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Lessons from Large-Scale Renewable Energy Integration Studies

Preprint

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Presented at the 2012 World Renewable Energy Forum (WREF 2012)
Denver, Colorado
May 13-17, 2012

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

Conference Paper
NREL/CP-6A20-54666
June 2012

Contract No. DE-AC36-08GO28308

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WREF 2012: LESSONS FROM LARGE-SCALE RENEWABLE ENERGY INTEGRATION STUDIES

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ABSTRACT

A number of large-scale studies have been conducted in the United States and Europe that examine the ability for electric grids to accommodate higher penetrations of variable renewable energy generation. Renewable sources, such as wind and solar, can pose difficulties because their output can vary according to seasonal and daily patterns and be uncertain due to changes in the weather. While the operational changes that are needed to accommodate higher penetrations of renewable energy vary depending on the characteristics of a particular grid, there are a number of common lessons from large integration studies. In general, large-scale integration studies in Europe and the United States find that high penetrations of renewable generation are technically feasible with operational changes and increased access to transmission. This paper describes other key findings such as the need for fast markets, large balancing areas, system flexibility, and the use of advanced forecasting.

1. INTRODUCTION

Renewable energy sources, such as wind and solar, are variable due to changes in the amount of available wind and sunlight and uncertain due to the vagaries of the weather. Integration of large amounts of variable renewable generation can pose challenges for the electricity grid. Electricity grids are designed to handle the frequent but difficult to predict changes in electric loads, but the presence of large amounts of wind and solar add to the variability and uncertainty.

Several large scale integration studies have been conducted in Europe and the United States that aim to understand how higher penetrations of variable renewable energy generation will impact the grid. These studies also examine the need for grid improvements and operational changes that may be necessary to integrate higher penetrations of variable renewable generation.

These studies have modeled the electricity system using production cost modeling and simulations of higher penetrations of renewable energy generation in future years. In general, these studies have aimed to understand the need for transmission improvements, interconnections, balancing area cooperation, market design issues, and other operational changes needed to economically operate the grid under high penetrations of variable renewable energy generation.

This paper identifies key insights and common themes from large-scale studies that examine issues associated with integrating high penetrations of renewables in the electric grid. While many of the general findings from the studies are similar, the results vary based on specific characteristics of the grids, the location of the renewable resources and the need for transmission, differences in existing operations, and the presence or absence of organized wholesale power markets.

2. OVERVIEW OF LARGE-SCALE INTEGRATION STUDIES

In the United States, two major integration studies have examined the impact of higher penetrations of renewable generation on the Eastern and Western electricity grids. In Europe, two Europe-wide studies have examined the needs to economically integrate higher penetrations of wind throughout Europe.

TABLE 1: LARGE-SCALE INTEGRATION STUDIES

Study	Year Published	Location	Grid Penetration Studied	Year of Completion
Western Wind and Solar Integration Study	2010	Western United States	11%–35%	Study uses estimates for grid performance for 2017, though 35% penetration is not expected by 2017
Eastern Wind Integration and Transmission Study	2011	Eastern United States	20%–30%	2024
TradeWind Study	2009	Europe	200 GW–350 GW (up to 25%)	2030
European Wind Integration Study	2010	Europe	70 GW–185 GW (up to 13%)*	2015

* This percentage calculation is based on the numbers direction above, from the TradeWind study.

2.1 Western Wind and Solar Integration Study (WWSIS)[1]

Sponsored by the U.S. Department of Energy and managed by the National Renewable Energy Laboratory, the WWSIS examined the planning and operational implications of adding up to 35% wind and solar energy penetration to the Western Interconnect of the United States. The study specifically examined: 1) different levels of energy penetration for wind and solar generation, ranging from 11% to 35%, 2) different geographic locations for the wind and solar resources, and 3) a wide array of sensitivities to assess issues such as fuel costs, operating reserve levels, unit commitment strategies, storage alternatives, PHEV, and balancing area size. The study had a technical review committee comprised of representatives of the power system industry in the West.

2.2 Eastern Wind Integration and Transmission Study (EWITS)[2]

The companion report to the Western study, the EWITS examined 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 by 2024. The study yielded detailed quantitative information on 1) transmission concepts for delivering energy economically for each wind energy penetration scenario, 2) economic sensitivity simulations of the hourly operation of the power system defined by a wind generation forecast scenario and the associated transmission overlay, and 3) the contribution made by wind generation to resource adequacy and planning capacity margin. The study had a technical review committee comprised of representatives of the regional transmission organizations, utilities, and other stakeholders in the East.

2.3 TradeWind Study (Europe)[3]

Initiated by the European Wind Energy Association, the TradeWind study was the first Europe-wide study to examine the infrastructure and operational changes needed to manage higher penetrations of wind energy in Europe. It included wind penetration scenarios across Europe ranging from approximately 200 GW to 350 GW by 2030 (300 GW is approximately 25% of electricity demand) and examined the effects of improved grid interconnections and potential modifications to power market design on the integration of higher levels of renewable generation.

2.4 European Wind Integration Study (EWIS)[4]

Undertaken by 15 Transmission System Operators in Europe acting through the trade association, the European Network of Transmission System Operators for Electricity (ENTSO-E), the EWIS examined the technical, regulatory, market, and transmission system impacts of higher penetration scenarios of renewable energy in Europe. The study examined near term impacts of wind generation on the electric grid with low, medium, and high penetration scenarios of installed wind generation across Europe ranging from 70 GW to 185 GW by 2015. The modeling effort included annual market simulations to assess a range of grid conditions and costs as well as detailed power flow modeling of grid pinch points.

3. LESSONS FROM LARGE INTEGRATION STUDIES

Collectively, large-scale integration studies shed light on the operational changes required to accommodate higher penetrations of renewable energy generation on electric grids. While some of the findings differed based on differences in grid operations, resources, transmission or other factors, a number of the findings are common among the various studies.

3.1 Higher Penetrations of Variable Renewable Generation are Manageable

How much renewable generation can the system handle? The large scale studies examined here found that high penetrations—up to 25% or 35%—of variable renewable generation are technically feasible with the addition of transmission infrastructure and with operational changes.

The EWIS found that the fuel cost savings and avoided carbon dioxide emissions from wind energy substantially exceed the balancing and grid reinforcement costs that can be attributed to wind.

The Western study showed significant benefits to integrating renewable energy in the 10% case, with no negative effects on the system. In the 20% penetration scenarios, increased renewable generation led to increased stress on system operations within a portion of the study footprint, with some instances of insufficient reserves due to wind and solar forecast error. The study found that this additional need for reserves can be addressed, but the system has to work harder to handle the variability of the renewables. In the 30% renewable energy case, the variability is even more challenging for system operations and the load and contingency reserves are met only if the wind and solar forecasts are perfect.

The WWSIS and EWITS estimated the fuel savings and reduced emissions from increased levels of wind and solar energy result in lower annual operating costs. In the Western study, the high wind and solar case (35% on an energy basis) reduced annual operating costs by 40% of $20 billion in 2017 dollars ($17 billion in 2009 dollars) compared to the case without any wind and solar. In the EWITS, the high renewable energy case (30%) reduced the annual production costs by 10% to $63 billion in 2006, compared to the reference case.

3.2 Larger Balancing Areas and Geographic Diversity of Renewable Resources are Preferred to Minimize Impacts

Integration studies have consistently found that expanding access to diverse resources aids in the integration of high penetrations of variable renewable generation.[5] This can be achieved in two ways—enlarging balancing areas and diversifying the location and types of the renewable energy facilities. By enlarging balancing areas, the relative variability and uncertainty in both the load and renewable energy generation will be lowered, smoothing out differences among individual loads and generators. Also, larger balancing areas reduce the costs of integrating wind and solar by reducing the need for reserves or enabling access to the most cost-effective reserves in a larger system. Larger balancing areas may also provide access to a greater amount of flexible generation. Greater geographic distribution of renewable resources reduces their variability because weather patterns are less correlated, reducing the magnitude of output changes, particularly the likelihood of a sudden drop in wind generation.

The Tradewind study found that the variability of wind generation was reduced when aggregated across Europe. It also found that cross-border exchange of wind is important for the system to be able to capture the benefits of high-levels of wind energy production, when it coincides with peak load levels.

The WWSIS found that balancing area cooperation can lead to cost savings because reserves can be pooled. It found that savings from reserve sharing can be significant with or without renewable energy on the system. In the study, a sensitivity analysis was performed, comparing the operating costs for running the system with 106 zones versus five large regions. The analysis found $1.7 billion in 2009 dollars in savings in operating costs from larger balancing areas in the scenario with 10% renewable energy penetration.

Larger balancing areas can be achieved through a variety of mechanisms, such as developing interconnections with other regions or expanding wholesale power markets. In the Western United States, where there are no wholesale power markets, efforts are underway to enable balancing areas to net their imbalances with neighboring balancing areas to reduce the need for regulation reserves. Also, a limited market for imbalance energy is under consideration, which would enable balancing areas to procure reserves from the most cost-effective resources in the region, if adopted.

3.3 Faster Markets are Preferred

Integration studies reinforce the concept that sub-hourly scheduling and dispatch is preferred with higher penetrations of variable renewable generation. Sub-hourly dispatch improves system efficiency, increases reliability, reduces the amount of reserves required to balance the system, and enables systems to integrate higher penetrations of variable renewable energy generation. The amount of imbalance energy is reduced because the dispatch is optimized more frequently. While sub-hourly scheduling and dispatch increases costs of managing the system because it is dispatched more frequently, the reserve requirements are reduced resulting in a net benefit.[6]

Faster dispatch can enable the system to access reserves from existing units at little or no extra cost. It can also reduce the need for regulation reserves, which are the most expensive types of reserves, because there are fewer minute-to-minute deviations between load and generation when the system is re-dispatched frequently. In areas with hourly dispatch, generators often must follow a set schedule for each hour, with the level typically set an hour or more before.[7] Thus, sub-hourly dispatch provides greater access to physically-available maneuverability of generation compared to hourly dispatch in which units can only change their output once an hour.

Sub-hourly scheduling between balancing areas, as opposed to within the balancing area, can lead to operational efficiencies and allow for more rapid balancing of generation changes in each region. The benefits of sub-hourly scheduling between interties are greater with higher levels of variable renewable generation. Particularly where transmission constraints exist, faster scheduling across interties would enable the variable generation to be more efficiently integrated through faster and coordinated dispatch with a neighboring market.[8]

Regional or local integration cost studies have found that the costs of integrating renewables to be less in areas with faster scheduling and dispatch. Integration studies conducted in RTO/ISO areas with 5- or 10-minute dispatch had integration costs of $0-$4/MWh, while areas with hourly scheduling and dispatch had integration costs of about $8-$9/MWh or higher. The lower integration costs in RTO/ISO markets are in part due to the faster scheduling intervals, but also because of the larger size of the balancing areas, which enable the ISO/RTO markets to access more cost-effective resources in the region for balancing.[9]

The Western study found sub-hourly scheduling to be important for minimizing regulation requirements on the system. By scheduling resources every 5 or 15 minutes, rather than every hour, the study found that the need to ramp units providing load following can be substantially reduced. The Western study case of high wind and solar penetration (30% energy) with sub-hourly scheduling required half the amount of quick maneuvering of combined cycle plants from what would be required with hourly scheduling. The amount of fast maneuvering of combined cycle plants was about the same in the 20% renewable energy penetration scenario with hourly scheduling and the 30% renewable energy penetration case with sub-hourly scheduling. This finding demonstrates that the use of sub-hourly scheduling could help accommodate higher penetrations of renewable energy on the system. Also, through minute-to-minute simulations, the study found that hourly scheduling has a greater impact on regulation requirements of the system than the variability introduced from the wind and solar.

The TradeWind study found that intraday markets for cross border trade are important for facilitating higher levels of wind penetration. The introduction of intraday trading resulted in savings of 1-2 billion euros annually compared to a scenario with only day ahead cross border trade.

A survey of grid operators from a variety of countries also supports the notion that faster scheduling and dispatch leads to more efficient system operations and helps to manage variable wind generation. Respondents that work in areas with and without wholesale electric power markets indicated that frequent generation scheduling and dispatch

are efficient methods of managing variable renewable generation on the grid. The survey also noted that a number of grid operators are working to increase the scheduling frequency between balancing areas.[10]

3.4 Incorporate Forecasts into Unit Commitment and Grid Operations

The use of forecasts in grid operations can help predict the amount of wind energy available and reduce the uncertainty in the amount of generation that will be available to the system. Renewable energy generation can be variable, changing with the time of day and weather patterns, and uncertain because of the inability to predict the weather with perfect accuracy. Integrating forecasts in system operations and unit commitment practices can reduce the cost of integrating renewables and reduce the need for reserves.

With higher penetrations of variable generation, the use of forecasting is important to operating efficient energy markets. Integrating wind and solar day-ahead forecasts into the process of committing power generation units to meet loads in coming days or hours is essential to help mitigate the uncertainty of wind and solar generation. Even though forecast errors sometimes result in reserve shortfalls, it is still beneficial to incorporate forecasts into the day-ahead scheduling process to reduce the amount of shortfalls.

The WWSIS found that using advanced wind and solar forecasts in the day-ahead unit commitment process would reduce annual system operating costs by up to $4 billion or $10-$17/MWh of renewable energy, compared to not considering renewables in the unit commitment process. The study further found that if forecasts were perfectly accurate they would reduce annual operating costs by another $425 million or $0.9-$1.7/MWh of renewable energy. All values in 2009 dollars.

The TradeWind study found that rescheduling generation intraday and incorporating wind power forecasts up to three hours before dispatch resulted in cost savings of about 260 million euros annually. The cost savings were primarily due to a reduction in reserves by incorporating more accurate forecasts into scheduling and dispatch.

3.5 Increasing the Flexibility of the System Helps Integrate Renewables

Higher penetrations of variable renewable generation require increased flexibility from the power system to manage the added variability and uncertainty. Flexibility can be achieved through increased transmission, or the addition of flexible resources to the system, such as more flexible generating units, storage, and demand response.

The TradeWind study identified transmission system upgrades to alleviate congestion and prevent high future system costs. It identified 42 connectors that would enable the European power system to more effectively integrate high penetrations of wind and avoid bottlenecks. It estimated that the benefits of the system upgrades in terms of operational savings would be approximately 1.5 billion euros annually, compared to the 22 billion euros in transmission investments.

Demand response can also provide systems with operational flexibility and can help address extreme events. Typically wind forecast errors are small but there are some hours when errors can be quite substantial, resulting in either contingency reserve shortfalls (over-forecasts) or wind curtailment (under forecasts). To address contingency reserve shortfalls, the WWSIS found that it is more cost-effective to use demand response for the 89 hours of over-forecasts rather than increase spinning reserves for all 8,760 hours of the year. Compared to committing additional spinning reserves, the use of demand response saved up to $510 million per year.

3.6 Additional Reserves may be Needed with Higher Penetrations of Renewables

Wind and solar energy increase the variability and uncertainty of output in the system, which results in a need for additional reserves. While wind and solar typically do not have an impact on contingency reserves that are needed to ensure system reliability in the case of unexpected system outages, they do generally require additional regulation and load following reserves needed to balance the system under normal operating conditions.[11] In some hours, the presence of variable generation can lead to steeper ramps, necessitating greater system flexibility and the use of units with faster ramp rates. However, the variability can be reduced if the renewable energy generators are geographically dispersed and if forecasting is used in system operations. Wind generation primarily increases the need for load following reserves because it adds variability and uncertainty in the minutes-to-hours timeframe. Minute-to-minute fluctuations generally smooth out with a larger number of wind turbines and if they are spread out geographically.[12] Solar generation has greater minute-to-minute variability due to the effects of cloud cover on generation. However, the daily and seasonal patterns of the sun are highly predictable and coincident with system peaks.

While variable generation requires additional reserves, it typically frees up thermal capacity on the system to provide additional reserves. The WWSIS found that the average variability reserve requirement doubles in the 30% case. However, when wind and solar are added to the system, thermal units are backed down because it can be more cost-effective to ramp down a unit rather than take it offline. As a result, the Western study cases with wind and solar had more up-reserves available to the system. Thus, the study found that there was not a need to commit additional reserves to cover variability resulting from increased wind and solar in the study footprint.

3.7 Integration Costs are Manageable

While it is very difficult to calculate the costs of integrating renewables, estimates indicate that these costs are manageable. When considering the question of integration costs, it is also important to keep in mind that all generation sources, including nuclear and fossil plants, have costs associated with managing them on the grid.[13] Despite these challenges, the EWITS found that interconnection-wide costs for integrating large amounts of wind generation are manageable with large regional operating pools and significant market and operational changes. For all scenarios in EWITS, the integration cost was estimated to be less than $5 per megawatt-hour (MWh) of wind, or less than $0.005 per kilowatt-hour (kWh) of electricity used by customers, assuming large balancing areas and fully developed regional electricity markets.

The EWIS found that the cost of managing the variability of wind on the European grid to be relatively small compared to the benefits. The study estimated that the costs of integrating the wind to be about 2.1 euros/MWh under the best estimate scenario and 2.6 euros/MWh in the optimistic wind energy penetration scenario. These figures represent less than 5% of the calculated benefits of the wind energy in terms of fuel cost savings and reduced carbon dioxide emissions.

4. CONCLUSIONS

Large-scale integration studies play an important role in helping to understand how to economically integrate variable generation. These studies have found that integrating penetrations of variable renewable energy generation on the order of 20%–35% of energy on the electric grid are technically feasible, but that operational changes and improved transmission access are necessary. In general, the studies find that the following operational or infrastructure changes can help facilitate the integration of higher renewable energy penetrations: faster scheduling and dispatch of generation, using advanced forecasting in fast market operations, greater system interconnections and balancing area cooperation, greater access to transmission, increased flexibility of dispatchable generation, and the use of demand response. A number of these changes are already underway in both Europe and the United States. Additional study is required to continue to refine economic options for managing the system and maintaining system reliability with higher penetrations of renewable energy.

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[1] Western Wind and Solar Integration Study, prepared by GE Energy for the National Renewable Energy Laboratory, Golden: CO, May 2010 http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf.

[2] Eastern Wind Integration and Transmission Study, prepared by EnerNex Corporation for the National Renewable Energy Laboratory, Golden: CO, revised February 2011 http://www.nrel.gov/wind/systemsintegration/pdfs/2010/ewits_final_report.pdf

[3] TradeWind 2009, Integrating Wind: Developing Europe's Power Market for the Large-Scale Integration of Wind Power. http://www.trade-wind.eu/fileadmin/documents/publications/Final_Report.pdf

[4] Winter, W. 2010 European Wind Integration Study: Towards a Successful Integration of Large Scale Wind Power into European Electricity Grids, March. http://www.wind-integration.eu/

[5] See for example, Corbus, D., D. Lew, G. Jordan, W. Winters, F. Van Hull, J. Manobianco, and R. Zavadil. November/December 2009. "Up with Wind: Studying the Integration and Transmission of Higher Levels of Wind Power." *IEEE Power and Energy*, 7(6): 36–46.

[6] Milligan and Kirby. Market Characteristics for Efficient Integration of Variable Generation in the Western Interconnection. .; NREL Report. August 2010. http://www.nrel.gov/docs/fy10osti/48192.pdf

[7] DeCesaro, J. and K. Porter. 2009. Wind Energy and Power System Operations: A Review of Wind Integration Studies to Date. NREL/SR-550-47256. December. *Integration costs of RTO/ISO vs. non-RTO/ISO. (p. 3) http://www.nrel.gov/docs/fy10osti/47256.pdf*

[8] ISO/RTO Council 2011 Briefing Paper: Variable Energy Resources, System Operations and Wholesale Markets, August http://www.isorto.org/atf/cf/%7b5B4E85C6-7EAC-40A0-8DC3-003829518EBD%7d/IRC_VER-BRIEFING_PAPER-AUGUST_2011.PDF

[9] ISO/RTO Council 2007 http://www.isorto.org/atf/cf/%7B5B4E85C6-7EAC-40A0-8DC3-003829518EBD%7D/IRC_Renewables_Report_101607_final.pdf

[10] Jones, L. 2011, Strategies and Decision Support Systems for Integrating Variable Renewable Resources in Control Centers for Reliable Grid Operations: Global Best Practices, Examples of Excellence and Lessons Learned, Prepared by Alstom Grid Inc. for the U.S. Department of Energy. http://www1.eere.energy.gov/wind/pdfs/doe_wind_integration_report.pdf

[11] Regulation reserves are used to balance load and generation on a momentary basis, while load following reserves are used to balance the system as load levels change over the course of the day, on a scale of minutes to hours. Contingency reserves are used to ensure reliability of the system in the case of the loss of a large power plant or contingency on the system.

[12] North Amercian Electric Reliability Corporation, 2009 Special Report: Accommodating High Levels of Variable Generation, April. http://www.nerc.com/files/IVGTF_Report_041609.pdf

[13] Milligan, M.; Ela, E.; Hodge, B. M.; Kirby, B.; Lew, D.; Clark, C.; DeCesaro, J.; Lynn, K. (2011). Cost-Causation and Integration Cost Analysis for Variable Generation. Electricity Journal, 24(9), November