional cost of approximately $0.50/MWh of wind (Ahlstrom 2013), or approximately $0.06 per month on a typical Texas household's $140 monthly electric bill.[12] Similarly, Midcontinent Independent System Operator has described the impact of more than 10,000 MW of wind generation on its regulation reserve needs as "little to none" (Navid 2012, Ruud 2014). This small increase in reserve requirements is consistent with the findings of grid integration studies.

3.2 Value of Efficient Operating Practices

ERCOT and Midcontinent Independent System Operator have been able to integrate large amounts of wind with minimal increases in reserve needs because they use efficient grid operating procedures. Of particular importance is that both ERCOT and Midcontinent Independent System Operator operate day-ahead and real-time energy markets with 5-minute energy markets, and they incorporate wind energy into power system dispatch by setting wind's output schedule based on the wind output level 10 minutes before real time. The energy markets are able to effectively react to and compensate for the aggregate wind and load variability and uncertainty. Conversely, in much of the western United States, because of inefficient operating practices, it is typical to utilize hourly energy schedules and to set the wind schedule an hour or more before the operating hour, during which time wind output can change significantly, unnecessarily increasing reserve needs and costs.

Additionally, ERCOT, Midcontinent Independent System Operator, and other areas benefit from large grid operating areas. This reduces wind energy's variability through the geographic diversity of wind energy's output and greater diversity with other sources of variability, and it provides access to a larger pool of flexible resources (Milligan, Kirby, and Beuning 2010). Centralized energy markets with fast generator dispatch and robust ancillary services markets also make these power systems more flexible (Milligan et al. 2009). Efforts to establish an energy imbalance market in the western United States would provide many of these benefits

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[12] Based on a calculated wind integration cost of $0.50/MWh of wind energy, which equals $.046/MWh of total load served in ERCOT at 9.2% wind energy use, multiplied by the 1.262 MWh used per month by the average Texas household. See http://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf.

(King et al. 2012). Wind energy forecasting is now widely used in areas with significant amounts of wind energy, and is also a critical tool for efficiently integrating large amounts of wind energy (NERC 2010a).

Figure 11 shows how faster energy scheduling and close coordination throughout larger geographic areas could reduce regulation requirements and wind integration costs in the Western Interconnection. Although the study investigated 10-minute energy scheduling, 5-minute scheduling, as implemented in BAAs that serve two-thirds of the U.S. load, would further reduce costs.

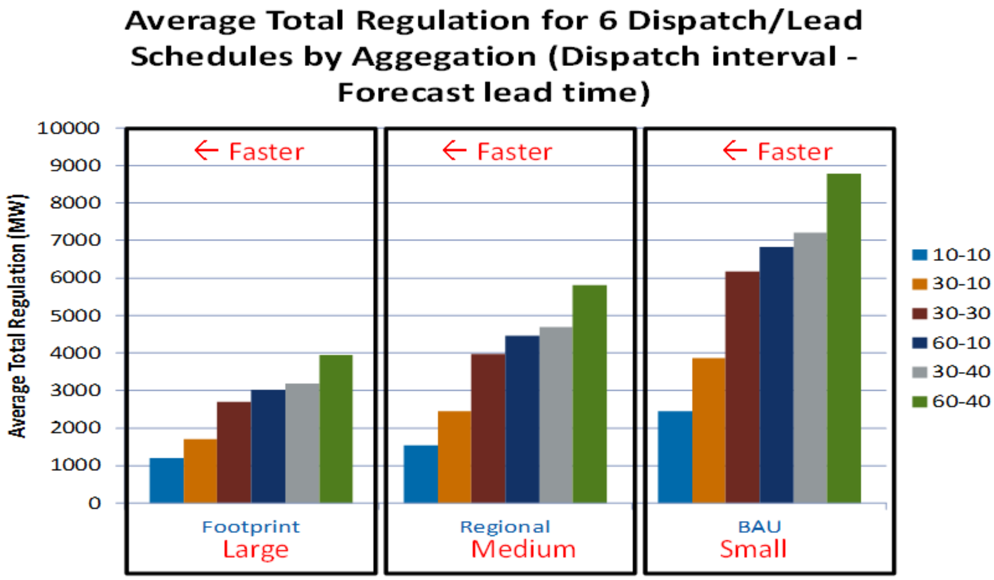


Figure 11 Faster energy scheduling and larger BAAs greatly reduce regulation requirements and wind integration impacts (Milligan et al. 2011).

3.3 Wind Power Forecasting

Wind forecasting is important for reducing the uncertainty of power delivery from wind power plants in all time frames. Forecasts are particularly important in the day-ahead, hours-ahead, and minutes-ahead time frames for scheduling wind energy into power systems and markets. Wind forecasting is also becoming a critical part of system flexibility discussions, because the variability, ramping, and uncertainty of wind output contribute to the need for overall system flexibility.

Wind energy is often criticized as being "too unpredictable," which implies that the error rates for wind forecasts are much higher than those for other aspects of the power system, such as load and conventional generators. A key breakthrough for integrating wind into most North American markets has been the realization that wind is actually very predictable in the dispatch time frame. When wind is dispatched, wind power plants are able to follow the dispatch signal at least as well as conventional units.

To appreciate that wind can be accurately (and easily) predicted for the next few minutes, consider the shape of the wind forecast error curve in Figure 12. The figure shows the mean absolute error of the wind power forecast for a modest-size power system. Forecast errors would be higher for a single wind power plant, and they could be lower for a larger power system with more geographically dispersed wind power plants, but the distinctive shape of the error curve would remain largely the same.

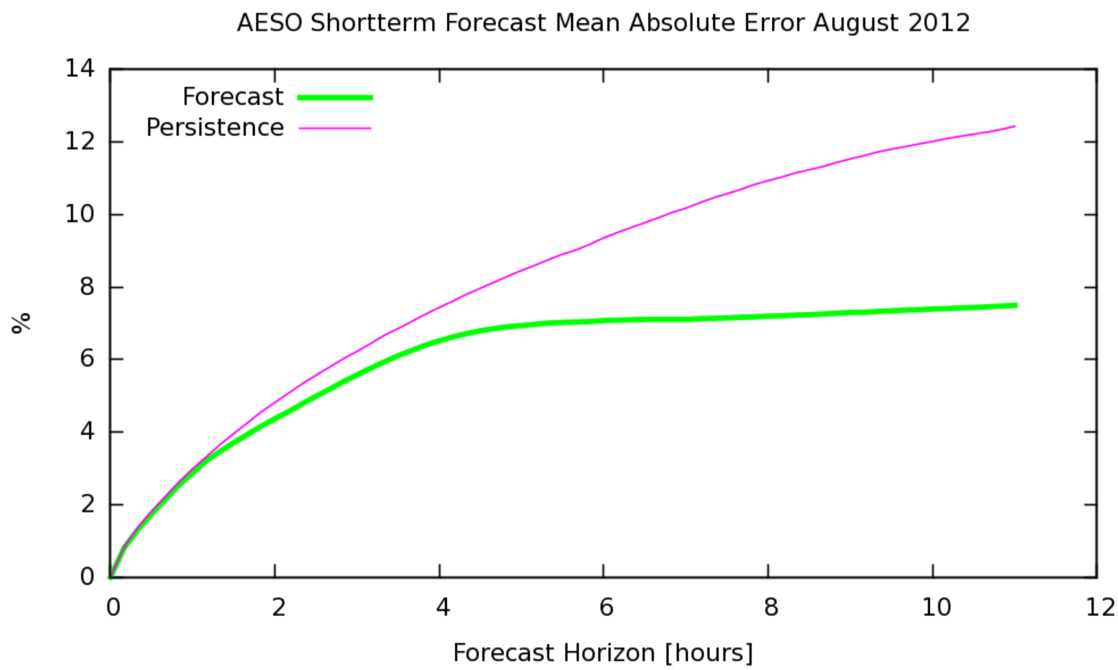


Figure 12. Plot showing system-wide wind forecast error compared to forecast time horizon, with error expressed as mean absolute error as a percentage of installed wind capacity. *Figure courtesy of Alberta Electric System Operator*

Figure 12 shows lines for both a persistence forecast and a wind power forecast based on state-of-the-art wind power prediction models. A persistence forecast simply uses the power output value for some recent period at time zero (for example, the most recent telemetered value or the average for the last 10 minutes) as the expected forecast value for all future times. This works very well in the near term, because wind power plant outputs do not typically change very quickly—especially when smoothed by the geographic size and mass of a large wind power plant.

The key point is that a simple persistence forecast is highly accurate for predicting the wind power output for the next few minutes. The major market systems that are dispatching wind in their systems using a forecast that is within 10 minutes of flow (Midcontinent Independent System Operator, ERCOT, New York Independent System Operator, and others) are able to dispatch wind with an accuracy that is comparable to that of load and conventional generators.

The initial portion of the persistence forecast error curve is very steep, as shown in Figure 12, so the forecast error for a period that is farther in the future will be many times higher than the error for 0 minutes to 10 minutes in the future. More advanced forecasts of energy production based on weather models are more accurate than persistence forecasts beyond a few hours. A more advanced forecast can also predict ramps and other dynamic changes in overall wind energy output.

Arguably, the biggest and most beneficial change since the earlier *20% Wind Energy by 2030* report is the considerable progress made in integrating wind energy into markets and systems in ways that allow wind to be a source of flexibility. Wind forecasts become more useful and valuable to wind power plant operators, market participants, and system operators as wind is more engaged in such systems and markets.

Most North American power markets now integrate wind energy into their security-constrained unit commitment and security-constrained economic dispatch[13] processes or real-time re-dispatch processes, allowing wind power plants and conventional power plants to be dispatched based on current grid conditions and economic offers. This effectively incorporates wind into the real-time optimization process for running the power system and, in turn, encourages wind power plants to fully participate in the day-ahead markets. Security-constrained economic dispatch also makes wind dispatchable and economical, providing wind power plants with on-demand ramping and thus the system operator with more flexibility. Improving wind forecast accuracy allows for greater and more efficient integration of wind into these security-constrained unit commitment and security-constrained economic dispatch processes.

Unit commitment and dispatch is a rolling optimization process of matching the generation to the expected demand. In the day-ahead (or even several-days-ahead) market, the unit commitment process can schedule slower-starting units such as large coal-powered plants. Within the day, the unit commitment process may add or change faster-starting units, but it is constrained by some of the decisions that were made earlier. In real time, the dispatch process instructs each generator to provide a specific amount of power for the real-time period. In many systems, the unit commitment and dispatch logic is virtually identical, but the pool of generators that can be started will change based on the remaining time available.

The day-ahead time frame will always be important for wind forecasting. The day-ahead unit commitment process is a cornerstone for operations in essentially all power systems, and most power markets also focus on the day-ahead market for energy and ancillary services. The day-ahead time frame is typically when the overall operating plan for the next day is put in place, including the selection of large thermal plants that may take many hours to start up so that they are ready when needed. The importance of using a good wind power forecast in the day-ahead unit commitment process has been widely discussed and incorporated into most power systems, because ignoring the expected wind energy would lead to a nonoptimal plan.

Because day-ahead forecasts are of such great value, they have become an area of ongoing research and improvement. Numerous commercial forecasting vendors provide day-ahead wind forecasts, and they are constantly working to improve the quality and performance of their products. The intra-day and multi-day weather forecast products from the National Oceanic and Atmospheric Administration and other sources are a critical input to the commercial wind power forecasts, so improvements to these foundational forecasts are benefiting the entire wind

[13] Unit commitment is the process of starting and synchronizing power plants to the grid. Economic dispatch is the process of altering the output of one or more generators on an economic basis.

community. The National Oceanic and Atmospheric Administration made significant improvements in the last five years to both multi-day and intra-day weather forecasts.

To make the most-informed decisions, power system operators benefit from knowing the degree of certainty associated with each forecast. One method of quantifying certainty of a forecast is to run multiple weather model configurations simultaneously; this is called an ensemble forecast. The degrees to which the model outputs in such an ensemble differ from one another is one indication of the uncertainty in the forecast. Generally, the greater the differences among various model outputs, the greater the uncertainty in the forecast. Decision makers, including utilities and power grid operators, need better information about forecast uncertainty.

4 Industry Organizations Are Addressing Integration Issues

A necessary, but not sufficient, condition to reliably integrate increasing amounts of wind generation into the power system is engagement by the overall industry. Institutional efforts to help tackle wind integration challenges and develop best planning and operating practices are underway at NERC, the Federal Energy Regulatory Commission, DOE, and others.

4.1 NERC

Anticipating substantial growth of variable generation, NERC's planning and operating committees created the IVGTF to undertake a three-phase approach to assess the potential reliability impacts of wind and solar generation on the electric power system and to recommend actions for NERC to implement.[14] The IVGTF is designed to be an ongoing process that incorporates feedback from continued operating experiences and advances in equipment and analysis tools. NERC utilized technical experts from throughout the electric power industry to develop broad-based consensus documents as work products from this effort.

In the first phase, NERC prepared a special report on *Accommodating High Levels of Variable Generation* (2009). In addition to defining various technical considerations for integrating high levels of variable generation, the report identified a work plan of follow-on tasks to investigate potential mitigating actions, practices, and requirements needed to ensure bulk system reliability.

The second phase of the IVGTF effort established 12 drafting groups, based on the follow-on tasks from the first phase, to address specific reliability concerns. A final report is now available for these 12 tasks, which also includes a summary of all recommendations (NERC 2014a):

- Task 1-1—Standard Models for Variable Generation
- Task 1-2—Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning
- Task 1-3—Interconnection Requirements for Variable Generation
- Task 1-4—Flexibility Requirements and Metrics for Variable Generation: Implications for Planning Studies
- Task 1-5—Potential Reliability Impacts of Emerging Flexible Resources
- Task 1-6—Probabilistic Methods
- Task 1-7—Low Voltage Ride-Through Requirements
- Task 1-8—Potential Bulk System Reliability Impacts of Distributed Resources
- Task 2-1—Variable Generation Power Forecasting for Operations

[14] See http://www.nerc.com/comm/PC/Pages/Integration%20of%20Variable%20Generation%20Task%20Force%20(IVGTF)/Integration-of-Variable-Generation-Task-Force-IVGTF.aspx.

- Task 2-2—BAA Communications
- Task 2-3—Ancillary Services and BAA Solutions to Integrating Variable Generation
- Task 2-4—Operating Practices Procedures and Tools

Findings and recommendations from these 12 reports provide a reference manual of best practices for planners, operators, regulators, developers, and investors dealing with the challenges and opportunities offered by variable generation. Specific recommendations for standards development are included. The reports also highlight areas that require further development. Some of these are technological, and others are institutional.

The task reports note that the growth of wind and solar generation is not happening in isolation. Variability and uncertainty from wind and solar generation must be considered in the context of the variability and uncertainty of load, as well as the probability of conventional generation and transmission contingencies. Tools, standards, and operating practices must address the aggregate power system to ensure reliability at least cost.

The third phase of NERC's IVGTF is developing new rules, practices, and standards requirements based on the recommendations contained in the 12 task reports.

4.2 DOE/NREL

NREL's WWSIS and Eastern Wind Integration and Transmission Study advanced wind integration analysis techniques, but they also developed and made publically available a database for others to use for their own analyses (Milligan et al. 2012a).[15] The data sets provide time series wind speed at hub height and wind power output on a 2-km grid spacing covering most of the mainland United States using 10-minute time steps for the years 2004, 2005, and 2006. Anyone can use these data sets, along with their own time-synchronized load data, to realistically model the power system in the presence of large amounts of wind generation. The user selects specific locations for proposed wind power plants to be modeled and then uses conventional security-constrained unit commitment and economic dispatch modeling to determine overall power system performance and costs under a variety of conditions. NREL is currently updating the data set for the years 2007 through 2013.

4.3 The Federal Energy Regulatory Commission

The Federal Energy Regulatory Commission's purview is the regulation of interstate energy transfers and markets and the reliability of the bulk power system. There have been many actions by the Federal Energy Regulatory Commission that spurred the development of bulk power markets, which resulted in the formation of all of the independent system operators and regional transmission organizations in the United States. Many of these were not specific to wind or other variable renewable energy sources, but they provided the framework for fundamental changes in bulk power market structures that increase the economic efficiency of operation with or without wind energy. However, in December 2005 the Federal Energy Regulatory Commission issued Order 661-A, which specified rules for low-voltage ride-through for wind turbines. Several other orders spurred more transparency in transmission service and promulgated regional transmission

[15] See http://www.nrel.gov/wind/systemsintegration/.

planning. Order 764 was issued in June 2012, which mandated that transmission operators offer 15-minute interchange scheduling, required the use of wind power forecasting, and offered the potential for cost-recovery of integration charges on a case-by-case basis if other prerequisites were met. More recently, the Federal Energy Regulatory Commission has held technical conferences to explore how to incentivize flexibility in generation and the potential need for capacity markets. Both of these issues are widely regarded as critical issues to address, and this is discussed in an IEA Task 25 paper (Milligan et al. 2012b).

4.4 Transmission Operation and Planning Organizations

Other examples of industry involvement include the various wind integration studies sponsored by independent system operators and regional transmission organizations described in Section 2.4. In addition, the Western Electricity Coordinating Council established the Variable Generation Subcommittee to help inform its membership about integration impacts and solutions. The Variable Generation Subcommittee has evolved and changed; most recently, it has been incorporated into the standing Western Electricity Coordinating Council committees on operation, market interface, and planning coordination.

4.5 Institute of Electrical and Electronics Engineers

In addition to work done by these individual government and regulatory entities, the Institute of Electrical and Electronics Engineers (IEEE) professional organization is promoting grid integration research and implementation across the interface of industry and academia. IEEE is uniquely positioned to encourage and disseminate grid integration research through its many peer-reviewed journals and conferences and to facilitate the advancement of the smart grid and associated role of variable renewables through its Standards Association. Further collaboration and consensus with industry is being accomplished through the Standard Association's Industry Connections Program, which includes multiple energy-specific groups, such as the Smart Energy Data Repository.

In response to the growing interest in and body of science produced by wind integration research, IEEE has carved out more space for wind (and other variable renewable technologies) at conferences and in peer-reviewed journals. For example, the Power and Energy Society of the IEEE has sponsored several wind energy "super sessions" at the annual General Meetings. On alternating years, the November/December issue of *Power and Energy Magazine* is devoted to wind integration issues; for example, the 2013 issue was the fifth such issue. In addition, the Wind Power Coordinating Committee of the IEEE Power and Energy Society was chartered in 2009 and later expanded to include solar power. The large and increasing number of grid integration research papers is reflected by the addition of many new energy-related journal publications, including the *IEEE Transactions on Sustainable Energy*, which was launched in 2010 and is devoted to wind power and other renewable technologies.

5 Transmission Expansion

Depending on its location and other factors, wind energy may require new transmission. In some regions, such as the Columbia Gorge in the Pacific Northwest, a significant amount of wind power may be located close to existing transmission. It is possible that in some case, locating wind power plants close to existing transmission instead of building new transmission to a remote location may result in less energetic wind power plant performance. This involves an implicit trade-off between the economics of building new transmission to access higher-quality wind resources and avoiding the cost of transmission to develop in less windy locations.

Designing and building the transmission network does not present any technical difficulty per se; however, siting and allocating the costs of transmission are both contentious topics (with or without wind), and there is currently a limited framework to resolve these issues. Radial transmission expansion does not generally pose the level of cost-allocation disagreements as a network addition would; however, network additions can provide a way to deliver wind energy (or another source) to the load centers and can often provide additional reliability or even economic benefits that are difficult to quantify and allocate.

Transmission lines can take five to seven years to develop. Much of the development time is absorbed by efforts to resolve cost-allocation and siting issues. Wind power plants can generally be developed in much less time; therefore, there is a timing misalignment if a new wind power plant needs additional transmission that may not be available for several years. Despite this timing challenge, data from NERC indicates that recently there has been an increase in transmission relative to 1990–2005, as shown in Figure 13.

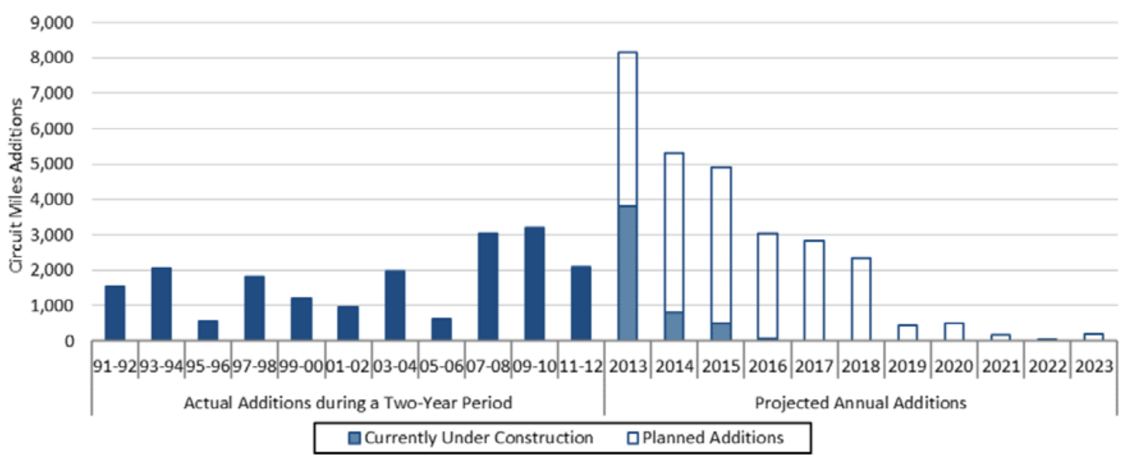
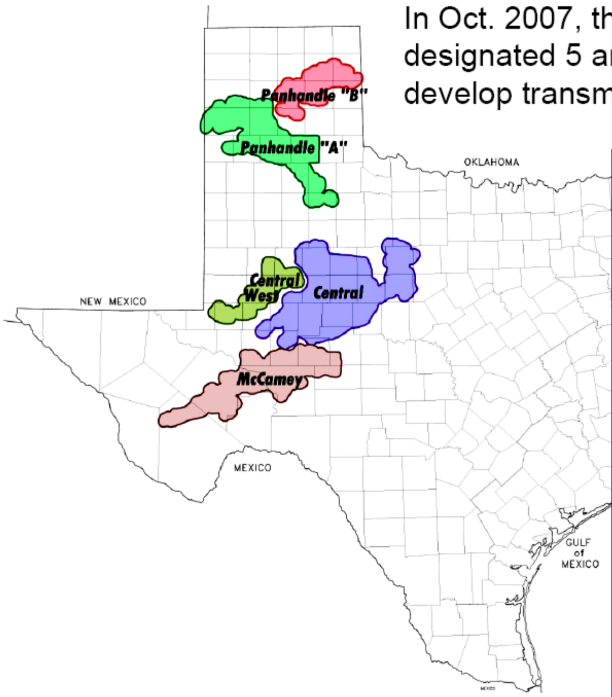


Figure 13. U.S. transmission historical actual circuit-miles of transmission additions and projected annual additions, showing an increase in installations placed in service in recent years (NERC 2013)

There have been efforts to provide solutions to this so-called “chicken and egg” problem. In Texas, for example, the Public Utility Commission of Texas issued an interim order that designed five areas as competitive renewable energy zones and requested that ERCOT develop transmission plans for four levels of installed wind capacity. For example, Figure 14 illustrates that the wind power plant locations in West Texas are relatively far from the major load pockets of Houston and Dallas. The unique feature of the competitive renewable energy zones is that, if approved by the Public Utility Commission of Texas, transmission could be built to a site prior to that site being fully developed with its ultimate level of installed capacity. Construction costs would be allowable in the rate base—which is a departure from most other regulatory requirements.

Designated Zones and Scenario Wind Levels



In Oct. 2007, the PUCT issued an Interim Order which designated 5 areas as CREZ and requested that ERCOT develop transmission plans for 4 levels of wind capacity.

Capacity of New CREZ Wind by Scenario (MW)

Wind Zone	Scen. 1	Scen. 2	Scen. 3	Scen. 4
Panhandle A	1,422	3,191	4,960	6,660
Panhandle B	1,067	2,393	3,720	0
McCamey	829	1,859	2,890	3,190
Central	1,358	3,047	4,735	5,615
Central West	474	1,063	1,651	2,051
Total*	12,053	18,456	24,859	24,419

* Assumes 6,903 MW of existing wind capacity

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Figure 14. Texas competitive renewable energy zone locations. ***Figure from ERCOT***

Other parts of the country have embarked on similar measures. One example is the Western Renewable Energy Zones project undertaken by the Western Interstate Energy Board.[16] Such processes can be challenged, however, when multiple BAAs and/or jurisdictions have competing interests. At the time of this writing, no robust, universally applicable approaches to solve the transmission issue are apparent.

[16] See www.westgov.org/wieb.

6 Summary

Since *20% Wind Energy by 2030* was published, a great deal has been learned about the impacts that wind generation can have on the power system and how to efficiently integrate wind power into the bulk power system. The United States obtains 4.2% of its annual electric energy requirement from wind; whereas Denmark obtains more than 28%, and Portugal, Spain, and Ireland all obtain more than 16% of their electric energy from wind. Two states, South Dakota and Iowa, obtain more than 20% of their electric energy from wind. Instantaneous penetrations are much higher: more than 60% for Public Service Company of Colorado, 93% for Portugal, and 50% for Ireland. This experience from integrating ever-increasing amounts of wind energy into power systems around the world is helping to develop a better understanding of the relative value provided by changing operating and market rules, augmenting the flexibility of generation and demand response, enhancing transmission, and improving the accuracy of wind energy forecasts. With a strong future likely for wind energy and other variable but partially predictable, renewable energy sources, the lessons learned from this accumulated experience will be integral to overcoming long-term reliability challenges from the continued integration of these resources.

The art and science of analyzing power systems with high penetrations of wind energy continues to improve as operating experiences enlighten and confirm study findings. Many studies are identifying methods to mitigate the impacts of integrating variable generation. No insurmountable obstacles have been found, but this does not mean that all methods for integrating wind will be successful. Increasing BAA size and implementing subhourly energy markets are the most effective means to facilitating reliable wind integration. Faster scheduling, with appropriate market rules, provides economic incentives for generators and responsive loads to offer their full flexibility to power system operators. Advanced wind turbine controls can enable the provision of synthetic inertia, governor response, and regulation to further augment power system flexibility and reduce the cost of reliably utilizing large amounts of wind generation. Additionally, depending on its location and other factors, wind energy may require new transmission. Designing and building the transmission network does not present a difficulty per se; however, siting and allocating the costs of transmission are both contentious topics (with or without wind), and there is currently a limited framework to resolve these issues.

Flexibility is the key to successfully and efficiently integrating wind. Large penetrations of wind energy will necessitate steeper ramp requirements from dispatchable generators and demand-response sources, require lower minimum generation operating levels than are required today, and increase the amount of reserves necessary to maintain reliability levels. Obtaining the needed flexibility requires both the institutional and market structures to induce the development and operation of this flexibility when needed and the physical capability of providing the needed flexibility. Understanding and providing the amount of flexibility required for system operations may be the most critical wind integration issue.

Wind forecasting is important for reducing the uncertainty of power delivery from wind power plants in all time frames. The business case for investing in better wind forecasts, however, requires a clear value proposition based on real costs and benefits in the evolving energy markets and systems. There will always be value in better wind power forecasts, but the evolution of operating practices and market rules will often have a larger initial impact, and it is important to appropriately align rules with forecasting capabilities and time horizons. As these rules further evolve to accommodate growing amounts of wind energy in logical ways, this will clarify the research and development requirements for wind power forecasting. Although there were heated discussions around the role of centralized wind forecasting only a few years ago, there is now a better appreciation for both forecasts for system operators and independent forecasts for market participants. In the end, it is not an either/or solution, but an appreciation of the merits of both. Today, most parties are becoming comfortable with making system operators' forecasts publicly available in some form, and as markets mature we are seeing the intelligent use of additional forecasts and information by market participants and scheduling centers.

The wind industry as a whole is actively engaged in understanding wind integration issues and in finding ways to reduce costs while maintaining power system reliability. Their cumulative efforts are contributing valuable analysis methods, data sets, market regulations, greater collaboration, and best practices to deal with the challenges and opportunities offered by variable generation. For example, NERC's IVGTF has provided ongoing development of best planning and operating practices for system reliability. DOE and NREL have advanced the state of the art of wind integration analysis with the eastern and western U.S. wind integration studies. They have also developed and made publically available a U.S. database of synthesized time-series wind output data. Some Federal Energy Regulatory Commission actions directly impact wind, such as Order 661-A, which specifies wind generation ride-through requirements. Other actions, such as encouraging the formation of geographically large and fast organized energy markets under independent system operators and regional transmission organizations, were not directly taken to encourage (or discourage) wind generation but indirectly lowered wind integration costs dramatically. Independent system operators and regional transmission organizations are also active in addressing wind integration issues, as are some NERC reliability councils, such as the Western Electricity Coordinating Council. IEEE is strengthening the bridge between industry and academia through more conferences, workshops, publications, and standards that support the grid integration of wind and other variable renewable sources. This industry-wide effort is a necessary but not sufficient condition to reliably integrate increasing amounts of wind generation into the power system.

The combination of actual operating experiences, the increasing advancement in production simulation modeling and methods for integration studies, and high-quality wind data sets have all helped propel the wind industry to a much greater understanding of wind energy impacts on the bulk power system. Industry engagement and innovative thinking have provided the framework for continuous improvement. All of these are necessary prerequisites for the U.S. DOE Wind Vision to be achieved.

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