EASTERN WIND INTEGRATION AND TRANSMISSION STUDY:

Executive Summary and Project Overview

Prepared for:
The National Renewable Energy Laboratory

Prepared by:
EnerNex Corporation

January 2010

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PREFACE

The Eastern Wind Integration and Transmission Study (EWITS) is the culmination of an effort that spanned two and one-half years. The study team began by modeling wind resources in a large part of the Eastern Interconnection and finished by conducting a detailed wind integration study and top-down transmission analysis. The study resulted in information that can be used to guide future work. A number of other studies have already examined similar wind integration issues, but the breadth and depth of the analysis in EWITS is unique. EWITS builds on the work of previous integration studies, which looked at considerably smaller geographic footprints, focused almost exclusively on wind integration, and did not include transmission. EWITS took the next step by expanding the study area and including conceptual transmission overlays.

Just a few years ago, 5% wind energy penetration was a lofty goal, and to some the idea of integrating 20% wind by 2024 might seem a bit optimistic. And yet, we know from the European experience—where some countries have already reached wind energy penetrations of 10% or higher in a short period of time—that change can occur rapidly and that planning for that change is critically important. Because building transmission capacity takes much longer than installing wind plants, there is a sense of urgency to studying transmission. It is already starting to limit wind growth in certain areas.

The goal of the EWITS team was not to further any specific agenda or regional vision of the future, but to be as objective as possible while conducting a technical study of future high-penetration wind scenarios. To help guide the EWITS work, the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) convened a Technical Review Committee (TRC) composed of regional electric reliability council representatives, expert reviewers, transmission planners, utility administrators, wind industry representatives, and the study subcontractor. Over a period of 14 months while the study was in progress, the TRC held 6 full-day meetings along with numerous Webinars and conference calls to review study progress; comment on study inputs, methods, and assumptions; assist with collecting data; and review drafts of the study report.

Planning for the expansion of the electrical grid is a process that requires an immense amount of study, dialogue among regional organizations, development of technical methodologies, and communication and coordination among a multitude of important stakeholders. Keeping abreast of the changes is challenging because there are so many different developments, ideas, and viewpoints. It is my hope that the EWITS results will be helpful to all those involved in the planning of the future electrical grid and form a foundation for future studies.

This document is intended as a high-level overview of the full report, which is forthcoming and will be posted at http://www. nrel.gov/ewits/ when available.

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Senior Engineer, NREL

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EXECUTIVE SUMMARY

The total installed capacity of wind generation in the United States surpassed 25 gigawatts (GW) at the end of 2008. Despite the global financial crisis, another 4.5 GW was installed in the first half of 2009. Because many states already have mandates in place for renewable energy penetration, significant growth is projected for the foreseeable future.

In July 2008, the U.S. Department of Energy (DOE) published the findings of a year-long assessment of the costs, challenges, impacts and benefits of wind generation providing 20% of the electrical energy consumed in the United States by 2030 (EERE 2008). Developed through the collaborative efforts of a wide-ranging cross section of key stakeholders, that final report (referred to here as the 20% Report) takes a broad view of the electric power and wind energy industries. The 20% Report evaluates the requirements and outcomes in the areas of technology, manufacturing, transmission and integration, environmental impacts, and markets that would be necessary for reaching the 20% by 2030 target.

The 20% Report states that although significant costs, challenges, and impacts are associated with a 20% wind scenario, substantial benefits can be shown to overcome the costs. In other key findings, the report concludes that such a scenario is unlikely to be realized with a business-as-usual approach, and that a major national commitment to clean, domestic energy sources with desirable environmental attributes would be required.

The growth of domestic wind generation over the past decade has sharpened the focus on two questions: Can the electrical grid accommodate very high amounts of wind energy without jeopardizing security or degrading reliability? And, given that the nation's current transmission infrastructure is already constraining further development of wind generation in some regions, how could significantly larger amounts of wind energy be developed? The answers to these questions could hold the keys to determining how much of a role wind generation can play in the U.S. electrical energy supply mix.

ABOUT THE STUDY

DOE commissioned the Eastern Wind Integration and Transmission Study (EWITS) through its National Renewable Energy Laboratory (NREL). The investigation, which began in 2007, was the first of its kind in terms of scope, scale, and process. The study was designed to answer questions posed by a variety of stakeholders about a range of important and contemporary technical issues related to a 20% wind scenario for the large portion of the electric load (demand for energy) that resides in the Eastern Interconnection (Figure 1). The Eastern Interconnection is one of the three synchronous grids covering the lower 48 U.S. states. It extends roughly from the western borders of the Plains states through to the Atlantic coast, excluding most of the state of Texas.

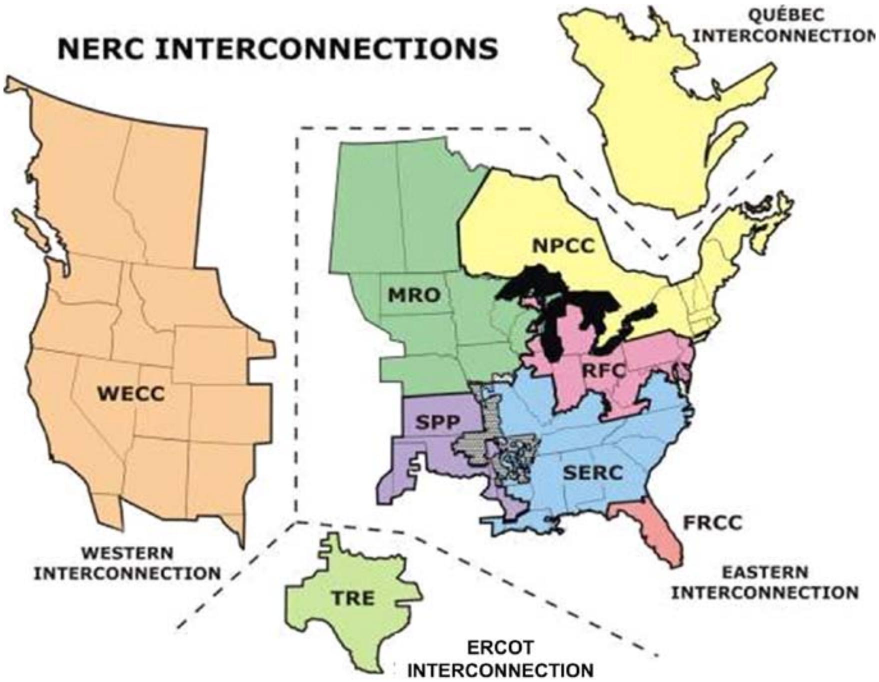


Figure 1. NERC synchronous interconnections

Notes: NERC = North American Electric Reliability Corporation; WECC = Western Electricity Coordinating Council; TRE = Texas Regional Entity; ERCOT = Electric Reliability Council of Texas; MRO = Midwest Reliability Organization; SPP = Southwest Power Pool; NPCC = Northeast Power Coordinating Council; RFC = ReliabilityFirst Corporation; SERC = Southeastern Electric Reliability Council; FRCC = Florida Reliability Coordinating Council

EWITS is one of three current studies designed to model and analyze wind penetrations on a large scale. The Western Wind and Solar Integration Study (WWSIS), also sponsored by DOE/NREL, is examining the planning and operational implications of adding up to 35% wind and solar energy penetration to the WestConnect footprint in the WECC. The European Wind Integration Study (EWIS) is an initiative established by the European associations of transmission system operators in collaboration with the European Commission. EWIS is aimed at developing common solutions to wind integration challenges in Europe and at identifying arrangements that will make best use of the pan-European transmission network, allowing the benefits of wind generation to be delivered across Europe.

EWITS was the first of its kind in terms of scope, scale, and process. Initiated in 2007, the study was designed to examine the operational impact of up to 20% to 30% wind energy penetration on the bulk power system in the Eastern Interconnection of the United States.

SCENARIO DEVELOPMENT AND ANALYSIS

To set an appropriate backdrop for addressing the key study questions, the EWITS project team—with input from a wide range of project stakeholders including the Technical Review Committee (TRC)—carefully constructed four high-penetration scenarios to represent different wind generation development possibilities in the Eastern Interconnection. Three of these scenarios delivered wind energy equivalent to 20% of the projected annual electrical energy requirements in 2024; the fourth scenario increased the amount of wind energy to 30%.

In each scenario, individual wind plants from the Eastern Wind Data Study database (see sidebar) were selected to reach the target energy level. The wind data consisted of hourly and 10-minute wind plant data for each of three years: 2004, 2005, and 2006. Wind plants were available in all geographic locations within the Eastern Interconnection except off the shore of the southeastern United States and Canada (because of limitations on the scope of work for the wind modeling). Approximately 4 GW of new Canadian renewable generation was modeled to cover imports of new Canadian wind and hydro to the northeast.

The Eastern Wind Data Study

A precursor to EWITS known as the Eastern Wind Data Study (AWS Truewind 2009) identified more than 700 GW of potential future wind plant sites for the eastern United States. All the major analytical elements of EWITS relied on the time series wind generation production data synthesized in this earlier effort. The data cover three historical years—2004, 2005, and 2006—at high spatial (2-kilometer [km]) and temporal (10-minute) resolution. On- and offshore resources are included, along with wind resources for all states.

A brief description of each scenario follows:

- **Scenario 1, 20% penetration –** High Capacity Factor, Onshore: Utilizes high-quality wind resources in the Great Plains, with other development in the eastern United States where good wind resources exist.
- **Scenario 2, 20% penetration –** Hybrid with Offshore: Some wind generation in the Great Plains is moved east. Some East Coast offshore development is included.
- **Scenario 3, 20% penetration –** Local with Aggressive Offshore: More wind generation is moved east toward load centers, necessitating broader use of offshore resources. The offshore wind assumptions represent an uppermost limit of what could be developed by 2024 under an aggressive technology-push scenario.

- **Scenario 4, 30% penetration –** Aggressive On- and Offshore: Meeting the 30% energy penetration level uses a substantial amount of the higher quality wind resource in the NREL database. A large amount of offshore generation is needed to reach the target energy level.

The study team also developed a **Reference Scenario** to approximate the current state of wind development plus some expected level of near-term development guided by interconnection queues and state renewable portfolio standards (RPS). This scenario totaled about 6% of the total 2024 projected load requirements for the U.S. portion of the Eastern Interconnection.

What Are ISOs and RTOs?

In the mid-1990s, independent system operators (ISOs) and regional transmission operators (RTOs) began forming to support the introduction of competition in wholesale power markets. Today, two-thirds of the population of the United States and more than one-half of the population of Canada obtain their electricity from transmission systems and organized wholesale electricity markets run by ISOs or RTOs. These entities ensure that the wholesale power markets in their regions operate efficiently, treat all market participants fairly, give all transmission customers open access to the regional electric transmission system, and support the reliability of the bulk power system.

Source: Adapted from IRC (2009).

Figure 2 depicts the installed capacity by regional entity (either independent system operators [ISOs] or regional transmission operators [RTOs]; see sidebar) for each of the wind generation scenarios in EWITS. Table 1 shows the contribution of total and offshore wind to the scenarios.

Supplying 20% of the electric energy requirements of the U.S. portion of the Eastern Interconnection would call for approximately 225,000 megawatts (MW) of wind generation capacity, which is about a tenfold increase above today's levels. To reach 30% energy from wind, the installed capacity would have to rise to 330,000 MW.

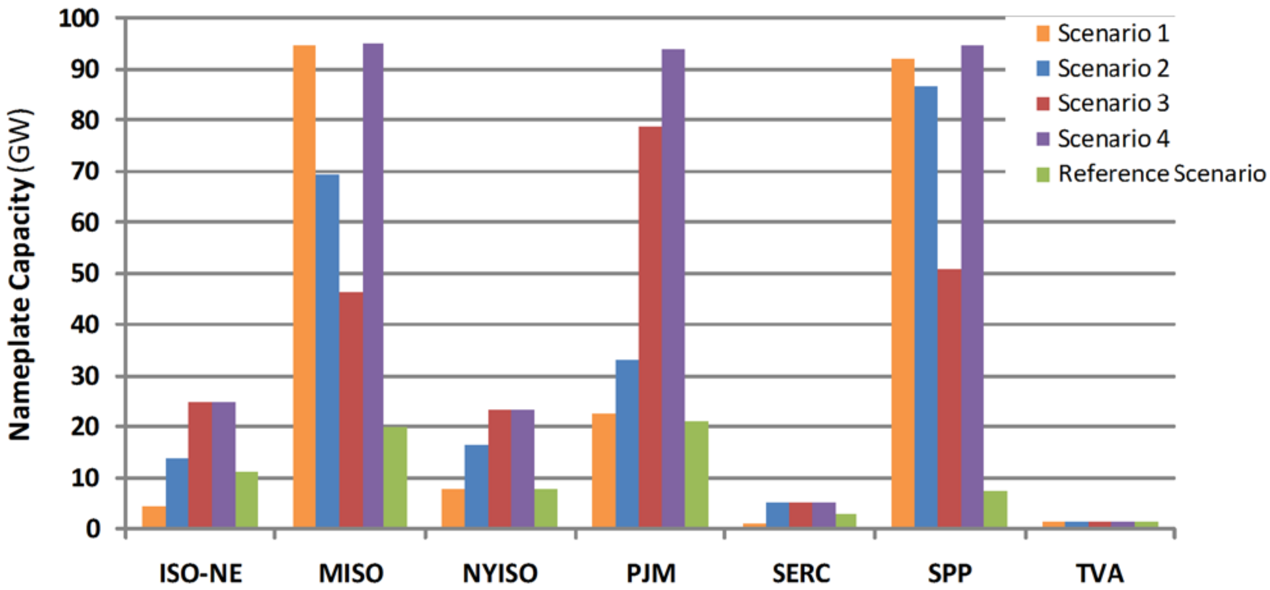


Figure 2. Summary of installed wind generation capacity by operating region for each scenario *(Notes: ISO-NE = New England Independent System Operator, MISO = Midwest ISO, NYISO = New York ISO, PJM = PJM Interconnection, SERC = Southeastern Electric Reliability Council, SPP = Southwest Power Pool, TVA – Tennessee Valley Authority)*

TABLE 1. TOTAL AND OFFSHORE WIND IN THE SCENARIOS

Region	Scenario 1 20% High Capacity Factor, Onshore		Scenario 2 20% Hybrid with Offshore		Scenario 3 20% Local, Aggressive Offshore		Scenario 4 30% Aggressive On- and Offshore	
	TOTAL (MW)	Offshore (MW)	Total (MW)	Offshore (MW)	Total (MW)	Offshore (MW)	Total (MW)	Offshore (MW)
MISO/ MAPP[a]	94,808		69,444		46,255		95,046	
SPP	91,843		86,666		50,958		94,576	
TVA	1,247		1,247		1,247		1,247	
SERC	1,009		5,009	4,000	5,009	4,000	5,009	4,000
PJM	22,669		33,192	5,000	78,736	39,780	93,736	54,780
NYISO	7,742		16,507	2,620	23,167	9,280	23,167	9.280
ISO-NE	4,291		13,837	5,000	24,927	11,040	24,927	11,040
TOTAL	**223,609**	**0**	**225,902**	**16,620**	**230,299**	**64,100**	**337,708**	**79,100**

[a] *MAPP stands for Mid-Continent Area Power Pool.*

KEY STUDY FINDINGS

The EWITS technical work yielded detailed quantitative information on

- Wind generation required to produce 20% of the projected electrical energy demand over the U.S. portion of the Eastern Interconnection in 2024
- Transmission concepts for delivering energy economically for each scenario (new transmission for each scenario is based on economic performance for the conditions outlined in that scenario)
- Economic sensitivity simulations of the hourly operation of the power system defined by a wind generation forecast scenario and the associated transmission overlay
- The contribution made by wind generation to resource adequacy and planning capacity margin.

The specific numeric results of the analysis are sensitive to the many assumptions that were required to define the 2024 study year. The study assumptions were developed in close coordination with the TRC. Changes in the assumptions, such as the cost of various fuels, the impact of regulation and policy, or the costs associated with new construction, would have a major influence. Other assumptions, such as the electrical energy demand and its characteristics—penetration and capabilities of demand response, influence of smart grid technologies, or the very nature of the load itself (as in an aggressive plug-in hybrid electric vehicle [PHEV] scenario)—would be likely to have a measurable impact on the results.

In general, though, the study shows the following:

- 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 the future wind scenarios in the Eastern Interconnection, including the Reference Case. Planning for this transmission, then, is imperative because it takes longer to build new transmission capacity than it does to build new wind plants.
- Without transmission enhancements, substantial curtailment (shutting down) of wind generation would be required for all 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.
- Transmission helps reduce the impacts of the variability of the wind, which reduces wind integration costs, increases reliability of the electrical grid, and helps make more efficient use of the available generation resources. Although costs for aggressive expansions of the existing grid are significant, they make up a relatively small portion of the total annualized costs in any of the scenarios studied.

- Carbon emission reductions in the three 20% wind scenarios do not vary by much, indicating that wind displaces coal in all scenarios and that coal generation is not significantly exported from the Midwest to the eastern United States; carbon emissions are reduced at an increased rate in the 30% wind scenario as more gas generation is used to accommodate wind variability. Wind generation displaces carbon-based fuels, directly reducing carbon dioxide (CO_2) emissions. Emissions continue to decline as more wind is added to the supply picture. Increasing the cost of carbon in the analysis results in higher total production costs.

The scenarios developed for EWITS do not in any way constitute a plan; instead, they should be seen as an initial perspective on a top-down, high-level view of four different 2024 futures. The transition over time from the current state of the bulk power system to any one of the scenarios would require additional technical and economic evaluation, including detailed modeling of power flows and a study of the effects on the underlying transmission systems. A more thorough evaluation of the sensitivity of the EWITS results to the range of assumptions made would also be required to guide the development of any specific bottom-up plans.

The significant amount of analytical work performed in EWITS, though, answers the questions posed at the outset of the project:

1. What impacts and costs do wind generation variability and uncertainty impose on system operations? **With large balancing areas and fully developed regional markets, the cost of integration for all scenarios is less than $10 per megawatt-hour (MWh) of wind, or less than $0.002 per kilowatt-hour (kWh) of electricity used by customers.**

2. What benefits accrue from long-distance transmission that accesses multiple and geographically diverse wind resources? **The study results show that long-distance (and high-capacity) transmission can assist smaller balancing areas with wind integration, allowing penetration levels that would not otherwise be feasible. Furthermore, all scenarios, including the Reference Case, made use of major transmission upgrades to better interlock Eastern Interconnection markets for assisting with wind integration.**

Why Regional Markets?

Because they span large geographic areas, regional markets optimize the power grid by promoting efficiency through resource sharing. These organized markets are designed so that an area with surplus electricity can benefit by sharing megawatts with another region in the open market. This allows participants and operators to see the big picture when it comes to dispatching electricity in the most efficient manner.

Source: Adapted from www.isorto.org. Accessed November 2009.

3. What benefits are realized from long-distance transmission that moves large quantities of remote wind energy to urban markets? **Long-distance transmission, along with assumed modifications to market and system operations, contributes substantially to integrating large amounts of wind that local systems would have difficulty managing. In addition, long-distance transmission has other value in terms of system robustness that was not completely evaluated in EWITS.**

4. How do remote wind resources compare to local wind resources? **In the Eastern Interconnection, the Eastern Wind Data Study database (AWS Truewind 2009) shows that the higher quality winds in the Great Plains have capacity factors that are about 7%–9% higher than onshore wind resources near the high-load urban centers in the East. Offshore plants have capacity factors on par with Great Plains resources but the cost of energy is higher because capital costs are higher.**

5. How much does geographical diversity, or spreading the wind out across a large area, help reduce system variability and uncertainty? **Quite substantially.**

6. What is the role and value of wind forecasting? **With significant wind generation, forecasting will play a key role in keeping energy markets efficient and reducing the amount of reserves carried while maintaining system security.**

7. What benefit does balancing area cooperation or consolidation bring to wind variability and uncertainty management? **This and other recent studies (see Bibliography) reinforce the concept that large operating areas—in terms of load, generating units, and geography—combined with adequate transmission, are the most effective measures for managing wind generation.**

8. How does wind generation capacity value affect reliability (i.e., supply resource adequacy)? **Wind generation can contribute to system adequacy, and additional transmission can enhance that contribution.**

SCENARIO COSTS

EWITS looks at a "snapshot" in time for a single year in the future. A transformation of the bulk power system in the Eastern Interconnection to the degree suggested by the study scenarios would result if many capital investments were made from the present through 2024. Consequently, economic analysis of the scenarios brings to light complicated questions that cannot be answered precisely without a detailed timeline of capital expenditures.

Because the study scenarios need to be compared on an economic basis, total costs for each scenario are approximated by identifying the fixed (investment) and variable (production) cost components. These costs are then summed, allowing the study team to view some measure of economic performance for each scenario side by side.

Study analysts calculated costs for each scenario as the sum of production-related costs (e.g., fuel costs) plus annualized amounts for capital investments in new conventional generation, wind plants, and transmission. The results for the Reference Case and the four high-penetration scenarios (Figure 3, in millions of US$2009) show that Scenario 1 is the least costly of the 20% scenarios, and that the increased cost of offshore wind adds to the costs in Scenarios 3 and 4.

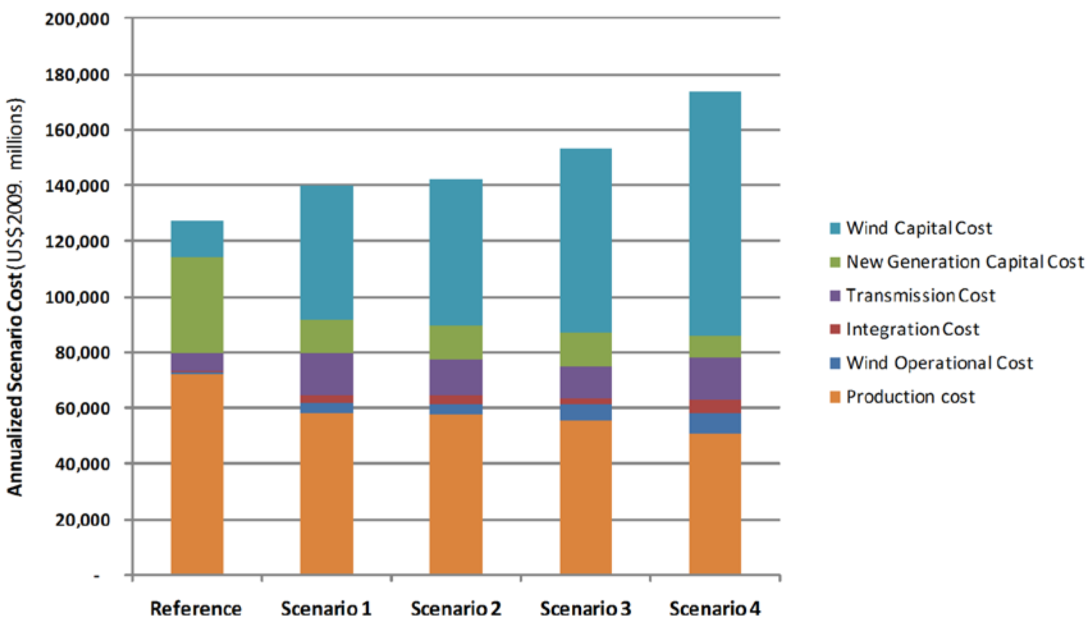


Figure 3. Comparison of scenario costs

Although production-related costs constitute a large fraction of the total costs for all scenarios, these decline as the amount of wind generation increases. In scenarios 3 and 4, capital costs for wind generation increase because of slightly lower capacity factors and the much higher capital cost of offshore construction.

Transmission costs are a relatively small fraction for all scenarios, with only a small absolute difference seen across the 20% cases. Wind integration costs are measurable but very small relative to the other factors.

None of the initial scenarios include any costs associated with carbon, which increases production costs significantly. The carbon price was addressed in a sensitivity analysis for Scenario 2, as described later in this *Executive Summary and Project Overview.*

STUDY METHODOLOGY

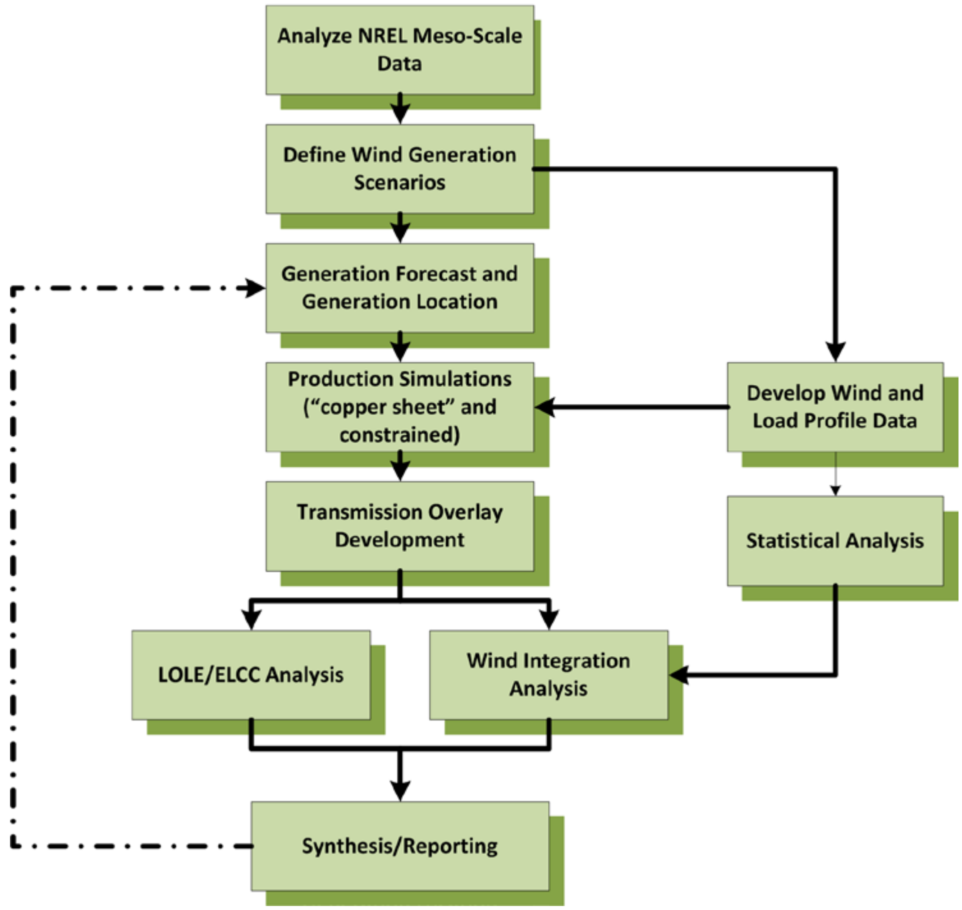
The EWITS project consisted of three major tasks: (1) wind plant output data development, (2) transmission requirements analysis, and (3) wind integration analysis. In wind integration studies, it is important to use concurrent load and wind data to capture the correlations between load and wind (i.e., weather; see sidebar).

The project team developed the quantitative information through a multistage analytical process, shown graphically in Figure 4. Methods developed and refined in previous integration studies formed the basis for the technical analysis, but were necessarily extended because the scope and size of this effort surpassed that of earlier studies. Focus on transmission requirements for the substantial amount of wind generation required to meet the 20% and 30% energy targets was a new and significant part of the study scope.

The Role of Weather and Wind Forecasting

Using numerical weather prediction models, also known as mesoscale models, is an accepted method for producing a time series of wind plant output data. Essentially, physics-based, numerical simulations on supercomputers, integrated with observational data sets, re-create the weather of historical years and generate a four-dimensional gridded wind-speed data set. A wind speed time series data set can be extracted and converted to wind power output. This approach produces a temporally, spatially, and physically consistent wind data set. For EWITS, this was done for hundreds of wind plants and the study team used these data sets in the modeling of the different scenarios.

Wind forecast data modeling is an increasingly common tool used by utilities and ISOs to schedule generation units. Wind integration studies typically include the effect of wind forecast errors on integration costs.



Notes: A copper sheet simulation assumes no transmission constraints or congestion.
LOLE = loss of load expectation and ELCC = effective load-carrying capability

Figure 4. Study process

Current transmission expansion planning is based on a decision-making process that starts with the present and looks forward through time. The existing bulk power grid in the United States is the result of such a bottom-up approach. In EWITS, the project team used top-down economic methods to develop the conceptual transmission capacity needed to deliver energy to load. These top-down methods tend to create designs with more transmission than bottom-up methods. The primary reason is that the total economic potential of increasing the economic efficiency of the generation fleet—including wind generation in the Eastern Interconnection—is used to justify transmission expansion. The combination of capturing the economic potential of both nonwind and wind generation loads the transmission lines more efficiently (i.e., the lines are not just being used for wind). The transmission requirements are mainly off peak for the wind generation and on peak for the nonwind generation.

Although the study assumptions were touched on previously, a more detailed look is helpful at this point. Peak demand and energy work assumptions for all study regions was based on 2004–2006 Federal Energy Regulatory Commission

(FERC) data combined with 2006 power flow data. These data had been compiled for a previous study, and were reviewed by all stakeholders at that time. To preserve correlation with the wind generation profile data, load data for EWITS were mapped to conform to actual wind profiles representing calendar years 2004, 2005, and 2006.

Because of the very large amount of wind generation studied, it was important to establish a framework for the day-to-day operations of the Eastern Interconnection in 2024. Results from past integration studies have shown that operational structure plays a major role in determining the difficulty or ease with which wind generation is integrated. Small balancing areas, which were the original building blocks of today's major interconnections, can be significantly challenged by large amounts of wind generation. Large effective balancing areas (see sidebar) have more supply resources to deploy and benefit substantially from diversity in both load and wind generation.

Extrapolating from trends that have been seen for the past decade, the study team—with input from the TRC—assumed that by 2024 operations in the Eastern Interconnection (at least the significant fraction modeled explicitly in EWITS) would be conducted under the auspices of seven large balancing areas, which are shown in Figure 5. The structure as it existed in August 2007 was used for comparison. Five of the seven correspond to existing RTOs in the Eastern Interconnection.

Operating the Grid

Balancing Authority

A balancing authority is the responsible entity that maintains load resource balance within a given, predefined area (the balancing authority area). The authority develops integrated resource plans, matches generation with load, maintains scheduled interchanges with other balancing authority areas, and supports interconnection frequency of the electric power systems in real time.

Reliability-Related Services

In the NERC Functional Model, which defines the set of functions that must be performed to ensure the reliability of the bulk electric system, these include the range of services, other than the supply of energy for load, that are physically provided by generators, transmitters, and loads in order to maintain reliability. In wholesale energy markets, they are commonly described as "ancillary services."

Source: Adapted from http://www.nerc.com/files/opman_12-13Mar08.pdf. Accessed November 2009.

The project team also assumed that operations in each area would conform to the same structure. For example, on the day before the operating day, all generating units bid competitively to serve load, and after market clearing, operators perform a security-constrained unit commitment to ensure that adequate capacity will be available to meet forecast load. During the operating day, generators are dispatched frequently to follow short-term demand trends under a fast, subhourly market structure. A competitive ancillary services market supplies regulation, balancing, and unused generation capacity to cover large events such as the loss of major generating facilities.

The assumptions made about operating structure are very significant given the current operations in the Eastern Interconnection. The assumed market mechanisms, however, are actually in use today, albeit not uniformly, and have been shown in previous studies to be of substantial value for wind integration. There is some probability that developments in market operation over the next decade could further enhance the ability to integrate wind energy.

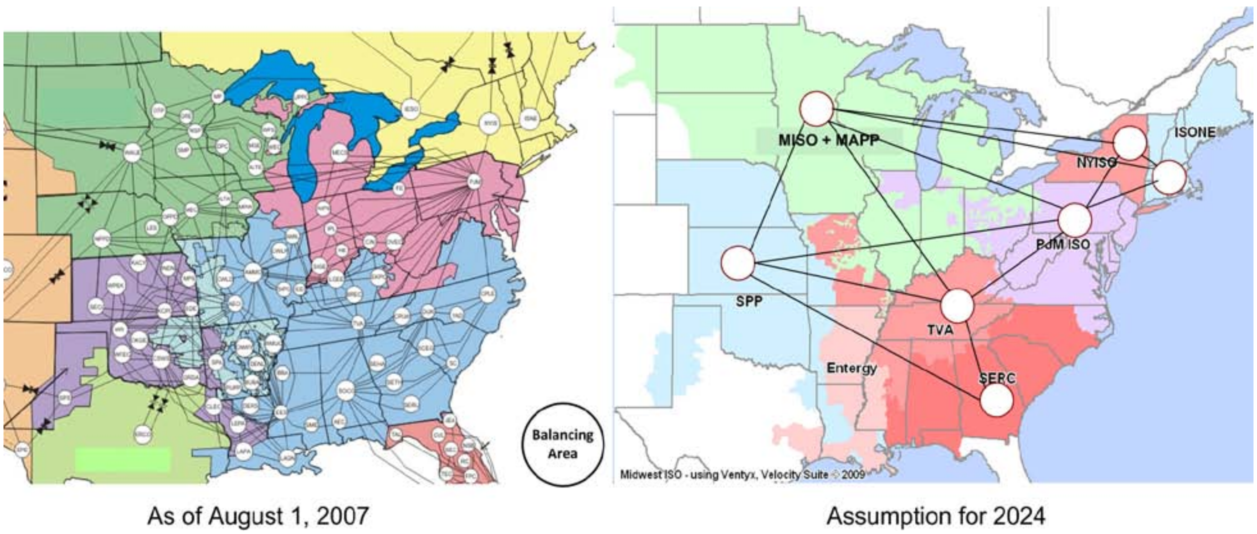


Figure 5. Assumed operational structure for the Eastern Interconnection in 2024
(white circles represent balancing authorities; Entergy is operated as part of SERC)

PROJECT OVERVIEW

This section describes the transmission requirements, wind operational impacts, production-cost modeling results, wind integration costs, carbon sensitivity analysis, and the wind contribution to resource adequacy for EWITS.

TRANSMISSION REQUIREMENTS

EWITS uses a deterministic, chronological production-cost model (PROMOD IV®)[1] for evaluating transmission requirements. The study process began with locating wind generation across the interconnection, and then determining what additional nonwind capacity would be required in each region to maintain reliability for the projected energy demand in the study year. No new transmission was considered at this stage. This step allowed the study analysts to identify the locations of electrical energy supply and locate the loads or demand for the energy. To develop the transmission overlays, then, the project team used economic signals to connect the “sources” (supply) to the “sinks” (loads).

The study team used an economics-based expansion planning methodology to develop transmission requirements for each scenario based on the output of the different production simulations. Before each set of simulations, the additional nonwind capacity required to reliably serve the projected load was determined using traditional generation expansion methodologies. Wind generation was assigned a firm capacity value of 20%. Next, wind generation and the indicated conventional expansion were added to the production-cost model that contained the existing transmission network.

After simulating system operation over an entire year of hourly data, study analysts then compared the results of this modeling simulation to those from a similar simulation in which constraints on the transmission system were removed. The comparison indicates how regional or interconnection-wide production costs increase because of transmission congestion, or put another way, what value could be achieved by eliminating or reducing transmission constraints. Differences between the “constrained” case and the “unconstrained” case yield the following information:

- The areas of economic energy sources and sinks
- The interface flow changes to determine the incremental transfer capacity needs
- The total benefit savings, which in turn gives a rough estimate of a potential budget for building transmission to relieve constraints and reduce congestion costs

[1] PROMOD IV (developed by Ventyx) is an integrated electric generation and transmission market simulation system that incorporates extensive details of generating unit operating characteristics and constraints, transmission constraints, generation analysis, unit commitment/operating conditions, and market system operations. PROMOD IV performs an 8,760-hour commitment and dispatch recognizing both generation and transmission impacts at the bus-bar level. (Bus-bar refers to the point at which power is available for transmission.)

Transmission flows between regions in EWITS are determined in part by the differences between production simulations using a “copper sheet” (i.e., no transmission constraints, no congestion) versus the existing transmission system. Transmission capacity is designed to deliver 80% of the desired energy flow. Figure 6 shows the annual generation differences between the unconstrained and constrained cases for Scenario 2. This helps to define the energy source and sink areas and gives insight into the optimal locations for potential transmission lines and substations. Red represents the energy source areas; blue signifies the energy sink areas. As Figure 7 illustrates, the price signal drives energy from low-cost source areas to high-cost sink areas if the transmission system is not constrained across the study footprint.

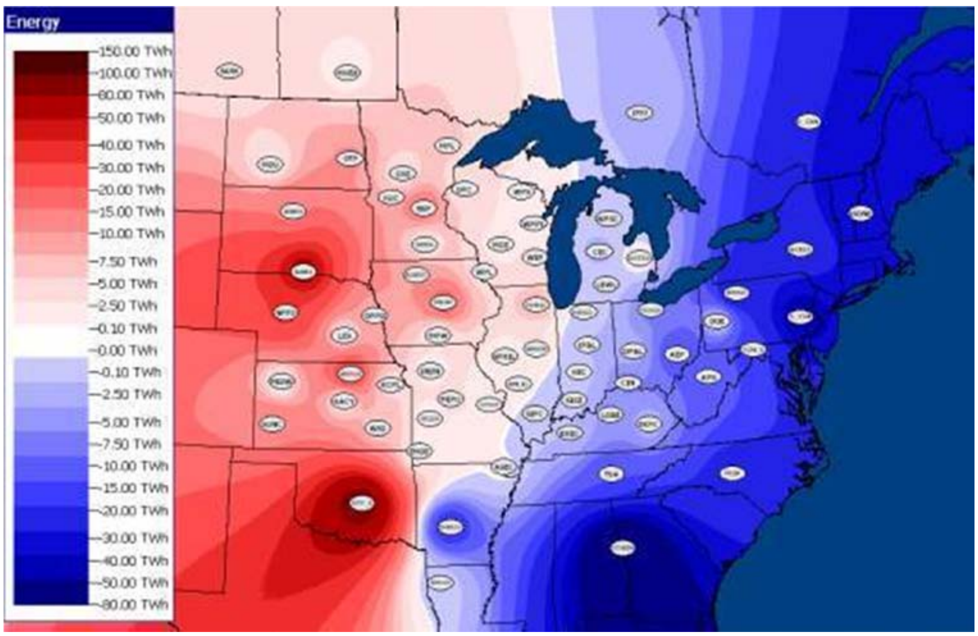


Figure 6. Scenario 2, annual generation differences between unconstrained case and constrained case *(Note: Because price contours developed from defined pricing hubs, they do not correspond exactly to geography.)*

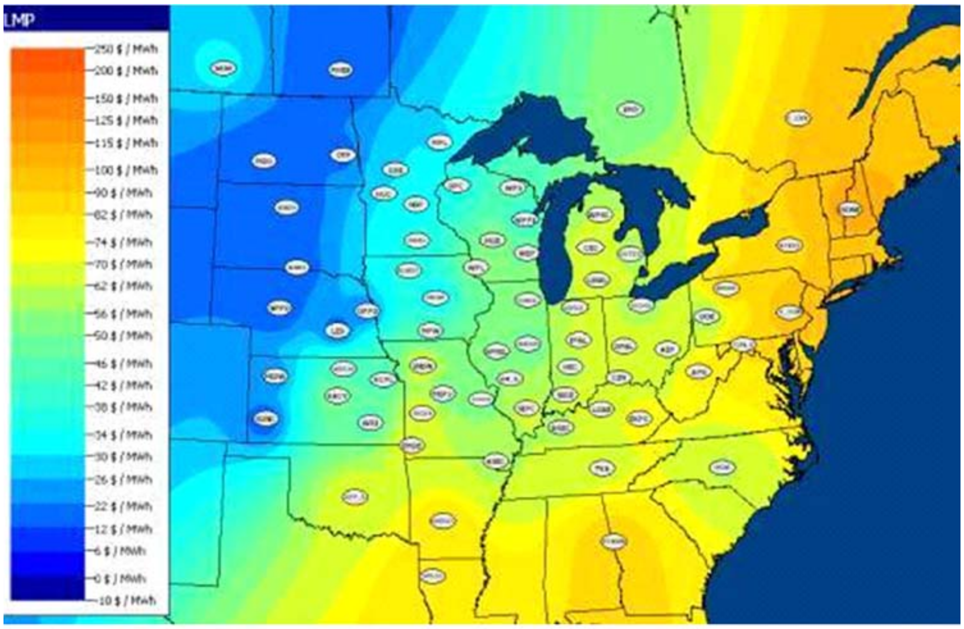


Figure 7. Scenario 2, annual generation weighted locational marginal price (LMP) for constrained case

Using these comparative results as a guide, and with input from the TRC, the study team developed transmission overlays for each scenario.

The conceptual transmission overlays, shown in Figure 8, consist of multiple 800-kilovolt (kV) high-voltage direct current (HVDC) and extra-high voltage (EHV) AC lines with similar levels of new transmission and common elements for all four scenarios. Tapping the most high-quality wind resources for all three 20% scenarios, the project team arrived at a transmission overlay for Scenario 1 that consists of nine 800-kV HVDC lines and one 400-kV HVDC line. For Scenario 2, analysts moved some wind generation eastward, resulting in a reduced transmission overlay with seven 800-kV HVDC lines and one 400-kV HVDC line. As more wind generation is moved toward the east and more offshore resources are used in Scenario 3, the resulting transmission overlay has the fewest number of HVDC lines, with a total number of five 800-kV HVDC lines and one 400-kV HVDC line. To accommodate the aggressive 30% wind target and deliver a significant amount of offshore wind along the East Coast in Scenario 4, the overlay must be expanded to include ten 800-kV HVDC lines and one 400-kV HVDC line.

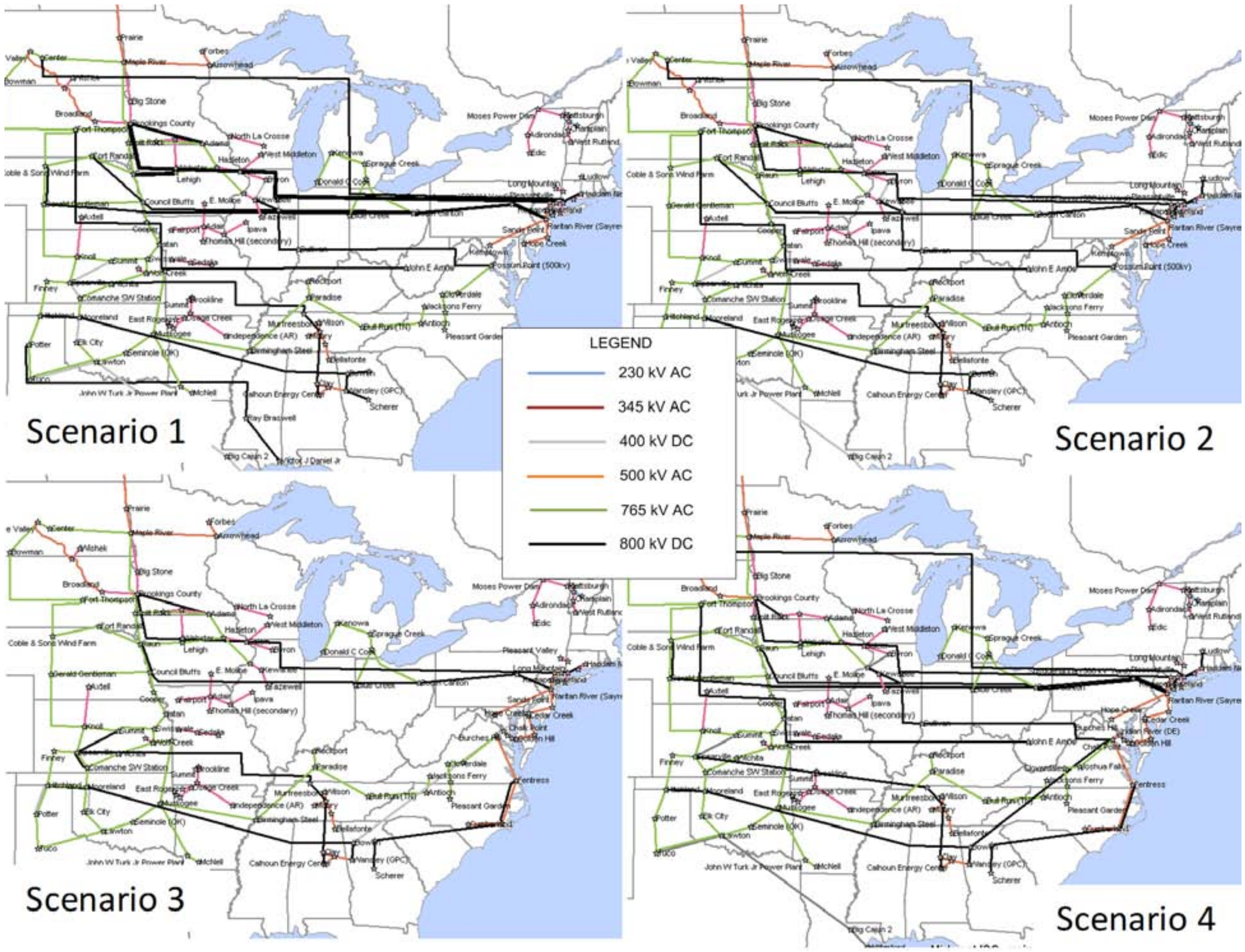


Figure 8. Conceptual EHV transmission overlays for each study scenario

Tables 2 through 4 summarize the transmission and construction cost-per-mile assumptions by voltage level, the estimated total line miles by voltage level, and the estimated cost in US$2024 for the four wind scenario conceptual overlays, respectively. In Table 4, the total AC line costs include a 25% margin to approximate the costs of substations and transformers. In addition, the total HVDC line costs include those for terminals, communications, and DC lines. Costs associated with an offshore wind collector system and those for some necessary regional transmission upgrades are not included in the total estimated cost and would increase total transmission costs. With approximately 22,697 miles of new EHV transmission lines, the transmission overlay for Scenario 1 has the highest estimated total cost at $93 billion (US$2009).

TABLE 2. TRANSMISSION COST ASSUMPTIONS							
Cost-per-Mile Assumption							
Voltage Level	345 kV	345 kV AC (double unit)	500 kV	500 kV AC (double circuit)	765 kV	400 kV DC	800 kV DC
US$2024 (millions)	2,250,000	3,750,000	2,875,00	4,792,00	5,125,000	3,800,000	6,000,000

TABLE 3. ESTIMATED LINE MILEAGE BY SCENARIO								
Estimated Line Mileage Summary								
Voltage Level	345 kV	345 kV AC (double circuit)	500 kV	500 kV AC (double circuit)	765 kV	400 kV DC	800 kV DC	TOTAL
Scenario 1	1,977	247	1,264	243	7,304	560	11,102	22,697
Scenario 2	1,977	247	1,264	243	7,304	560	8,352	19,947
Scenario 3	1,977	247	1,264	742	7,304	769	4,747	17,050
Scenario 4	1,977	247	1,264	742	7,304	560	10,573	22,667

TABLE 4. ESTIMATED COSTS BY SCENARIO (US$2009, MILLIONS)								
Estimated Cost Summary (US $2024, millions)								
Voltage Level	345 kV	345 kV AC (double circuit)	500 kV	500 kV AC (double circuit)	765 kV	400 kV DC	800 kV DC	Total
Scenario 1	5,560	1,158	4,543	1,456	46,791	2,397	83,265	145,170
Scenario 2	5,560	1,158	4,543	1,456	46,791	2,397	62,640	124,545
Scenario 3	5,560	1,158	4,543	4,445	46,791	2,957	35,603	101,057
Scenario 4	5,560	1,158	4,543	4,445	46,791	2,957	79,298	144,752

Specific findings and conclusions from development of the transmission overlays for each scenario include the following:

- The 800-kV HVDC and EHV AC lines are preferred if not required because of the volumes of energy that must be transported across and around the interconnection, as well as the distances involved.
- Similar levels of new transmission are needed across the four scenarios, and certain major facilities appear in all the scenarios. This commonality is influenced by the top-down method used and the location of the wind generation in each scenario. The study focuses on four possible 2024 "futures." Determining a path for realizing one or more of those futures was outside the study scope. Large amounts of transmission are also required in the Reference Case.
- The modeling indicates that significant wind generation can be accommodated as long as adequate transmission capacity is available and market/operational rules facilitate close cooperation among the operating regions.
- Transmission offers capacity benefits in its own right, and enhances wind generation's contribution to reliability by a measurable and significant amount.

- The EHV DC transmission that constitutes a major portion of the overlays designed for the scenarios in EWITS has benefits beyond those evaluated here. For example, it would be possible to schedule reserves from one area to another, effectively transporting variability resulting from wind and load to areas that might be better equipped to handle it. And the transfer capability of the underlying AC network could be enhanced by using the DC terminals to mitigate limitations caused by transient stability issues.

WIND OPERATIONAL IMPACTS

Reliable delivery of electrical energy to load centers entails a continuous process of scheduling and adjusting electric generation in response to constantly changing demand. Sufficient amounts of wind generation increase the variability and uncertainty in demand that power system operators face from day to day or even from minute to minute. Quantifying how the amounts of wind generation in each of the study scenarios would affect daily operations of the bulk system and estimating the costs of those effects were major components of EWITS.

Using detailed chronological production simulations for each scenario, the study team assessed impacts on power system operation. The objective of these simulations was to mimic how day-to-day operations of the Eastern Interconnection would be conducted in 2024 with the prescribed amounts of wind generation in each scenario, new conventional generation per the expansion study, and the transmission overlays the study team developed. Ways to manage the increased variability and uncertainty attributable to wind generation, along with the resulting effect on operational costs, were of primary interest.

EWITS uses a deterministic production-cost model to run hourly power system operational simulations using the transmission overlays for each scenario and the wind plant outputs and actual load data for 2004, 2005, and 2006. The model takes the wind generation at each "injection bus" (i.e., the closest transmission connection to the wind plant) and dispatches nonwind generation units accordingly for each market region while solving at the model node for the LMP. The tool simulates actual power system operations by first solving the unit-commitment problem (i.e., what conventional generators will be dispatched to meet load), then using the wind power and load forecasts, and finally dispatching the units based on the actual modeled wind and load data. Obtaining realistic results is necessary because unit-commitment decisions must actually be made well in advance, allowing generators sufficient time to start up and synchronize to the grid. A hurdle rate accounts for hourly transactions among eight different market regions. The simulation is done over the entire study region and the wind plant and load time series data capture geographic diversity.

RESERVE REQUIREMENTS

With large amounts of wind generation, additional operating reserves (see sidebar) are needed to support interconnection frequency and maintain balance between generation and load. Because the amounts of wind generation in any of the operating areas, for any of the scenarios, dramatically exceed the levels for which appreciable operating experience exists, the study team conducted statistical and mathematical analyses of the wind generation and load profile data to estimate the additional requirements. These were used as inputs to the production-cost modeling. The analysis focused on the major categories of operating reserves, which included needs for regulation, load following, and contingencies.

In the production simulations for each scenario, study analysts took into account the additional uncertainty and variability resulting from wind generation by

- Incorporating the increased operating reserves as constraints on the commitment and dispatch of generating resources in each operating area
- Committing generating units for operation based on forecasts of load and wind generation, then dispatching the available units against actual quantities.

The levels of wind generation considered in EWITS increase the amount of operating reserves required to support interconnection frequency and balance the system in real time. Contingency reserves are not directly affected, but the amount of spinning reserves assigned to regulation duty must increase because of the additional variability and short-term uncertainty of the balancing area demand.

Types of Reserves

In bulk electric system operations, different types of generation reserves are maintained to support the delivery of capacity and energy from resources to loads in accordance with good utility practice.

Contingency Reserves

Reserves to mitigate a "contingency," which is defined as the unexpected failure or outage of a system component, such as a generator, a transmission line, a circuit breaker, a switch, or another electrical element. In the formal NERC definition, this term refers to the provision of capacity deployed by the balancing authority to meet the disturbance control standard (DCS) and other NERC and regional reliability organization contingency requirements.

Operating Reserves

That capability above firm system demand required to provide for regulation, load forecasting error, forced and scheduled equipment outages, and local area protection. This type of reserve consists of both generation synchronized to the grid and generation that can be synchronized and made capable of serving load within a specified period of time.

Regulating Reserves

An amount of reserve that is responsive to automatic generation control (AGC) and is sufficient to provide normal regulating margin. Regulating reserves are the primary tool for maintaining the frequency of the bulk electric system at 60 Hz.

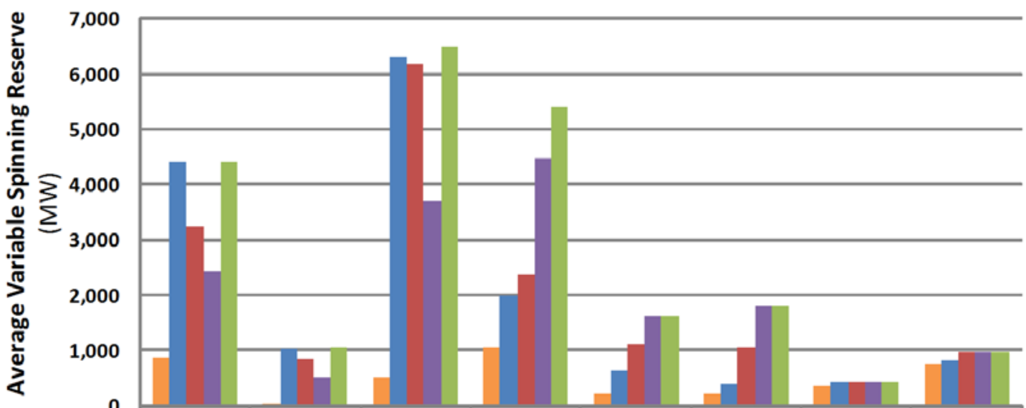
Spinning Reserves

The portion of operating reserve consisting of (1) generation synchronized to the system and fully available to serve load within the disturbance recovery period that follows a contingency event; or (2) load fully removable from the system within the disturbance recovery period after a contingency event.

The assumption of large balancing areas does reduce the requirement, however. Under the current operational structure in the Eastern Interconnection, the total amount of regulation that would need to be carried would be dramatically higher.

Using the methodology developed for EWITS, the study team calculated regulating reserve requirements for each region and each scenario from hourly load data and 10-minute wind production data. The result is an hourly profile that varies with both the amount of load and the level of wind generation. The calculations account for important characteristics of the wind generation scenario, such as the amount of geographic diversity and its influence on the aggregate short-term variability.

Figure 9 summarizes the regulating reserve requirements for each region and each scenario. The value indicated by the bar is the average of the annual hourly profile. The load-only case is a reference for calculating the incremental requirement resulting from wind generation.



	MISO	MAPP	SPP	PJM	NYISO	ISO-NE	TVA	SERC
Load Only	885	43	514	1055	217	202	365	741
Actual Wind S1	4,424	1,020	6,308	1,994	618	399	420	816
Actual Wind S2	3,245	835	6,176	2,359	1,118	1,046	418	955
Actual Wind S3	2,419	503	3,695	4,463	1,614	1,789	418	955
Actual Wind S4	4,423	1,038	6,487	5,410	1,614	1,789	418	955

Region

Figure 9. Regulating reserve requirements by region and scenario. *The incremental amount resulting from wind generation is the difference between the scenario number and the load-only value.*

Current operating experience offers little guidance on managing the incremental variability and uncertainty associated with large amounts of wind generation in the operating footprints defined for EWITS. The statistical analysis conducted on the time series data from the scenarios, however, forms a highly reasonable analytical foundation for the assumptions and reserve requirement results that the study team carried forward to the production simulations.

The team's analysis of reserve requirements with substantial amounts of wind generation resulted in the following findings and conclusions:

- The assumptions made about how the Eastern Interconnection will be operated in 2024 played an important role in minimizing the additional amounts of spinning reserve that would be required to manage the variability of large amounts of wind generation.
- The large size of the market areas assumed in the study allows substantial benefits of geographic diversity to be realized.
- The pooling of larger amounts of load and discrete generating resources via regional markets also realizes diversity benefits. The per-unit variability of load declines as the amount of load increases; larger markets also have more discrete generating units of diverse fuel types and capabilities for meeting load and managing variability.
- With real-time energy markets, changes in load and wind that can be forecast over a short interval—10 minutes in EWITS, 15 to 20 minutes in current practice—are compensated for through economic movements of participating generating units. Because load changes over 10-minute intervals can be accurately forecast, they can be cleared in a subhourly market.
- The fastest changes in balancing area demand—on time scales from a few to tens of seconds—are dominated by load, even with very large amounts of wind generation.
- Incremental regulating reserve requirements are driven by errors in short-term (e.g., 10 to 20 minutes ahead) wind generation forecasts.
- Data from the Eastern Wind Data Study can be used to characterize both variability and uncertainty for a defined scenario. With more wind generated over a larger geographic area, percentages of aggregate wind variability and uncertainty decrease. These quantitative characterizations are useful for estimating incremental reserve requirements.
- Current energy market performance shows that, on average, subhourly market prices do not command a premium over prices in the day-ahead market. Consequently, the hourly production simulation will capture most of the costs associated with units moving in subhourly markets, and the spinning reserve requirements for regulation and contingency will appropriately constrain the unit commitment and dispatch.

The EWITS analysis addresses these requirements only; as wind displaces marginal conventional generation, those nonwind resources deliver less energy and thus realize less revenue. With large amounts of wind generation such as those considered in EWITS, additional costs could be associated with those displaced marginal units that are not captured in the production modeling.

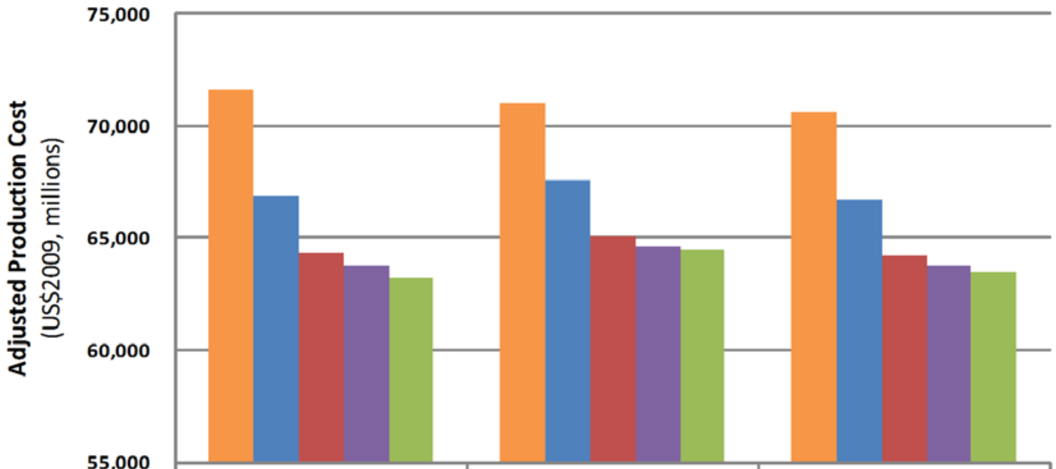
PRODUCTION-COST MODELING RESULTS

The project team ran annual production simulations for all three wind and load years and all scenarios. The raw results included hourly operations and costs for each generator and flows on each transmission element in the model, but because of the sheer volume of data generated, the project team had to analyze summary information.

The detailed production modeling of a system of such size and scope reduces the number of assumptions and approximations required. Although the large volume of results is a disadvantage, the results do contain information from which conclusions can be drawn—with relatively high confidence—about wind generation impacts on other system resources. Specifically,

- Generation displacement depends on the location and amount of wind generation.
- Because of its low dispatch price, wind generation will reduce LMPs. The effect in a particular region is greater with local wind resources.
- The addition of overlay transmission works to equalize LMPs across the footprint. Because of transfer limits, there are still price differences across the footprint, but the magnitude of the difference is reduced with the overlays.
- Offshore wind has more effect on LMPs in eastern load centers because of its proximity to large load centers otherwise served by generation with higher costs.

Figure 10 shows total production costs for each of the high-penetration wind scenarios and for the Reference Case. The primary effect of wind generation is to displace production from conventional sources; as the amount of wind generation increases, so does the magnitude of the displacement. The location of wind generation, however, also has an influence. Under the baseline assumptions used for the study, energy prices are higher in the East and lower in the western portion of the interconnection. Consequently, production costs are reduced more by wind in areas with higher costs; the production costs shown in Figure 10 do not account for the capital costs of the wind or infrastructure required to deliver wind energy to load.



	2004	2005	2006
Reference	71,642	71,042	70,623
Scenario 1	66,834	67,571	66,700
Scenario 2	64,380	65,059	64,226
Scenario 3	63,769	64,653	63,754
Scenario 4	63,219	64,509	63,474

Year

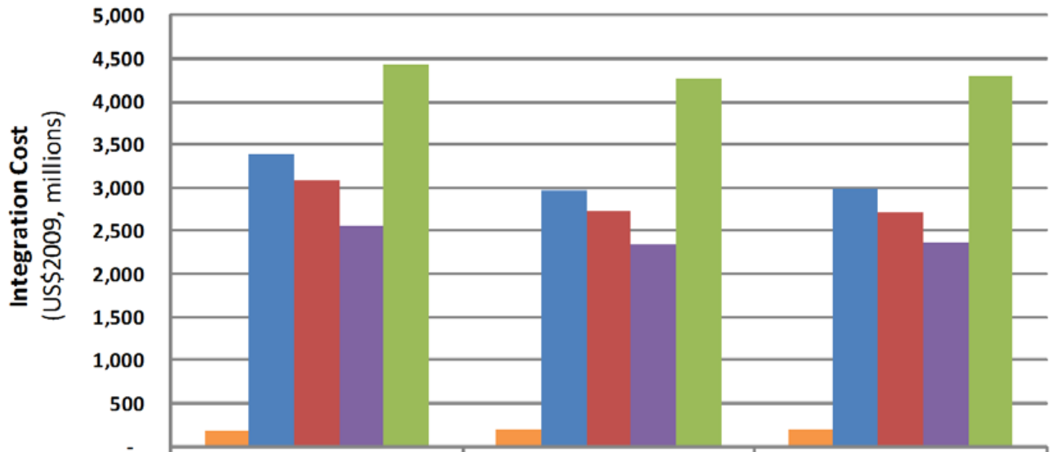
Figure 10. Annual production-cost comparison *(US$2009, millions)*

WIND INTEGRATION COSTS

Assessing the costs for integrating large amounts of wind generation was another key aspect of EWITS. Team members used methods and analytical approaches employed in earlier integration studies as their starting point. As interim results became available, nuances in and challenges to applying that methodology to a large, multiarea production model became apparent. This project significantly bolstered the knowledge base and perspective on the components of the total cost associated with managing wind energy delivery.

The study team computed the cost of managing the delivery of wind energy (i.e., the integration cost) by running a set of comparative production simulations. In these cases, analysts assumed that wind energy did not require carrying additional regulating reserves for managing variability and short-term uncertainty. They also assumed that the hourly wind energy delivery was known perfectly in the unit-commitment step of the simulation. The differences in production costs among these cases and the corresponding cases where wind generation is not ideal can be attributed to the incremental variability and uncertainty introduced by the wind resource.

Figure 11 shows the calculated integration cost for each scenario normalized to the amount of wind energy delivered. Costs vary by scenario and by year, but all are less than 10% of the bus-bar cost of the wind energy itself.



	2004	2005	2006
Reference	174	189	199
Scenario 1	3,396	2,967	2,989
Scenario 2	3,078	2,728	2,720
Scenario 3	2,560	2,337	2,359
Scenario 4	4,439	4,269	4,285

Year

Figure 11. Integration cost by scenario and year *(US$2009)*

Salient points from the integration impacts and costs analysis include the following:

- Because the production simulation model contains multiple operating areas, and because transactions between and among these areas are determined on an economic basis, variability from wind in a given area is carried through economic transactions to other areas. In earlier integration studies, wind impacts were isolated in the subject area by restricting transactions to predefined shapes based on historical contracts.
- Costs for integrating wind across the interconnection vary by scenario. For the 20% cases, Scenario 1 shows the highest cost at $5.13/MWh (US$2009) of wind energy; Scenario 3 shows the lowest integration cost at $3.10/MWh (US$2009).
- Integration costs average $4.54/MWh (US$2009) for the 30% scenario, which is roughly a combination of scenarios 1 and 3.
- Results for the 20% scenarios show that spreading the wind more evenly over the footprint reduces integration costs. This is particularly noticeable in the East, where there is more load and a larger number of resources to manage variability.

The project team also analyzed production simulation results to assess curtailment of wind generation resulting from transmission congestion or other binding constraints. Such constraints include excess electricity supply relative to demand and must-run generation (“minimum generation” limits), limitations in ramping capability, or availability of adequate operating reserves.

Varying amounts of wind generation curtailment were observed in the production simulation results. Findings include the following:

- Wind generation was assigned a very low dispatch price in the production simulations, allowing other sources to be redispatched first to relieve congestion. Even so, study analysts observed a modest amount of curtailment in some operating areas. This is likely the result of local or subregional transmission congestion.
- After conducting a sensitivity analysis consisting of additional production simulation runs, the study team determined that transmission congestion caused most of the curtailment. In these results, minimum generation levels, reserve constraints, and ramp limitations accounted for less than 1% of the curtailed energy.
- In developing the conceptual transmission overlays, facilities were sized to accommodate a large fraction—though not 100%—of the transaction energy from the unconstrained production simulation case. Consequently, a certain amount of wind generation curtailment was a likely outcome.

Ramp Rates

For a generator, the ramp rate (typically expressed in megawatts per minute) is the rate at which a generator changes its output. For an interchange, the ramp rate or ramp schedule is the rate, also expressed in megawatts per minute, at which the interchange schedule is attained during the ramp period.

Because wind is variable and results in ramping, it is important to understand these ramp rates and maintain reserves to cover them as needed.

CARBON SENSITIVITY ANALYSIS

The entire analytical methodology, except for the loss of load expectation (LOLE) analysis (see the next section for more information on LOLE), was run for a scenario that considered a carbon price of $100/metric ton. The study team determined that the high price was necessary to bring about a significant change in the type of new generation built during the expansion modeling process. In addition, because it was a sensitivity analysis, choosing a high price helped to illustrate sensitivities. Figure 12 shows the results of the expansion, and Figure 13 compares the expansion for the carbon sensitivity case to the base scenarios and the existing Eastern Interconnection queue.

Results from the production simulations show that the impact on carbon emissions is substantial. Even though the carbon sensitivity case was based on Scenario 2, in which wind generation provides 20% of the energy in the Eastern Interconnection, carbon emissions are lower than those from Scenario 4, in which wind generation delivers 30% of that energy (Figure 14).

Little impact was observed on wind generation curtailment or integration cost. Relative to the original Scenario 2 (Figure 15), fossil-fuel generation is reduced; nuclear generation increases because the nuclear share of the new generation expansion is larger. Energy from combined-cycle plants also increases because it became the preferred resource for managing variability.

With the high cost of carbon, energy prices increase across the footprint (Figure 16). The present value of the accumulated costs more than doubles from the base scenarios (Figure 17).

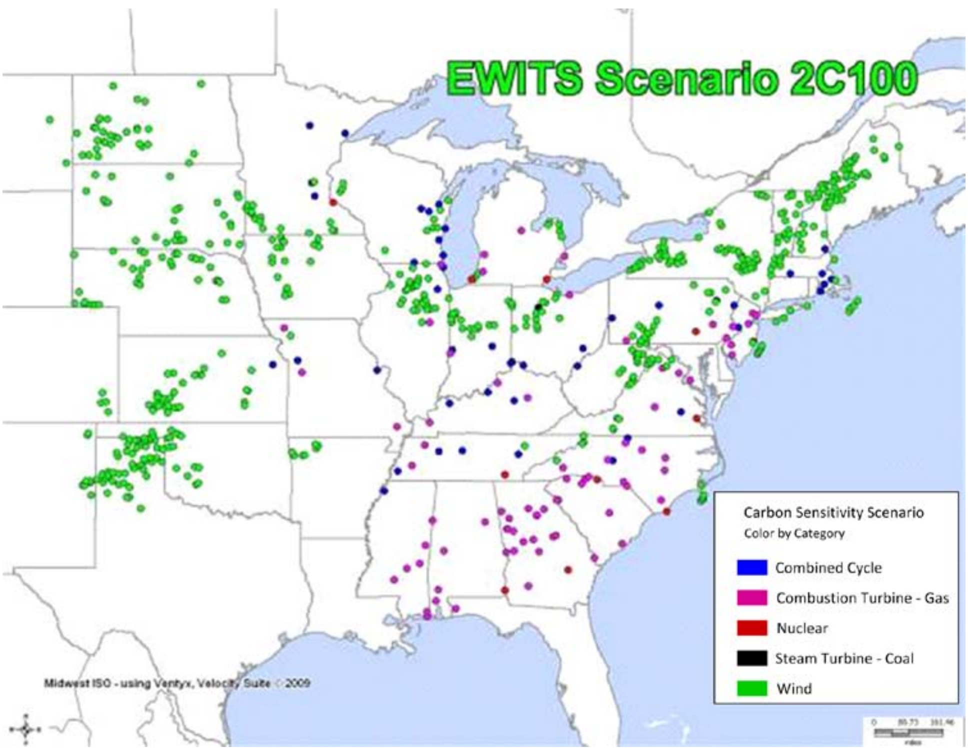
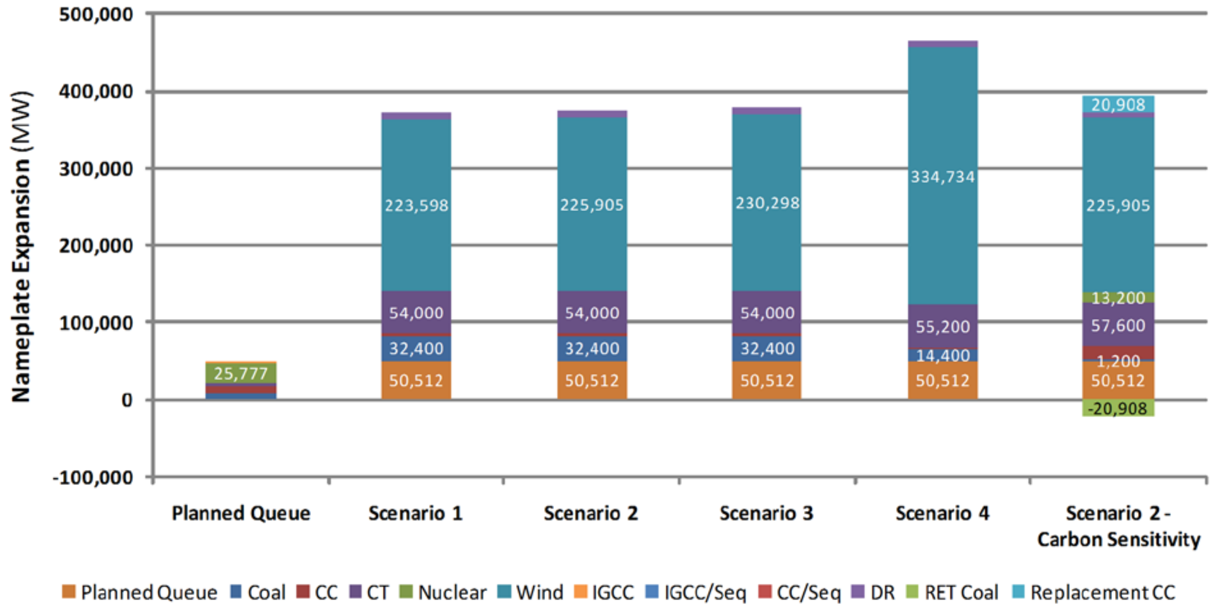


Figure 12. Generation expansion for the Scenario 2 carbon sensitivity case



CC = combined cycle; CT = combustion turbine; DR = demand response; IGCC = integrated gas combined cycle; IGCC/Seq = integrated gas combined cycle with sequestration; CC/Seq = combined cycle with sequestration; RET Coal = coal plant retirements; Replacement CC = replacement combined cycle

Figure13. Generation expansion by scenario, including the carbon sensitivity case

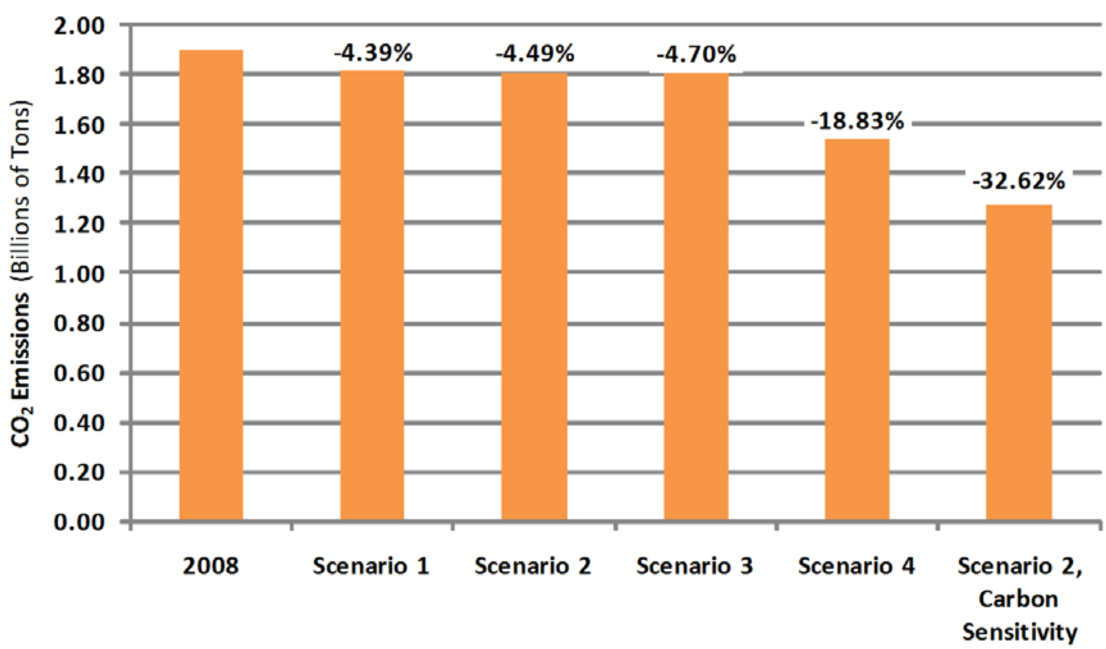
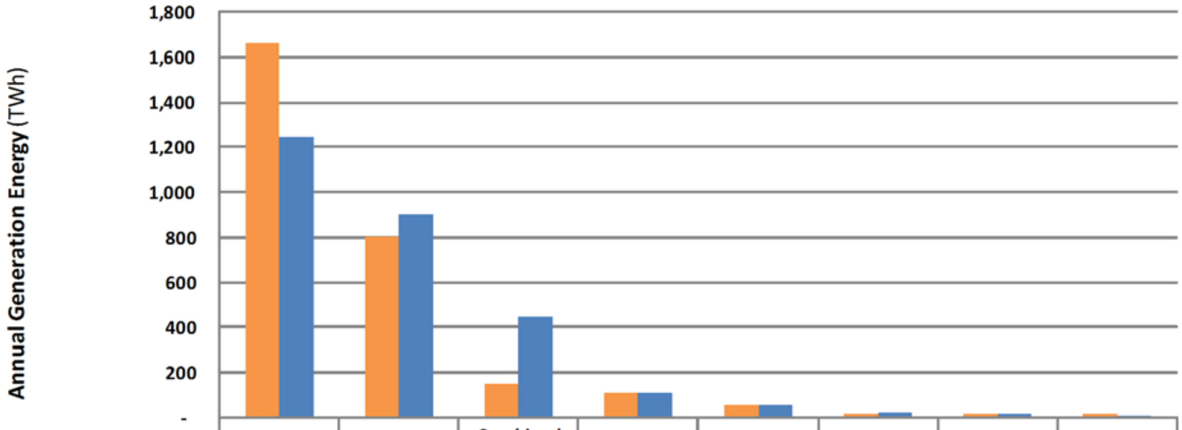
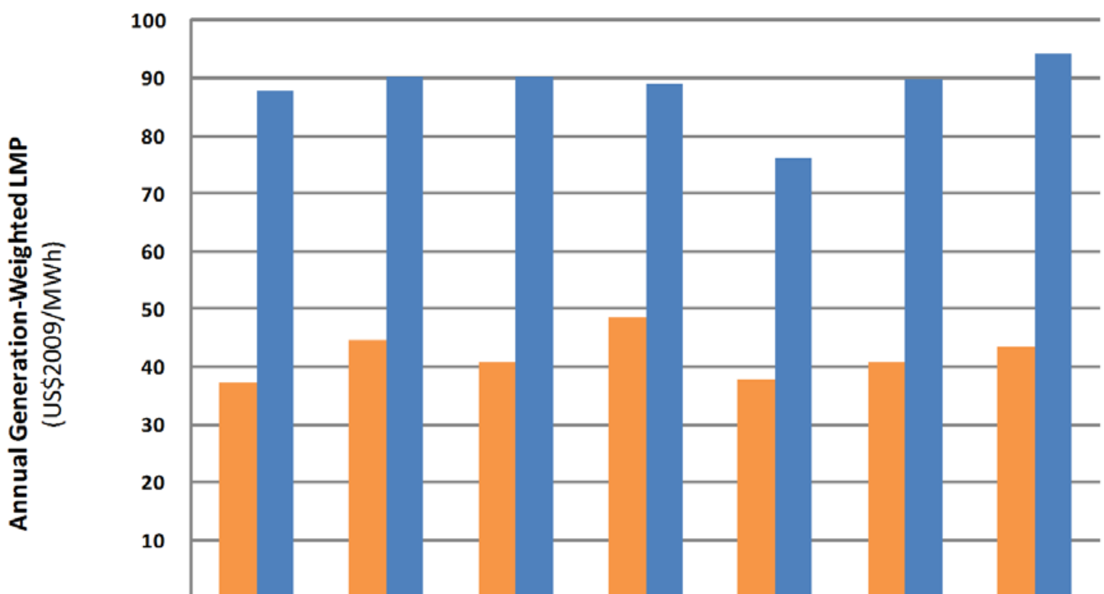


Figure 14. Carbon emissions for different scenarios *(carbon price applies only to carbon scenario)*



	ST Coal	Nuclear	Combined Cycle	Hydro	CT Gas	IGCC	ST Gas	Other
Scenario 2	1,667	801	146	106	55	16	13	16
Scenario 2, Carbon 100$/Ton	1,249	906	444	106	53	18	14	5

Figure 15. Generation utilization by unit and fuel type for Scenario 2 and carbon sensitivity case



	MISO	SPP	PJM	ISO-NE	NYISO	TVA	SERC
Scenario 2	37.11	44.57	40.78	48.49	37.68	40.75	43.53
Scenario 2, Carbon 100 US$2024/Ton	87.85	90.16	90.20	88.91	76.22	89.94	94.40

Figure 16. Comparison of generation-weighted LMP by region for Scenario 2 and carbon sensitivity case

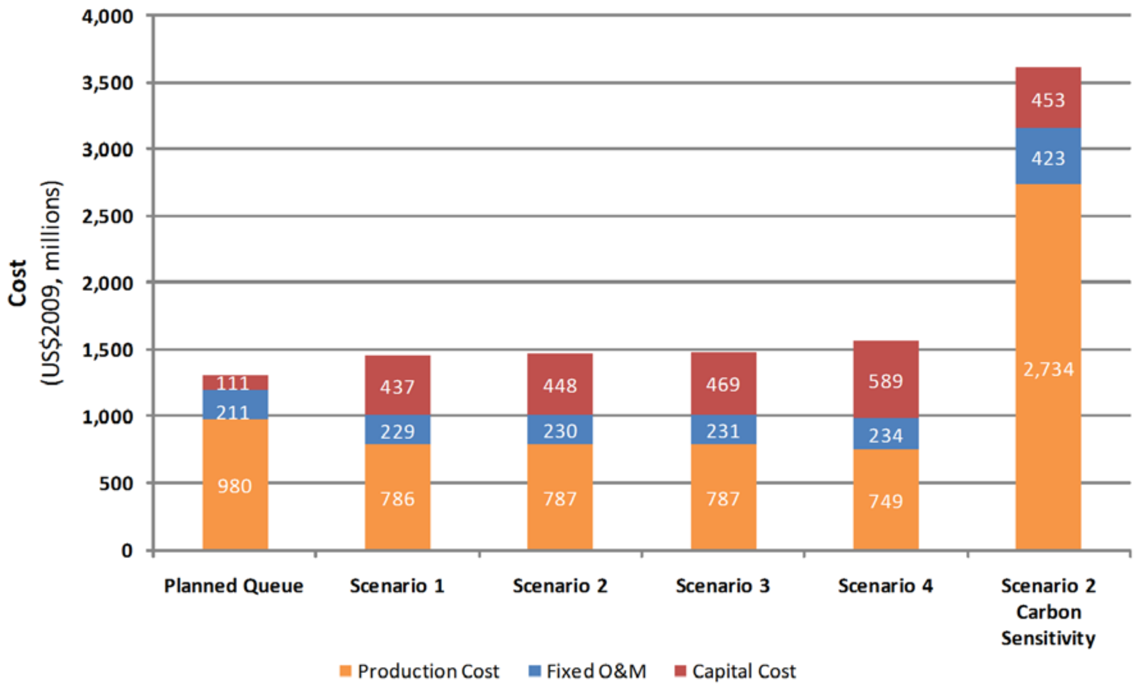


***Figure 17. Present value of accumulated costs for base scenarios and carbon sensitivity** (US$2009)*

CONTRIBUTIONS TO RESOURCE ADEQUACY

Having sufficient generation capacity to meet forecast load is an important aspect of bulk power system reliability. Although wind generation cannot be dispatched to meet peak loads, EWITS shows some probability that wind generation would be available during periods of system stress (i.e., it needs additional energy to meet demand). Unlike conventional generating units, only a small fraction of the nameplate capacity rating of a wind plant can be counted on to be available for serving peak loads. With the amounts of wind generation considered in EWITS, though—more than 200,000 MW—understanding the small fraction in quantitative detail is important because it equates to billions of dollars of capital investment.

Reliability of the Grid

EWITS: The EWITS results represent a first detailed look at several "snapshots" of the Eastern Interconnection as it could exist in 2024 and is therefore not intended to provide a complete analysis of the reliability impacts to the present bulk power system. EWITS is aimed at characterizing the operational impacts for future scenarios, primarily through economics-based transmission expansion planning, resource adequacy studies, and hourly modeling simulations. Important technical aspects in the study related to Bulk-Power System reliability were not studied or were represented approximately or by means of best engineering judgments. A variety of comprehensive power system engineering analyses and studies still need to be conducted (see Summary and Future Work Section) to determine what additional situations should be addressed to maintain system reliability from the present to the 2024 study year when integrating large quantities of renewable generation.

The fraction of the nameplate rating of a wind plant that can be counted as dependable or firm capacity, expressed as a percentage, is known as the capacity value.

To estimate a 2024 capacity value for wind, the study analysts used the 2004, 2005, and 2006 effective load-carrying capability (ELCC) of wind at the future penetration level. The team analyzed each of the high-penetration wind scenarios that were explored in the operational analysis.

Reliability of the Grid (continued)

Federal Energy Regulatory Commission (FERC) Study: FERC is conducting a new study with Lawrence Berkeley National Laboratory that is intended to validate whether frequency response is an appropriate metric for gauging the impacts on reliability of integrating increasing amounts of variable-output generation capacity into the three electrical interconnections. The study will do this by using today's transmission networks and generating facilities—including facilities under construction—as the basis for the models and studies in contrast to the alternative scenarios for 2024 used in EWITS. The new study is intended to investigate the frequency metric as an approach to identifying critical factors when integrating large amounts of variable generation into the bulk power system.

The EWITS team examined three different levels of transmission sensitivities. The level of transmission being modeled varied from no ties between areas to the different transmission levels of each existing and conceptual overlay scenario. These transmission sensitivities were

- Isolated system, stand-alone zone (no zone-to-zone interfaces modeled)
- Existing transmission system (constrained case and interface limits)
- Conceptual transmission overlay (increased zone-to-zone interface limits and new ties).

Data from the operational simulations were conditioned into the correct format for implementation into the LOLE model. Because that model uses a transportation representation for the transmission network, the study team ran a large number of additional production simulations to estimate the import capacity for each reliability zone. Predefined regional and planning areas were used as the modeling zones. Table 5 lists these zones along with the total nameplate amount of wind generation for each EWITS scenario.

TABLE 5. RELIABILITY ZONES FOR LOLE ANALYSIS WITH INSTALLED WIND GENERATION CAPACITY (NAMEPLATE WIND IN MEGAWATTS)				
Zone	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
MISO West	59,260	39,953	23,656	59,260
MISO Central	12,193	11,380	11,380	12,193
MISO East	9.091	6,456	4,284	9,091
MAPP USA	13,809	11,655	6,935	14,047
SPP North	48,243	40,394	24,961	50,326
SPP Central	44,055	46,272	25,997	44,705
PJM	22,669	33,192	78,736	93,736
TVA	1,247	1,247	1,247	1,247
SERC	1,009	5,009	5,009	5,009
NYISO	7,742	16,507	23,167	23,167
ISO-NE	4,291	13,837	24,927	24,927
Entergy	0	0	0	0
IESO[a]	0	0	0	0
MAPP Canada	0	0	0	0
FULL STUDY SYSTEM	**223,609**	**225,902**	**230,299**	**337,708**

[a] *Independent Electricity System Operator*

Results of the ELCC analysis, shown graphically in Figure 18 for the cases with existing and overlay transmission, indicate that the transmission network has a significant positive impact on the capacity value of wind generation. For the calendar year with the smallest contribution, the aggregate capacity value of wind generation by scenario ranges from 53 GW to almost 65 GW.

Although the influence of transmission on wind generation capacity value is intuitive, the magnitude of the contribution is striking. Considering both the existing and the overlay transmission concepts developed for EWITS, the aggregate wind generation capacity value is increased by more than 20 GW in the 20% cases, and by nearly 30 GW at 30% wind penetration.

The capacity value results vary depending on the year, which is consistent with observations in previous studies (see Bibliography). The magnitude of the interannual variation is actually smaller than that seen in some of the earlier results. This could be a consequence of both the scale of the model and the large volume of wind generation.

Assessing the capacity value of wind generation has been a staple of most of the integration studies conducted over the past several years. The approach taken in the EWITS project likely represents the most thorough and detailed investigation to date because of the size and scope of the model, the process by which area transfer limits were determined, and the sensitivities evaluated. The wind capacity values calculated in EWITS are significantly higher than those found in previous studies. The study team recognizes that the results represent a macro view, in which some important intraregional transmission constraints are not considered. Because the project focuses on transmission, though, the results represent a target resource adequacy contribution that could be achieved for the wind generation scenarios studied.

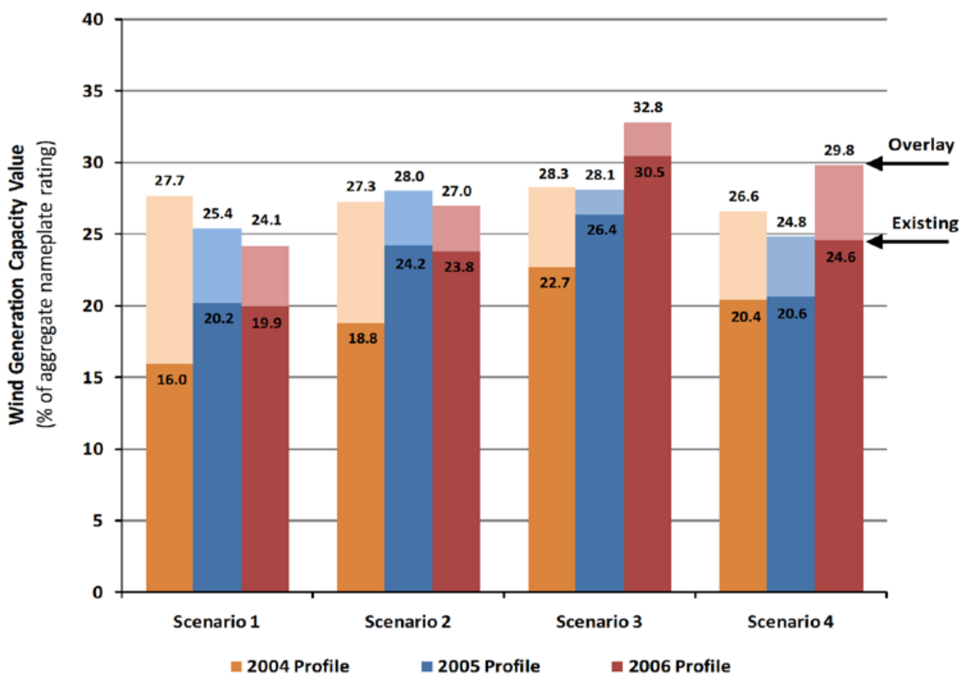


Figure 18. LOLE/ELCC results for high penetration scenarios, with and without transmission overlays

Specific findings and conclusions include the following:

- The LOLE analysis performed for EWITS shows that the existing transmission network in the Eastern Interconnection contributes roughly 50,000 MW of capacity benefits. With the transmission overlays developed for the EWITS wind scenarios, the benefit is increased by up to 8,500 MW.
- The LOLE analysis of the Eastern Interconnection with wind generation and the transmission overlays shows that the ELCC of the wind generation ranges from 24.1% to 32.8% of the rated installed capacity.
- The transmission overlays increase the ELCC of wind generation anywhere from a few to almost 10 percentage points (e.g., 18% to 28%).
- The ELCC of wind generation can vary greatly by geographic region depending on which historical load and wind profiles are being studied. Although interannual variations were observed, they are much smaller than those seen in previous studies (see, for example, EnerNex Corporation [2006]).
- Characteristics of the zonal ELCC differences among profiles tended to be the same across all four scenarios.

SUMMARY AND FUTURE WORK

The EWITS results represent a first detailed look at a handful of future snapshots of the Eastern Interconnection as it could exist in 2024. The analysis was driven primarily by economic considerations, with important technical aspects related to bulk power system reliability represented approximately or through engineering judgments.

EWITS is an important step in the uncertain world of long-range planning because it addresses questions such as feasibility and total ultimate costs, and begins to uncover important additional questions that will require answers. Although the TRC's representation from the Eastern Interconnection is extensive, the study team also recognizes that additional key stakeholders must be involved to further develop an interconnection-wide view of transmission system plans.

A complete evaluation of any of the scenarios would require a significant amount of additional technical analysis. The framework established by the scenario definitions and transmission overlay concepts, however, forms a foundation for conducting conventional power system planning to further evaluate the feasibility of these high-penetration scenarios and to improve the cost estimates.

Production simulation results from EWITS could be used to identify times of binding constraints or other periods of interest, such as large changes in wind production, minimum load periods, and conditions where loss of significant generation would raise questions about the security of the system. The state of the system during these periods—loads, committed generation and dispatch levels, and wind generation levels, among others—would be transferred to an appropriate AC power system model. A variety of power system engineering analyses could then be conducted to determine what additional equipment or operating limitations would be necessary to maintain system reliability. These analyses would include the following.

- An AC analysis that examines in more detail the power transfer limitations assumed in the production modeling. For EWITS, the team conducted production simulations using a DC power flow that does not consider the wide range of issues associated with voltage control and reactive power dispatch. An AC analysis would involve power flows that look at voltage and reactive compensation issues, dynamic and transient stability, and HVDC terminal control. Local and regional transmission needs could then be analyzed in much greater detail.
- Longer term dynamic analysis, where the actions of AGC, load tap changing on transformers, and capacitor or reactor switching for voltage control can be simulated and analyzed in much greater detail. Such dynamic analysis could examine subhourly market operation and

the response of generation to either AGC or market dispatch instructions while considering the limitations caused by prime mover or governor response, HVDC control actions, or special protective schemes. This analysis could be used to zoom in on system operation in real time, resulting in a higher confidence estimate of the operating reserve requirements and policies needed to maintain performance and reliability.

The analysis suggested for the large footprint considered in EWITS would require that many entities across the interconnection participate and collaborate. Personnel engaged in running similar studies with a regional focus would need to be involved, at a minimum, in a review capacity and for interpreting results. National entities such as NERC would also need to be engaged to oversee the development of the data sets and models. And because the size and scope of the system models might also require computational power beyond what is used today in the power industry, these suggested analyses could involve universities or national laboratories with appropriate resources.

The top-down views of the interconnection that EWITS yields constitute, in essence, the starting point for a substantially significant amount of subsequent engineering analysis. The analysis would paint a more accurate picture of the total transmission investment necessary, and illuminate measures necessary to preserve the security of the bulk power system. As with EWITS, such an effort would be beyond the scope of previous attempts, and would require cooperation and coordination at many levels to succeed.

Although EWITS is a technical study that examines future wind scenarios, the results pose some interesting policy and technology development questions:

- Could the levels of transmission, including the Reference Case, ever be permitted and built, and if so, what is a realistic time frame?
- Could the level of offshore wind energy infrastructure be ramped up fast enough to meet the aggressive offshore wind assumption in the EWITS scenarios?
- Would a different renewable profile or transmission overlay arise from a bottom-up process with more stakeholders involved?
- How can states and the federal government best work together on regional transmission expansion and the massive development of onshore and offshore wind infrastructure?
- What is the best way for regional entities to collaborate to make sure wind is optimally and reliably integrated into the bulk electrical grid?
- What is the difference between applying a carbon price instead of mandating and giving incentives for additional wind?

As is expected in a study of this type, especially when a wide variety of technical experts and stakeholders are giving ongoing input, a number of important variations on the 2024 future scenario can be envisioned. In addition, several technical areas in the study present opportunities for further technical investigation that could deepen understanding or reveal new insights:

- **Further analysis of production-cost simulation results:** The output from the many annual production simulations performed in EWITS contains detail on every generator and monitored transmission interface in the Eastern Interconnection. Because of scope and schedule constraints, the EWITS analysis was necessarily limited to summary results. Further analysis of these output data would likely generate additional valuable insights on impacts of wind generation on nonwind generation, and help define more detailed analyses that could be conducted in the future.
- **Smart grid implications and demand response sensitivities:** The Eastern Interconnection load considered in EWITS was based on regional projections out to the study year (2024). For the most part, load was considered "static." Major industry initiatives are currently exploring means by which at least a portion of the load might respond like a supply resource, thereby relaxing the constraints on scheduling and dispatch of conventional generating units. The implications for wind generation are potentially very significant, which is why alternative 2024 scenarios that consider the range of smart grid implications for the bulk electric system merit further consideration (scope limitations prevented these from inclusion in this phase of EWITS).
- **Nighttime charging of PHEVs:** Widespread adoption of electric vehicles has the potential to alter the familiar diurnal shape of electric demand. Because the wind resource is abundant at night and during the low-load seasons, increases in electric demand during these times could ease some of the issues associated with integration.
- **Commitment/optimization with high amounts of wind:** The approach for scheduling and dispatching generating resources used in the production simulations is based on current practice. In the future, new operating practices and energy market structures might be implemented that take advantage of the fact that uncertainty declines as the forecast horizon is shortened (for both load and wind generation). Intraday energy markets that allow reoptimization of the supply resources more frequently could offer some advantage for accommodating large amounts of variable and uncertain wind energy.
- **Fuel sensitivity:** In this phase of EWITS, the study team considered a single future for prices of other fuels used for electric generation. As history attests, there is much uncertainty and volatility inherent in some fuel markets, especially for natural gas. Alternate scenarios that explore the impacts of other fuel price scenarios on integration impacts and overall costs would be valuable.

- **The role and value of electrical energy storage:** With the substantial transmission overlays and the assumption of large regional markets, the EWITS results show that large amounts of wind generation can be accommodated without deploying additional energy storage resources. The ability to store large amounts of electrical energy, though, could potentially obviate the need for some of the transmission and reduce wind integration impacts. Analysis of bulk energy storage scenarios with generic storage technologies of varying capabilities would quantify the costs and benefits of an alternate means for achieving high penetrations of renewable energy.
- **Transmission overlay enhancement:** As described earlier, the analytical methodology was based on a single pass through what is considered to be an iterative process. Further analysis of the existing results could be used to refine the transmission overlays, which would then be tested in additional production simulations and LOLE analyses, along with AC power flow and stability analyses. This could reduce the estimated costs of the overlay and bolster the view of the required regional transmission expansion that would be needed to deliver the large amounts of wind energy to load.
- **Sequencing of overlay development:** EWITS focused on a snapshot of a 2024 scenario using a top-down perspective. The resulting transmission overlays and substantial amounts of wind generation would be developed over many years. An analysis over time—beginning now and extending to 2024—would yield important insights into the overall feasibility and costs of an aggressive transmission development future.
- **Wind generation curtailment:** Using wind generation curtailment selectively and appropriately could have high operational value. Although wind plants cannot increase their output at will without first spilling wind generation, downward movement is easily accomplished with today's wind generation technology. This could have very high economic value under certain circumstances. Wind generation is very capable of "regulating down"; for example, in an ancillary services market where the regulation service is bifurcated (i.e., regulation up and regulation down are separate services). Additional analysis of the scenarios studied in EWITS could help quantify what such a service would be worth to wind plant operators.

The current installed capacity of wind generation in many areas of the United States, coupled with prospective development over the next several years, requires that assessments of the bulk electric power system take a much broader view than has been typically employed. In addition, the unique characteristics of wind generation as an electrical energy supply resource are leading the power industry to new approaches for planning and analyzing the bulk electric power system.

Several of these techniques were demonstrated in EWITS, and are also being used in other large-scale wind integration analyses. The data sets compiled for the study represent the most detailed view to date of high-penetration wind energy futures and potential transmission. Given the significant changes coursing through the electric power industry, many alternative scenarios for the Eastern Interconnection in 2024 can be postulated. In that sense, EWITS is a solid first step in evaluating possibilities for the twenty-first century grid in the United States, with many more to follow.

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