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C. Smith
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D. Piwko and D. Lew
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A. Bloom, T. Mai, K. Clark, and M. Milligan
National Renewable Energy Laboratory

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Technical Report
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June 2015

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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List of Acronyms

BAU	business as usual
CO_2	carbon dioxide
CPP	Clean Power Plan
EFRS	Eastern Frequency Response Study
EGEAS	Electric Generation Expansion Analysis System
EPA	Environmental Protection Agency
EWITS	Eastern Wind Integration and Transmission Study
FRCC	Florida Reliability Coordinating Council
GE-MARS	GE Energy Multi-Area Reliability Simulation
ISO-NE	Independent System Operator New England
LOLE	loss-of-load expectation
MISO	Midcontinent Independent System Operator
MIT	Massachusetts Institute of Technology
MRITS	Minnesota Renewable Energy Integration and Transmission Study
MTEP	MISO Transmission Expansion Plan
NERC	North American Electric Reliability Corporation
NEWIS	New England Wind Integration Study
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PRIS	PJM Renewable Energy Integration Study
ReEDS	Regional Energy Deployment System
REF	Renewable Electricity Futures Study
RTEP	PJM's Regional Transmission Expansion Planning
SERC	Southeast Electric Reliability Corporation
SNSP	Simultaneous non-synchronous penetration
WECC	Western Electricity Coordinating Council
WWSIS	Western Wind and Solar Integration Study

Executive Summary

The proposed Environmental Protection Agency (EPA) Clean Power Plan (CPP) aims to cut carbon dioxide (CO_2) emissions from existing power plants to 30 percent below 2005 levels by 2030. The North American Electric Reliability Corporation (NERC) is preparing a series of reports to examine possible reliability concerns from the required change in the generation mix needed to achieve this target. In addition to describing their own analysis, NERC plans to highlight and summarize relevant and technically sound studies completed by other parties.

The purpose of this paper is to describe multiple studies of wind and solar integration that have found CO_2 reductions of approximately 30%. These studies can be viewed in several ways, including as viable paths to compliance with the EPA rule, alternative "bookend cases" to compare to compliance based largely on natural gas, or something in between. The studies in this paper represent a body of work that can help inform the public discussion surrounding the cost and reliability impacts of complying with the proposed EPA CPP.

Although it is possible to assume that a large-scale transition from coal to natural gas generation is the primary path to CPP compliance, there are actually many available paths toward compliance, and states will have significant flexibility in their approaches. Another path toward compliance emphasizes the use of wind and solar energy, and it has been studied very extensively during the past 15 years. Several recent wind and solar integration studies focused on power system operations, reliability, and stability while reducing CO_2 emissions by 30% or more.

The summaries that follow were initially drafted by principal investigators or technical review committees for each study and then edited to a consistent format. Not all studies examined all aspects of maintaining operational balance or reliability, but as a group these studies have examined a wide range of operational and reliability implications. We hope that this document assists NERC's efforts to include this relevant material in their reports. And more generally, we hope that this report is useful in showing that a 30% CO_2 reduction has already been extensively studied, and the body of work taken as a whole shows that reliable and cost-effective compliance is possible.

Table ES-1. Summary of Integration Studies and CO_2 Reduction Levels

Study	Region Scenario, Year	Primary Investigators	Variable Energy Resource Level	Carbon Reduction	Transmission Assumption	Focus of Analysis
PRIS	PJM, 2026	GE, AWS, EnerNex, Exeter, Intertek, PowerGEM	Multiple 20% and 30% scenarios	27% to 41%	2016–17 RTEP plus economic expansion	Broad, including subhourly operations, O&M, cycling, emissions
NEWIS	ISO-NE, 2020	GE, ISO-NE, EnerNex, AWS	Multiple scenarios up to 24%	30% at 24% wind penetration	2019 ISO-NE plus overlay from *New England Governors' Renewable Energy Blueprint*	Production simulation and LOLE reliability analysis
MRITS	MN and MISO-North/ Central, 2028	GE, Excel Engineering, MISO, MN utilities and transmission companies	Starting from 28.5% baseline, considered 40% and 50% levels of variable energy resource penetrations	Starting from the 28.5% baseline, some scenarios showed further CO_2 reductions of 11.5% to 19%	MTEP 2013, expanded via power flow analysis	Dynamics including transient stability and system strength analysis, production simulation
WWSIS	WECC, 2017 and 2022	NREL, GE, Intertek, 3TIER, others	Up to 35% in WestConnect and 23% in the rest of the Western Interconnection WWSIS-2: 33% in the United States (equivalent to 24% to 26% across the Western Interconnection)	WWSIS-1: Reduced CO_2 emissions by 25% to 45%, depending on gas price, across Western Interconnection WWSIS-2: Reduced CO_2 by 29% to 34%	Use of current underutilized transmission plus various interstate transmission expansion options	WWSIS-1: production simulation; WWSIS-2: cycling; WWSIS-3: stability and dynamics
EFRS	Eastern Interconnection, 2013	GE, NREL	25% in Eastern Interconnection (40% in Eastern Interconnection excluding SERC and FRCC)	Wind replaced thermal generation at existing power plant sites	Detailed model of the current system	AC power flow, 60-s dynamic simulations
EWITS	Eastern Interconnection, 2024	NREL, EnerNex, MISO, Ventyx	30% and multiple 20% scenarios	19% with 30% wind and no carbon price, 32% with 20% wind plus carbon price	Economic build-out using EGEAS model	Production cost (PROMOD) and power flow (GE-MARS)
REF	National	NREL, MIT, others	50% variable energy resource, 80% total renewable energy	40% by 2030, 80% by 2050	Expansion estimated in ReEDS	Capacity expansion and production simulation

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PJM Renewable Energy Integration Study (2014)

Relevance to NERC and EPA CPP Analysis

While working closely with PJM during a period of three years, GE and numerous stakeholders examined aspects of power system performance incorporating renewable energy integration, including hourly operation, subhourly operation (variability and fast ramps), transmission utilization/congestion, thermal plant cycling, operating costs, emissions, and resource adequacy using extensive loss-of-load expectation (LOLE) analysis. Based on this modeling of subhourly operation, O&M, cycling, and LOLE, no significant risks to system security were found. The study concluded that as long as sound engineering practices and judgment were applied to system design/implementation, the PJM system would be as robust with 20% to 30% renewable energy penetration as it would be with the existing generation fleet.

Overview

This study did an exhaustive analysis of many scenarios, as shown in the following table, including various mixes of offshore wind, onshore wind, solar photovoltaic, and dispersed wind. The impacts on coal- and gas-fired generators were carefully studied with respect to ramping, cycling operations, and environmental emissions. GE MAPS production cost simulations were used to calculate the steady-state "without cycling" emission amounts, which were then updated using Intertek's regression results to generate the total "with cycling" emissions estimates.

Table 1. CO_2 Emissions from PJM Power Plants for the PRIS Study Scenarios

Scenario	Reduction in MWh Energy Output from Coal and Gas Plants Relative to 2% BAU Scenario	Reduction in Heat Input (Fuel) Relative to 2% BAU Scenario	Reduction in CO_2 Emissions Relative to 2% BAU Scenario
14% Renewable Portfolio Standards	15%	14%	12%
20% HOBO[a]	20%	18%	14%
20% HSBO[b]	18%	16%	15%
20% LOBO[c]	19%	19%	18%
20% LODO[d]	18%	18%	17%
30% HOBO	35%	32%	27%
30% HSBO	31%	29%	28%
30% LOBO	40%	40%	41%
30% LODO	30%	29%	29%

[a] HOBO: High offshore, best onshore
[b] HSBO: High solar, best onshore
[c] LOBO: Low offshore, best onshore
[d] LODO: Low offshore, dispersed onshore

Major Assumptions

The study evaluated renewable energy (wind and solar) penetration levels of 2%, 14%, 20%, and 30% for the entire PJM system. PJM annual load energy was extrapolated to the study year 2026 using a method to retain critical daily and seasonal load shape characteristics with average annual load growth for PJM assumed to be 1.1%. Load for the rest of the Eastern Interconnection was based on Ventyx "Historical and Forecast Demand by Zone" data.

Some existing PJM power plants were assumed to retire by 2026, per retirement forecast data from PJM and Ventyx. New thermal generators (approximately 35 GW from simple-cycle gas turbines and 6 GW from combined-cycle gas turbines) were added to the PJM system in the 2% business-as-usual (BAU) scenario to meet the reserve margin requirements in 2026 consistent with the assumed load growth (for a total of approximately 65 GW from simple-cycle gas turbines and 38 GW from combined-cycle gas turbines). For consistency among scenarios, the new thermal generators added to meet reserve requirements in the 2% BAU scenario remained available in all higher renewable penetration scenarios. All operating power plants were assumed to have the necessary control technologies to comply with emissions requirements.

Summary of the Analysis

The study included the following analytical tasks:

- Statistical characterization of load, wind, and solar power profiles to understand how variability and uncertainty change with increasing levels of variable energy resource penetration
- Analysis of reserve requirements as a function of wind and solar generation, with results verified using production simulations and subhourly operation simulations
- Conceptual transmission plans developed to serve new generation resources
- Production simulation analysis to evaluate hourly operations for three calendar years
- Subhourly operation simulations to evaluate performance during fast-ramping events, showing if reserves and system ramping capability are adequate to keep the system within required performance targets. This analysis used PROBE, a tool that PJM regularly uses to verify the performance of its subhourly markets.
- Capacity value of wind/solar resources using LOLE analysis to establish the ability of wind and solar resources to contribute to resource adequacy
- Analysis of cycling duties on thermal plants, including potential increases in wear and tear caused by increased cycling, analyzed by experts in this field from Intertek.

Key Findings

The study findings indicated that the PJM system, with transmission expansion and regulating reserves as identified in the report, would not have any significant issues operating with up to 30% of its energy provided by wind and solar generation.

- Although the values varied based on total penetration and the type of renewable generation added, on average 36% of the delivered renewable energy displaced PJM coal-fired generation, 39% displaced PJM gas-fired generation, and the rest displaced PJM imports (or increased exports).

- No insurmountable operating issues were uncovered during the many simulated scenarios of system-wide hourly operations, and this was supported by hundreds of hours of subhourly operations using actual PJM ramping capability.
- Curtailment of the renewable generation was minimal, and this tended to be from localized congestion rather than from broader system constraints.
- Every scenario resulted in lower PJM fuel and variable operations and maintenance (O&M) costs as well as lower average locational marginal prices (LMPs). When combined with the reduced capacity factors, the lower LMPs resulted in lower gross and net revenues for the conventional generation resources. No examination was made to determine if this might result in advanced retirement dates for some of the less viable generation.
- Some additional regulation was required to compensate for the increased variability introduced by the renewable generation. The 30% scenarios, which added more than 100,000 MW of renewable capacity, required an annual average of only 1,000 MW to 1,500 MW of additional regulating reserves compared to the approximately 1,200 MW of regulating reserves modeled for load alone. No additional operating (spinning) reserves were required.
- In addition to the reduced capacity factors on the thermal generation, some of the higher penetration scenarios showed new patterns of usage. High penetrations of solar generation significantly reduced the net loads during the day and resulted in economic operations that required the peaking turbines to run for a few hours prior to sunrise and after sunset rather than committing larger intermediate and baseload generation to run throughout the day.
- The renewable generation increased the amount of cycling (start-up, shutdown, and ramping) on the existing fleet of generators, which increased variable O&M costs on these units. These increased costs were small relative to the value of the fuel displacement and did not significantly affect the overall economic impact of the renewable generation.
- Although cycling operations will increase a unit’s emissions relative to steady-state operations, these increases were small relative to the reductions caused by the displacement of the fossil-fueled generation.

Study Report

- PRIS website: https://www.pjm.com/committees-and-groups/subcommittees/irs/pris.aspx
- GE Energy, *PJM Renewable Integration Study*: https://www.pjm.com/committees-and-groups/subcommittees/irs/pris.aspx.

New England Wind Integration Study (2010)

Relevance to NERC and EPA CPP Analysis

The Independent System Operator New England (ISO-NE) study found that 24% wind penetration would reduce ISO-NE's CO_2 emissions by 30% (a reduction of 15 million tons annually), whereas SO_X and NO_X would be reduced by 8% and 30%, respectively. At 24% wind energy penetration, natural gas resources would still provide more than 25% of total annual energy, but this would represent a major shift in the fuel mix for the region. Because total annual energy output from conventional resources would decline and energy prices would also decline under these study assumptions, capacity prices from these plants may need to increase.

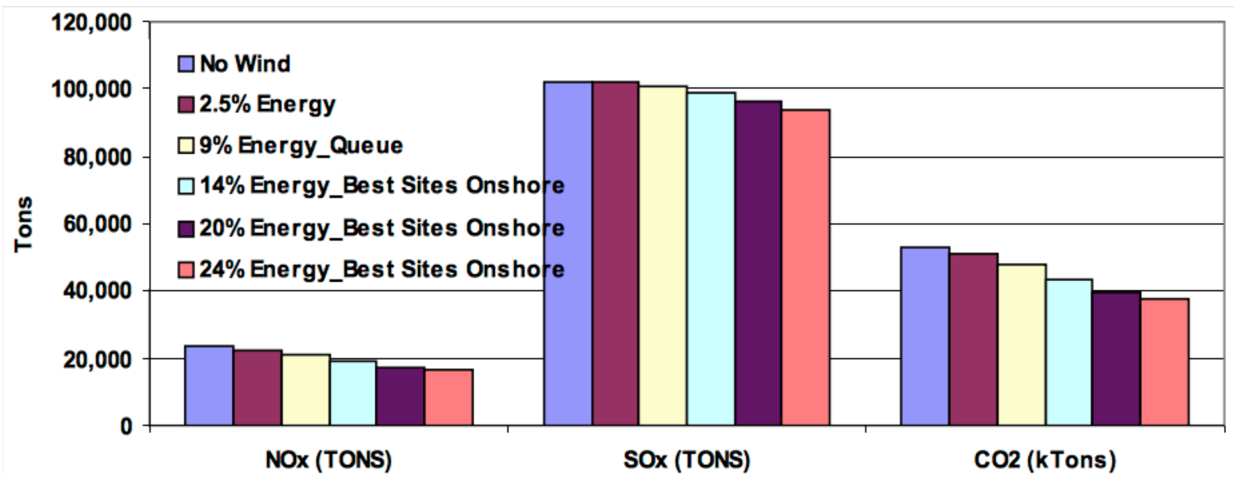

Figure 1. ISO-NE total emissions state-of-the-art forecast, best sites onshore. ***Image from*** **Final Report: New England Wind Integration Study** ***(p. 217)***

Major Assumptions

The base case and wind generation scenarios, developed in consultation with ISO-NE and stakeholders, included potential and probable scenarios for wind power development up to 24% annual wind energy penetration. Three years of synthesized meteorological and wind production data corresponding to calendar years 2004, 2005, and 2006 were used. Historical load data for those same calendar years were scaled up to account for anticipated load growth through year 2020. Production simulations were conducted to evaluate the hourly operation of the various scenarios and penetration levels for three calendar years, and rigorous reliability calculations were made using LOLE methods to evaluate the capacity value of the wind generation.

A fundamental assumption in the New England Wind Integration Study (NEWIS) is that the transmission required to integrate the wind generation into the bulk power system would be available and that wind power resources would interconnect to those bulk transmission facilities. The available portfolio of non-wind generation in New England and neighboring systems was held constant among all scenarios.

Summary of the Analysis

The primary objective of this study was to identify and quantify system performance or operational problems with respect to load following, regulating, and operating reserves operation during low-load periods. Three primary analytical methods were used to meet this objective: statistical analysis, hourly production simulation analysis, and reliability analysis.

Statistical analysis was used to quantify variability due to system load as well as wind generation during multiple time frames (annual, seasonal, daily, hourly, and 10-minute). Production simulation analysis was used to evaluate hour-by-hour grid operation of each scenario for three years with different wind and load profiles. The production simulation results included an analysis of the available ramp-up and ramp-down capability to deal with grid variability due to load and wind and changes in emissions due to renewable generation, among others. The reliability analysis involved LOLE calculations for the ISO-NE system, including capacity value of the wind resources.

Key Findings

The study results showed that New England could integrate wind resources to meet up to 24% of the region's total annual electric energy needs in 2020 if its system includes transmission upgrades comparable to the configurations identified in the *New England Governors' Renewable Energy Blueprint* (a prior analysis performed at the request of the six New England governors).[1] The existing ISO-NE generation fleet is dominated by natural gas–fired resources, which are potentially very flexible in terms of ramping and maneuvering. Natural gas resources provide approximately 50% of total annual electric energy in New England assuming no wind generation on the system. Wind generation would primarily displace natural gas–fired generation, because gas-fired generation is most often on the margin in the ISO-NE market.

The results of this analysis indicated that integrating wind generation up to the 24% wind energy scenario is operationally feasible and may reduce average system-wide variable operating costs (i.e., fuel and variable O&M costs) in ISO-NE by $50/MWh to $54/MWh of wind energy. Considering that wind generation primarily displaces natural gas–fired generation in New England, the overall CO_2 production declines by 30% with 24% wind energy penetration.

Self-scheduled generation reduces the flexibility of the dispatchable generation resource and can lead to excessive wind curtailment at higher penetrations of wind generation. It is recommended that ISO-NE examine its policies and practices for self-scheduled generation and possibly change those policies to encourage more generation to remain under the control of ISO-NE dispatch commands. ISO-NE may need to investigate operating methods and/or market structures to encourage the generation fleet to make its physical flexibility available for system operations.

Study Reports

- Executive summary—GE Energy, *Final Report: New England Wind Integration Study*: http://variablegen.org/wp-content/uploads/2013/01/newis_es.pdf
- Final report—GE Energy, *Final Report: New England Wind Integration Study*: http://variablegen.org/wp-content/uploads/2013/01/newis_report.pdf.

[1] See http://www.nescoe.com/uploads/September_Blueprint_9.14.09_for_release.pdf.

Minnesota Renewable Energy Integration and Transmission Study (2014)

Relevance to NERC and EPA CPP Analysis

The Minnesota Renewable Energy Integration and Transmission Study (MRITS) broke new ground in the level of attention brought to dynamics analysis and transient stability analysis at high wind and solar penetration levels, so it should be of great interest to those interested in system stability. This builds on a rich history of Minnesota and Midcontinent Independent System Operator (MISO) studies, including the 2006 Minnesota Wind Integration Study, the 2007 Minnesota Transmission for Renewable Energy Standard Study, the 2009 Minnesota RES Update, Corridor, and Capacity Validation studies, the 2008 and 2009 Statewide Studies of Dispersed Renewable Generation, the 2010 Regional Generation Outlet Study, the 2011 Multi Value Project Portfolio Study, the 2013 Minnesota Biennial Transmission Project Report, the 2013 MISO Transmission Expansion Plan, and recent and ongoing MISO transmission expansion planning work.[2]

Major Assumptions

MRITS focused on the combined operating areas of the Minnesota utilities and transmission companies in the context of the MISO North/Central market and the neighboring regions to the west and north. It evaluated the impacts on reliability and costs associated with increasing renewable energy to 40% of Minnesota retail electric energy sales by 2030, and to higher proportions thereafter, with a conceptual plan for transmission necessary for access to regional geographic diversity and regional system flexibility.

For the dynamic and stability analysis, it was assumed that:

- New wind turbine generators are a mixture of Type 3 and Type 4 turbines with standard controls.
- New wind and utility-scale solar generation is compliant with present minimum performance requirements—i.e., they provide voltage regulation/reactive support and have zero-voltage ride-through capability.
- Local-area issues are addressed through normal generator interconnection requirements.

Summary of the Analysis

The key study tasks were to:

- Develop study scenarios and site wind and solar generation (Lead contributors: Minnesota Utilities and Minnesota Department of Commerce)
- Perform production simulation analysis (Lead contributor: MISO)
- Perform power flow analysis and develop transmission conceptual plan (Lead contributors: Minnesota utilities and transmission owners and Excel Engineering)

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[2] See http://uvig.org/resources/#!/3700/u-s-regional-and-state-studies.

- Evaluate operational performance (Lead contributor: GE Energy)
- Screen for challenging periods (Lead contributor: GE Energy)
- Evaluate stability-related issues, including transient stability performance, voltage regulation performance, adequacy of dynamic reactive support, and weak system strength issues (Lead contributor: GE Energy)
- Identify and develop mitigations and solutions (Lead contributor: GE Energy)

Key Findings

The analytical results from this study showed that the addition of wind and solar (variable renewable) generation to supply 40% of Minnesota's annual electric retail sales can be reliably accommodated by the electric power system. The MRITS operational and dynamics analyses results showed that with upgrades to existing transmission, the power system can be successfully operated for all hours of the year (with no unserved load, no reserve violations, and minimal curtailment of renewable energy) with wind and solar resources increased to achieve 40% renewable energy in Minnesota and with current renewable energy standards fully implemented in neighboring MISO North/Central markets.

This is operationally achievable with most coal power plants operated as baseload must-run units, similar to existing operating practice. It is also achievable if all coal power plants are economically committed per MISO market signals, but additional analysis would be required to better understand the implications, trade-offs, and mitigations related to increased cycling duty. Dynamic simulation results indicated that no fundamental system-wide dynamic stability or voltage regulation issues would be introduced by the renewable generation

Further analysis would be needed to ensure system reliability at 50% of Minnesota's annual electric retail sales from variable renewables. With wind and solar resources increased to achieve 50% renewable energy in Minnesota and 25% renewable energy in MISO North/Central (10% above current renewable energy standards in neighboring states), MRITS production simulation results showed that, with significant transmission upgrades and expansions in the five-state area, the power system could be successfully operated for all hours of the year (with no unserved load, no reserve violations, and minimal curtailment of renewable energy). Because of study schedule limitations, no dynamic analysis was performed for 50% renewable energy in Minnesota, and this analysis is necessary to ensure system reliability.

Study Reports and Presentations

- GE Energy, *Minnesota Renewable Energy Integration and Transmission Study: Final Report*: https://mn.gov/commerce/energy/images/final-mrits-report-2014.pdf.

Western Wind and Solar Integration Study Phases 1–3 (2010–2013)

Relevance to NERC and EPA CPP Analysis

Through a coordinated sequence of three major studies funded by the U.S. Department of Energy, the Western Interconnection has become one of the most thoroughly studied areas for wind and solar integration. The Western Wind and Solar Integration Study Phase 2 (WWSIS-2) was the first study to thoroughly analyze the impacts on the conventional generator fleet in terms of O&M costs and emissions. WWSIS Phase 3 (WWSIS-3) broke new ground in the analysis of reliability at high wind and solar penetrations, including detailed modeling of dynamics and stability.

Overview

Supported by funding from the U.S. Department of Energy, the National Renewable Energy Laboratory (NREL) undertook extensive research into the operation of the power system under high penetrations of wind and solar generation in the Western Interconnection. NREL worked closely with a diverse committee of regional experts to push the limits of existing modeling capabilities to perform rigorous and objective analyses at increasing levels of precision, fidelity, and resolution.

In Phase 1 (WWSIS-1) NREL teamed with GE to analyze the operational impacts of integrating 30% wind and 5% solar for WestConnect, with 23% annual levels of variable generation in the rest of the Western Interconnection. (WestConnect consists of the major transmission providers in the states of Arizona, Colorado, Nevada, New Mexico, Wyoming, and parts of other states. It includes Arizona Public Service, El Paso Electric Company, NV Energy, Public Service Company of New Mexico, Salt River Project, Tri-State Generation and Transmission Association, Tucson Electric Power, Western Area Power Administration, and Xcel Energy.)

Two years later, in WWSIS-2 NREL modeled the entire Western Interconnection with new data sets, production cost models, and subhourly analysis to understand how cycling of fossil-fueled generators impacted system emissions and production costs under different wind and solar mixes totaling 33% combined wind and solar generation in the western United States (equivalent to 24% to 26% across the Western Interconnection).

More recently, in WWSIS-3 NREL and GE conducted frequency response and transient stability analysis on select intervals from Phase 2 to understand the reliability impacts of up to a combined 53% instantaneous wind and solar penetration level. Taken as a whole, these studies document how wind and solar generation can effectively be used to reduce system-wide emissions while meeting several key metrics with respect to economics and reliability, given the assumptions discussed in more detail below.

Major Assumptions and Summary of the Analysis

WWSIS-1

- Region: Focused on WestConnect; modeled all of the Western Interconnection
- Type: Production simulation

- Temporal resolution: Hourly, with limited 10-minute and 1-minute resolutions
- Transmission representation: Zonal
- Power flow: DC
- Model: GE MAPS
- Reserves: Contingency at 6% of load (3% spinning and 3% nonspinning)
- Fuel prices: $2/MBTU coal, $9.50/MBTU natural gas
- Regional cooperation: Extensive
- Thermal expansion: Gas combined-cycle generation, not optimized for renewables
- Hydropower: Not meteorologically synchronized with wind, solar, and load data

WWSIS-2

- Region: Western Electricity Coordinating Council (WECC)
- Type: Production simulation
- Temporal resolution: 5-minute
- Transmission representation: Zonal, no hurdle rates, expansion performed using PLEXOS iterations
- Power flow: DC
- Model: PLEXOS
- Reserves: Contingency (3% spinning), regulating, flexibility
- Fuel prices (vary by region): $1.60/MMBtu coal; $2.30/MMBtu, $4.60/ MMBtu, $9.20/MMBtu gas
- Regional cooperation: Regulating reserves shared across WECC, contingency and flexibility reserves held by zone
- Thermal expansion: Not optimized for renewables, based on projected build-out by WECC for 2022
- Hydropower: One-third of hydropower has no flexibility, two-thirds of hydropower has some flexibility based on WECC assumptions

WWSIS-3

- Region: WECC
- Type: Transient stability and frequency response
- Time frame: 60-second dynamic simulations
- Power flow: AC
- Model: PSLF (Positive sequence load flow)
- Transmission: Detailed model, with additions deemed likely by WECC stakeholders during WECC power flow case development

- Wind and solar generation aligned with WWSIS 2
- Change in conventional generation dispatch due to wind and solar aligned with WWSIS 2

Key Findings

WWSIS-1

- It is feasible for the WestConnect region to accommodate 30% wind and 5% solar energy penetration. This requires key changes to current practice, including substantial balancing area cooperation, subhourly scheduling, and access to underutilized transmission capacity.
- Both variability and uncertainty of wind and solar generation impact grid operations; however, the uncertainty (due to imperfect forecasts) leads to a greater impact on operations and results in some contingency reserve shortfalls and some curtailment, both of which are relatively small. The variability leads to a greater subhourly variability reserve requirement, but because conventional units are backed down, the system naturally has extra reserve margins.

WWSIS-2

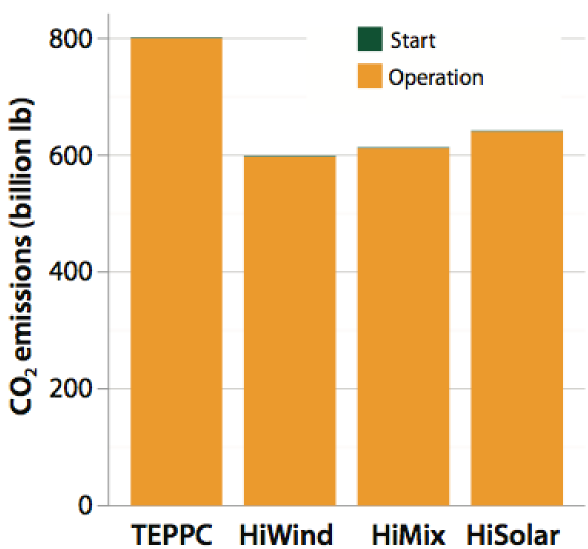

Figure 2. WWSIS-2 results showing absolute $CO2_2$ emissions disaggregated into operations and starts. (Ramping emissions are not shown, because they were found to have no significant impact.)

- High penetrations of wind and solar increase annual wear-and-tear costs from cycling from $35 million to $157 million. This represents an additional $0.47/MWh to $1.28/MWh of cycling costs for the average fossil-fueled generator. Cycling diminishes the production cost reduction of wind and solar from $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/MWh to $29/MWh of wind and solar generated). However, the costs are significant compared to the average steady-state variable O&M and cycling costs of fossil-fueled plants ($2.43/MWh to $4.68/MWh, depending on scenario). Production costs do not include the capital or power purchase agreement costs to construct power plants or transmission lines.

- 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 the wind and solar generation. 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 from 2% to 5% less than expected and NO_X emissions reductions to be from 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.
- Solar tends to dominate variability challenges for the grid; wind tends to dominate uncertainty challenges. Both of these challenges can be mitigated. Because the largest component of solar variability is known—the path of the sun through the sky—this can be planned for in the unit commitment. The day-ahead wind forecast error can be mitigated with a 4-hour-ahead commitment of gas units to take advantage of the improved forecasts.
- Although wind and solar affect the grid in very different ways, their impacts on system-wide production costs are remarkably similar.

WWSIS-3

Transient Stability

- System-wide transient stability can be maintained with high levels of wind and solar generation if local stability, voltage, and thermal problems are addressed with traditional transmission system reinforcements (e.g., transformers, shunt capacitors, local lines). With these reinforcements, an 80% reduction in coal plant commitment, which drove simultaneous non-synchronous penetration (SNSP) to 56%, resulted in acceptable transient stability performance.
- With further reinforcements, including nonstandard items such as synchronous condenser conversions, a 90% reduction in coal plant commitment, which drove SNSP to 61%, resulted in acceptable transient stability performance.
- Additional transmission and concentrating solar power generation with frequency-responsive controls are effective at improving transient stability.

Frequency Response

- System-wide frequency response can be maintained with high levels of wind and solar generation if local stability, voltage, and thermal problems are addressed with traditional transmission system reinforcements (e.g., transformers, shunt capacitors, local lines).
- Limited application of nontraditional frequency-responsive controls on wind, solar photovoltaic, concentrating solar power plants, and energy storage are effective at improving both frequency nadir and settling frequency, and thus frequency response. Refinements to these controls would further improve performance.
- Individual balancing authority area frequency response may not meet its obligation without additional frequency response from resources both inside and outside the particular area. As noted above, nontraditional approaches are effective at improving frequency response. Current operating practices use more traditional approaches (e.g., committing conventional plants with governors) to meet all frequency-response needs.

- Using new, fast-responding resource technologies (e.g., inverter-based controls) to ensure adequate frequency response adds complexity and flexibility to high levels of wind and solar generation. Control philosophy will need to evolve to take full advantage of easily adjustable speed of response, with additional consideration of the location and size of the generation trip.
- For California, adequate frequency response was maintained during acute depletion of headroom from the afternoon drop in solar production, assuming the ability of California hydropower to provide frequency response.

Additional Conclusions

- Accurate modeling of solar photovoltaic, concentrating solar power, wind, and load behavior is extremely important when analyzing high-stress conditions, because all of these models had an impact on system performance.
- Attention to detail is important. Local and locational issues may drive constraints on both frequency response and transient stability.
- The location of generation tripping (e.g., distributed generation compared to a central station) is not as important as the amount of generation that is tripped; however, widespread deliberate or common-mode distributed generation tripping after a large disturbance has an adverse impact on system performance. It is recommended that practice adapt to take advantage of new provisions in IEEE 1547 that allow for voltage and frequency ride-through of distributed generation to improve system stability.
- Further analysis is needed to determine operational limits with low levels of synchronous generation to identify changes to path ratings and associated remedial action schemes and quantify the impact of distributed generation on transmission system performance.
- Because a broad range of both conventional and nonstandard operation and control options improved system performance, further investigation of the most economic and effective alternatives is warranted. This should include consideration of the costs and benefits of constraining commitment and dispatch to reserve frequency response and the capital and operating costs of new controls and equipment.

Study Reports and Presentations

- Western Wind and Solar Integration Study website: http://www.nrel.gov/electricity/transmission/western_wind.html
- GE Energy, *Western Wind and Solar Integration Study*: http://www.nrel.gov/docs/fy10osti/47434.pdf
- NREL, *The Western Wind and Solar Integration Study Phase 2*: http://www.nrel.gov/docs/fy13osti/55588.pdf
- GE Energy Management, *The Western Wind and Solar Integration Study Phase 3: Frequency Response and Transient Stability*: http://www.nrel.gov/docs/fy15osti/62906.pdf.

Eastern Frequency Response Study (2013)

Relevance to NERC and EPA CPP Analysis

NERC is concerned about the transition from conventional thermal generation to wind and other new sources of energy and reliability services, and frequency response is a topic of particular concern. This has motived the creation of NERC's Essential Reliability Services Task Force. The Eastern Frequency Response Study (EFRS) specifically looked at this topic for the Eastern Interconnection in a way that informs both the modeling of the Eastern Interconnection as it exists today and how it would behave with a high level of wind penetration: 25% overall in the Eastern Interconnection, or 40% in the balance of the Eastern Interconnection NERC regions if the Southeast Electric Reliability Corporation (SERC) and the Florida Reliability Coordinating Council (FRCC) are excluded from the calculation.

Major Assumptions

- Region: Eastern Interconnection
- Type: Frequency response
- Time frame: 60-second dynamic simulations
- Power flow: AC power flow
- Model: PSLF
- Transmission: Detailed model
- Broad changes to governor models so simulations match measurements
- 25% wind penetration across the Eastern Interconnection
- New wind generation replaced thermal generation at existing power plant sites
- No solar generation added

Summary of the Analysis

NREL teamed with GE to analyze the frequency response of the Eastern Interconnection under possible future system conditions with high levels of wind generation. The main goals of this work were to create a realistic baseline model of the Eastern Interconnection to examine frequency response, investigate the possible impact of large amounts of wind generation, and examine means to improve Eastern Interconnection frequency response by using active power controls on wind power plants.

The dynamic representation of the Eastern Interconnection is known to poorly reflect the observed behavior. To develop the desired benchmark system performance, broad changes were made to models throughout the system. GE expertise on power plant control and operation were used to improve the standard database, particularly with regard to the possible root causes of the observed frequency response of the Eastern Interconnection. Power plant models for hundreds of plants across the interconnection were modified based on plant size, fuel, and turbine type. These changes were based on a general understanding of plant behavior, not on any knowledge of the specific behavior of individual plants.

To examine the possible impact of high levels of wind penetration on the Eastern Interconnection, new wind generation of approximate 85GW, operating at a total production of 68 GW, was added across all of the NERC regions except SERC and FRCC. This represented a wind penetration of approximately 40% for those regions and 25% for the Eastern Interconnection as a whole.

Modern wind turbines and wind power plants can contribute to frequency response with governor and inertial response controls. These controls are commercially available and vary somewhat between suppliers. Their use is not widespread in North America at this time. Simulations in which these controls were enabled were examined to test mitigation options.

Key Findings

The dynamic model of the Eastern Interconnection can be adjusted to more closely capture observed behavior. The Eastern Interconnection model improvements made in this investigation were not performed with the necessary rigor to be definitive. The evidence indicated that many generators must be operating differently than the current model from the multiregional modeling working group. Specifically, most machines must have their governors disabled or be equipped with load reference set-point controls that defeat or diminish governor response. A detailed investigation of the performance of individual units in response to actual grid events is recommended.

The overall frequency response of the Eastern Interconnection is adequate for the cases examined. The overall frequency response of the Eastern Interconnection to a large system event is above the frequency response obligation currently proposed by NERC. This study was not intended to verify the performance of individual regions or balancing authority areas. None of the conditions that were examined, including cases with high levels of wind generation (up to 40% penetration in all NERC regions except FRCC and SERC), resulted in underfrequency load shedding or other stability problems.

The fraction of generation providing governor control must be maintained above a minimum level. This study showed that the fraction of generation participating in governor control, Kt, is a primary metric for expected performance. Broadly, maintaining a minimum Kt on the order of 30% appears necessary, and it is consistent with other findings.

Governor withdrawal on thermal plants causes degradation in frequency response. Governor withdrawal occurs when a deliberate load control acts to nullify a plant's governor response. In this study, it caused an approximate 44% degradation in frequency response for the case with approximately 30% of the generation participating in governor control. Approximately two-thirds of the responsive plants were affected, which is similar to levels found in NERC's work.

Governor response from wind power plants can provide significant primary frequency response. The systemic benefit of these responses can be several times greater per megawatt than was observed for governor response in the synchronous fleet. Curtailment of available wind generation to provide this service would represent a substantial opportunity cost to wind power plant owners. Governor controls for wind power plants are commercially available, but at present they are not used on wind power plants in the Eastern Interconnection.

Inertial controls on wind power plants can improve the frequency nadir. Reduction in system inertia resulting from higher penetrations of renewable generation per se may not have a significant impact on frequency response when compared to governor action. Fast transient frequency support via controlled inertial response from wind turbines, however, was shown to significantly improve the frequency nadir.

Damping of inter-area oscillations in the Eastern Interconnection tended to improve with wind penetration; however, further analysis is necessary to determine whether this because of the increasing wind penetration, the associated decommitment of thermal generation, or modeling inaccuracies. Such analytical efforts can be performed in conjunction with improvements to the Eastern Interconnection model fidelity.

Frequency response of the Eastern Interconnection for this challenging condition with high levels of wind generation met current standards of performance. Operational options using both synchronous generation and wind power plant controls can beneficially affect system performance. Changes to operational procedures, markets, and interconnection requirements could be needed to avoid frequency response problems in the future.

Study Reports and Presentations

- GE Energy, *Eastern Frequency Response Study*: http://www.nrel.gov/docs/fy13osti/58077.pdf.

Eastern Wind Integration and Transmission Study (2010)

Relevance to NERC and EPA CPP Analysis

The Eastern Wind Integration and Transmission Study (EWITS) was the first wind integration study of this scope. It considered the entire Eastern Interconnection and initially focused on 20% wind penetration scenarios but added a 30% scenario as well.

Major Assumptions

- Region: Eastern Interconnection—ISO-NE, NYISO, MISO, PJM, SERC, Southwest Power Pool, and Tennessee Valley Authority
- Type: Production simulation
- Temporal resolution: Hourly, with limited 15-minute resolution
- Transmission representation: Zonal

Production cost modeling

- Power flow: DC
- Model: PROMOD IV

Reliability modeling

- Power flow: Transportation model
- Model: GE Energy Multi-Area Reliability Simulation (GE-MARS)

Capacity expansion

- Model: Electric Generation Expansion Analysis System (EGEAS)
- Reserves: Regulating (1% of load), flexibility (1% of load)
- Fuel Prices (vary regionally): Average \$2.45/MBTU coal; average \$15.84/MBTU natural gas
- Regional cooperation: Extensive

Summary of the Analysis

The U.S. Department of Energy commissioned EWITS through NREL. The investigation began in 2007, and the resultant report was published in 2010. The study was the first of its kind in terms of scope, scale, and process. It 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. The Eastern Interconnection is one of 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 Texas.

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

Key Findings

- High penetrations of wind generation—from 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 in the Eastern Interconnection, including the reference case. Planning for this transmission is imperative, because it takes longer to build new transmission capacity than it does to build new wind power plants.
- Without transmission enhancements, substantial curtailment (shutting down) 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.
- 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 comprise a relatively small portion of the total annualized costs in any of the scenarios studied.
- Carbon emission reductions in the three 20% wind scenarios did not vary by much, indicating that wind displaced coal in all scenarios and that coal generation is not significantly exported from the Midwest to the eastern United States. Carbon emissions were reduced at an increased rate in the 30% wind scenario as more gas generation was used to accommodate wind variability. Wind generation displaced carbon-based fuels, directly reducing CO_2 emissions. Emissions continued to decline as more wind was added to the supply picture. Increasing the cost of carbon in the analysis resulted in higher total production costs and higher reductions. For example, CO_2 emissions were reduced by 19% with 30% wind and no carbon price, but by 32% with 20% wind in the carbon price scenario.

Study Reports and Presentations

- EnerNex Corporation, *Eastern Wind Integration and Transmission Study*: http://www.nrel.gov/docs/fy11osti/47078.pdf.

Renewable Electricity Futures Study (2012)

Relevance to NERC and EPA CPP Analysis

The Renewable Electricity Futures (REF) Study went well beyond the level of the EPA CPP by considering the capability and issues for obtaining 30% to 90% of U.S. electricity generation from renewable energy. Reductions in annual greenhouse gas emissions of approximately 80% (on a direct combustion basis and on a full life-cycle basis) and in annual power sector water use of approximately 50% were found for the scenarios of obtaining 80% renewables by 2050.

Overview

REF was an initial investigation of the extent to which renewable energy supply can meet the electricity demands of the contiguous United States throughout the next several decades. This study included geographic and electric system operation resolution that was unprecedented for long-term studies of the U.S. electric sector. The analysis examined the implications and challenges of renewable electricity generation levels in 2015—from 30% up to 90%, with a focus on 80%, of all U.S. electricity generation from renewable technologies. At such high levels of renewable electricity penetration, the unique characteristics of some renewable resources, specifically geographical distribution and variability and uncertainty in output, pose challenges to the operability of the U.S. electric system. The study focused on some key technical implications of this environment, exploring whether the U.S. power system can supply electricity to meet customer demand with high levels of renewable electricity, including variable wind and solar generation. The study also began to address the potential economic, environmental, and social implications of deploying and integrating high levels of renewable electricity in the United States. REF was led by a team from NREL and the Massachusetts Institute of Technology (MIT), and it is the culmination of contributions from more than 110 individuals representing more than 35 organizations.

Major Assumptions

The NREL Regional Energy Deployment System (ReEDS) capacity expansion model and the ABB GridView production cost model were the primary tools used in the study. ReEDS is a linear programming capacity expansion and dispatch model for the contiguous United States. It is a sequential optimization model that simulates the evolution of the U.S. power system from 2010 to 2050 using high spatial resolution (134 model balancing authority areas and 356 wind/solar regions) and a statistical framework for estimating capacity value, increased operating reserve needs from renewables, and renewable curtailment. GridView is a security-constrained unit commitment and economic dispatch model with hourly time resolution and zonal DC power flow transmission (among the same 134 balancing authority areas). Economic dispatch was assumed at the national level in both GridView and ReEDS; however, planning and operating reserves were still assumed to be maintained regionally. The generation expansion model uses an LOLE target to ensure long-term reliability of supply. The Gridview model was used to assess whether the system could be balanced under the study assumptions. No dynamic stability or N-1 reliability analysis was done in this study.

The study relied on 27 separate scenarios, including baselines and scenarios with prescribed amounts of renewable energy penetration in 2050 ranging from 30% to 90%. The study focused on 80%-by-2050 renewable energy scenarios, including up to nearly 50% variable generation. GridView was used to analyze a subset of these scenarios.

Summary of the Analysis

- Region: Contiguous United States
- Type: Capacity expansion and production simulation
- Temporal Resolution: Expansion to 2050, hourly dispatch
- Transmission: Expansion estimated in ReEDS
- Power flow: Zonal DC
- Model: ReEDS, GridView
- Reserves: Spinning, regulating, forecast error
- Technology and fuel prices: Range of sensitivities explored
- Regional cooperation: Nationwide dispatch with regional reserves

Key Findings

Deployment of Renewable Energy Technologies

- Renewable energy resources, accessed with commercially available generation technologies, could adequately supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level.
- All regions of the United States could contribute substantial renewable electricity supply in 2050, consistent with their local renewable resource base.
- Multiple technology pathways exist to achieve a high renewable electricity future. Assumed constraints that limit power transmission infrastructure, grid flexibility, or the use of particular types of resources can be compensated for through the use of other resources, technologies, and approaches.
- Annual renewable capacity additions that enable high renewable generation are consistent with current global production capacities but are significantly higher than recent U.S. annual capacity additions for the technologies considered. No insurmountable long-term constraints to renewable electricity technology manufacturing capacity, materials supply, or labor availability were identified.
    - The analysis showed that achieving high renewable electricity futures would require a sustained increase in renewable capacity additions. In the core 80% renewable energy scenarios, average annual renewable capacity additions from 19 GW/yr to 22 GW/yr from 2011 to 2020 were estimated, increasing to a maximum rate from 32 GW/yr to 46 GW/yr from 2041 to 2050.

Grid Operability and Hourly Resource Adequacy

- Electricity supply and demand can be balanced in every hour of the year in each region with nearly 80% electricity from renewable resources, including nearly 50% from variable renewable generation, according to simulations of 2050 power system operations.

- Additional challenges to power system planning and operations would arise in a high renewable electricity future, including management of low-demand periods and curtailment of excess electricity generation.
    - The hourly dispatch analysis estimated that overall in 2050, from 8% to 10% of wind, solar, and hydropower generation would need to be curtailed in an 80%-by-2050 renewable energy (with nearly 50% variable generation) scenario.
- Electric sector modeling showed that a more flexible system is needed to accommodate increasing levels of renewable generation. System flexibility can be increased using a broad portfolio of supply- and demand-side options, and it will likely require technology advances, new operating procedures, evolved business models, and new market rules.

Reliability

- All studies that examined balancing found that the system could be balanced with no unserved demand.
- Most studies did not examine dynamic stability or N-1 analysis; however, analysis described here on the Eastern and Western Interconnections found no reliability problems for the cases analyzed.
- Reliability from a resource adequacy perspective using LOLE targets was part of some studies.
- As a whole, these studies suggest that reliable operation can be achieved under high renewable penetrations; however, not all cases have been studied, and specific analyses of other scenarios would be needed.

Transmission Expansion

- As renewable electricity generation increases, additional transmission infrastructure is required to deliver generation from cost-effective remote renewable resources to load centers, enable reserve sharing over greater distances, and smooth output profiles of variable resources by enabling greater geospatial diversity.

Cost and Environmental Implications of High Renewable Electricity Futures

- High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use.
    - Reductions in annual greenhouse gas emissions of approximately 80% (on a direct combustion basis and on a full life-cycle basis) and in annual power sector water use of approximately 50% were found for the 80%-by-2050 renewable energy scenarios.
    - Greenhouse-gas reductions in 2030 were found to be approximately 40% relative to the 2010 baseline.

- The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Improvement in the cost and performance of renewable technologies is the most impactful lever for reducing this incremental cost.

Effects of Demand Growth

- With higher demand growth, high levels of renewable generation present increased resource and grid integration challenges.

Study Reports and Presentations

- Renewable Electricity Futures Study website: http://www.nrel.gov/analysis/re_futures/
- NREL, *Renewable Electricity Futures: Executive Summary*: http://www.nrel.gov/docs/fy13osti/52409-ES.pdf
- NREL, *Renewable Electricity Futures: Volume 1—Exploration of High-Penetration Renewable Electricity Futures*: http://www.nrel.gov/docs/fy12osti/52409-1.pdf
- NREL, *Renewable Electricity Futures: Volume 2—Renewable Electricity Generation and Storage Technologies*: http://www.nrel.gov/docs/fy12osti/52409-2.pdf
- NREL, *Renewable Electricity Futures: Volume 3—End Use Electricity Demand*: http://www.nrel.gov/docs/fy12osti/52409-3.pdf
- NREL, Renewable Electricity Futures: Volume 4—*Bulk Electric Power Systems: Operations and Transmission Planning*: http://www.nrel.gov/docs/fy12osti/52409-4.pdf.

Conclusion

This paper provided a series of high-level summaries of recent studies that have quantified variable generation emission reductions that are largely compliant with the proposed EPA 111(d) CPP rule. These studies examined significantly high wind and solar penetration rates, ranging from 20% to 50% of annual energy demand. Each of the studies utilized production simulation tools that are capable of calculating carbon emission impacts based on thermal plant operating characteristics. Carbon reductions generally ranged from 20% to 40% and resulted from wind and solar energy penetrations that were generally from 20% to 40% of annual energy. Note that REF had higher penetrations and higher emission reductions. All studies that used production simulation tools found that electricity demand can be served at all times. Some studies performed LOLE analysis, and a few of the most recent studies examined issues such as dynamic stability.

These studies represent the analysis of potential paths to achieving the EPA 111(d) objective, but there are other approaches we did not evaluate. However, as the power system industry moves forward in analyzing the potential reliability impacts of the proposed EPA rule, these studies can help shed light on some of the important issues.

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