NREL National Renewable Energy Laboratory
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Innovation for Our Energy Future

Large-Scale Wind Integration Studies in the United States: Preliminary Results

Preprint

Conference Paper
NREL/CP-550-46527
September 2009

M. Milligan, D. Lew, and D. Corbus
National Renewable Energy Laboratory

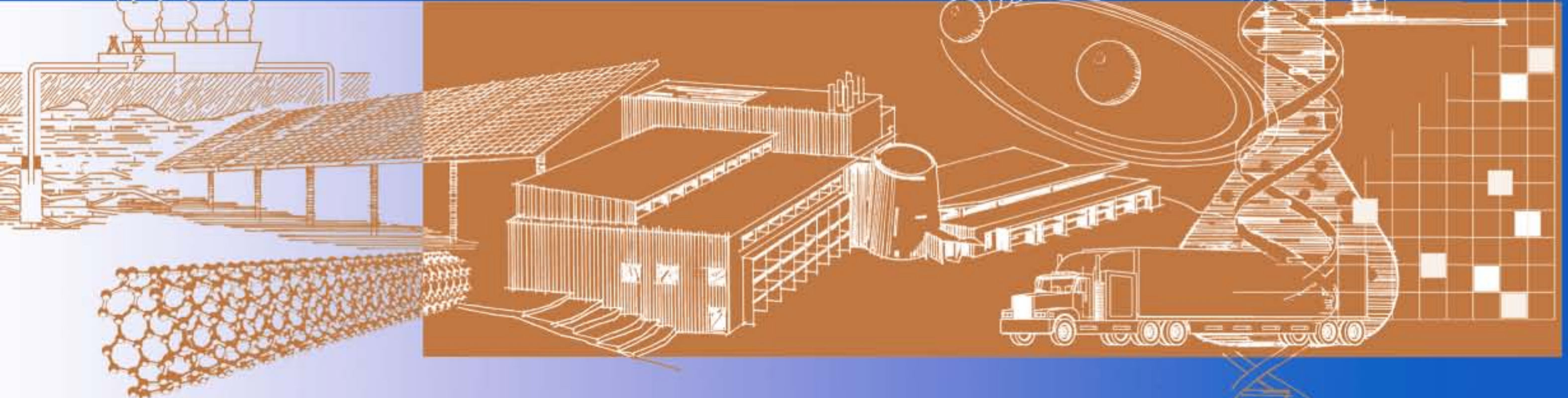
R. Piwko, N. Miller, K. Clark, G. Jordan, and L. Freeman
GE Energy

B. Zavadil
EnerNex Corp.

M. Schuerger
Energy Systems Consulting Services

To be presented at the 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms
Bremen, Germany
October 14–15, 2009

NREL is operated for DOE by the Alliance for Sustainable Energy, LLC Contract No. DE-AC36-08-GO28308



Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Large-Scale Wind Integration Studies in the United States: Preliminary Results

Michael Milligan[1], Debbie Lew[1], Dave Corbus[1], National Renewable Energy Laboratory; Richard Piwko[2], Nicholas Miller[2], Kara Clark[2], Gary Jordan[2], Lavelle Freeman[2], GE Energy; Bob Zavadil[3] EnerNex Corporation; Matt Schuerger[4], Energy Systems Consulting Services

***Abstract*-- The National Renewable Energy Laboratory, under the sponsorship of the U.S. Department of Energy, is managing two large-scale wind integration studies. The Western Wind and Solar Integration Study (WWSIS) covers the footprint of WestConnect, a group of transmission owners that covers most of Colorado, New Mexico, Arizona, Nevada, and Wyoming. The Eastern Wind Integration and Transmission Study (EWITS) covers a large part of the Eastern Interconnection, and leverages a large-scale transmission study known as the Joint Coordinated System Plan (JCSP). Both studies analyze the impact of 20-30% wind energy penetration within the study footprint based on energy. This paper discusses key results that have emerged so far from each study, focusing primarily on simulation results based on hourly production simulations. Results from both studies show that high wind penetrations can be successfully integrated into the power system, but depend on sufficient transmission and significant changes in operations.**

***Index Terms*—Wind Energy, Wind Integration**

I. Introduction

The National Renewable Energy Laboratory is managing two large regional wind integration studies on behalf of the United States Department of Energy. These two studies are believed to be the largest ever undertaken in the United States. Both studies evaluate wind energy penetrations up to 30% of annual energy demand. Although there are some differences in the study objectives and characteristics, a common objective of both studies is to perform electric system production simulation modeling, using realistic wind energy data that covers three years. In addition to the operational modeling that is performed on an hourly time step, each study also analyzes sub-hourly wind and load data to provide insight into the intra- hour impacts and variability characteristics. Each study also evaluates alternative wind energy build-out scenarios that help to show the impacts of developing local wind with lower capacity factors against more remote wind resources that require more transmission.

An evaluation of wind capacity value using reliability-based modeling methods is also part of each study. This paper provides a broad look at each study and presents preliminary results and conclusions.

[1] National Renewable Energy Laboratory, Golden, CO, USA +1 303-384-6927, michael.milligan@nrel.gov
[2] GE Energy, Schenectady, NY, USA
[3] EnerNex Corporation, Knoxville, TN, USA
[4] Energy Systems Consulting Services, St. Paul, MN, USA

Both studies have extensive project teams and stakeholder groups. Project teams include staff from 3-Tier Group, GE Energy, National Renewable Energy Laboratory, AWS TrueWind, EnerNex, Ventyx, and the Midwest Independent System Operator (MISO). In addition, the Eastern Wind Integration and Transmission Study (EWITS) is leveraged from the Joint Coordinated System Plan (JCSP) and includes representatives from PJM, TVA, and SPP.

II. Study Overviews and Preliminary Results

Both the Western Wind and Solar Integration Study (WWSIS) and EWITS evaluate the operational impact of large-scale wind energy—up to 30% of annual energy demand—on the power system. Both studies cover a large geographic scope, and collectively cover most of the continental United States. Modeling large regions allows additional questions to be answered, including:

- How do local wind resources compare with higher capacity-factor wind that requires more transmission?
- How does geographic diversity of wind power reduce wind integration costs (i.e., spreading the wind over a larger region and thereby “smoothing” out some of the variability)?
- How does offshore wind compare with onshore wind?
- How does balancing area consolidation or cooperation affect wind power integration costs?
- How much new transmission is needed to facilitate higher penetrations of wind power?
- What is the role and value of wind forecasting?
- What role do shorter scheduling intervals have to play?
- How are wind power integration costs spread over large market footprints and regions?
- What additional operating reserves are needed for large wind power deployments?

A. WWSIS

The key objectives of WWSIS are to answer questions about large-scale wind and solar integration in the southwestern part of the United States. This region corresponds to the footprint of WestConnect, which is a group of utilities that operate in Arizona, Colorado, Nevada, New Mexico, and Wyoming as shown in Fig. 1. The study addresses the following:

- Does geographic diversity of renewable energy resource help mitigate variability?
- How do local resources compare to out-of-state resources?
- Can balancing area cooperation help mitigate variability?
- What is the role and value of energy storage?
- Should reserve requirements be modified?
- What is the benefit of forecasting?
- How can hydro help with integration of renewables?

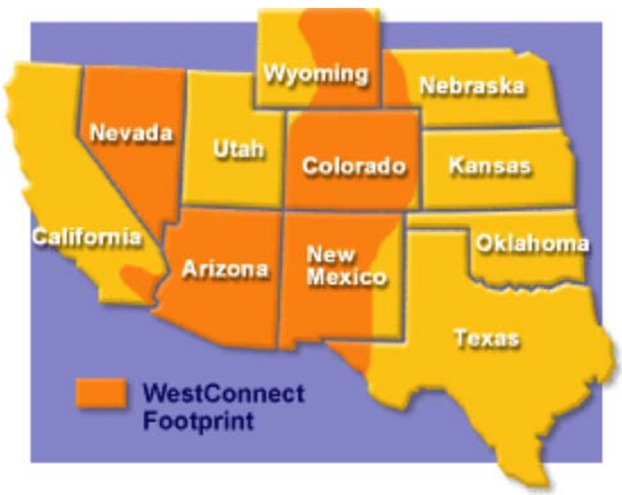


Fig. 1. Study footprint for the WWSIS.

Several scenarios represent alternative wind build-outs, both at different penetration levels and different locations. Penetrations are depicted in TABLE I.

TABLE I. Wind and solar penetrations for the WWSIS.

In Footprint		Rest of WECC	
Wind	Solar	Wind	Solar
10%	1%	10%	1%
20%	3%	10%	1%
30%	5%	20%	3%

Variations in these scenarios include (1) in-area: each transmission area meets its target from wind and solar resources in that area, (2) mega-project: wind and solar projects are concentrated in the best resource areas, (3) local priority: a balance of the first two variations. As this project is still in process, additional scenarios are yet to be determined.

A number of different aspects of system operational impacts are investigated in this study. This include

- Impact on hydro operations and alternative hydro dispatch
- Comparison of scenario variations to assess potential differences in overall variability and operational impacts
- Impact of balancing area consolidated operations
- Impact of alternative wind forecasts on operations
- Analysis of displaced generation
- Gas price sensitivities
- Alternative transmission build-out scenarios

The study also examines the capacity value of wind and solar power. Many of these results are shown in Lew et al [1].

GE modeled the Western Electricity Coordinating Council (WECC) footprint, but the study focused on WestConnect. Including WECC allows the study to take into account the flows and interchanges with neighboring systems, and provides a more realistic evaluation of the study area.

At low wind penetration, the primary impact on conventional generation appears on the gas combined-cycle generation. As wind penetration increased to 20%, the impact on combined cycle units increased and there is an additional impact on gas combustion turbines. At 20% penetration, there was a small reduction in coal generation, but this increased substantially at the 30% wind penetration rate along with an additional 5% solar penetration. This can be seen in Figs. 3-5 that are selected from a particularly challenging week in April using the 2006 load and renewable profiles. During this time of the year, the load is significantly less than during the summer and winter seasons, and there is much more wind generation in the spring than during high-demand periods. At the 10% wind penetration (for brevity, we refer to the penetrations in terms of wind only, but solar's penetration is implicit as shown in TABLE I) there is a significant impact on gas combined-cycle generation, along with a small impact on coal. As the penetration of wind and solar increase, the impact on base-load coal increases, becoming very challenging at the 30% penetration. We note that the modeling of the power system included details on coal ramping capability and minimum up- and down-times from publically-available data.

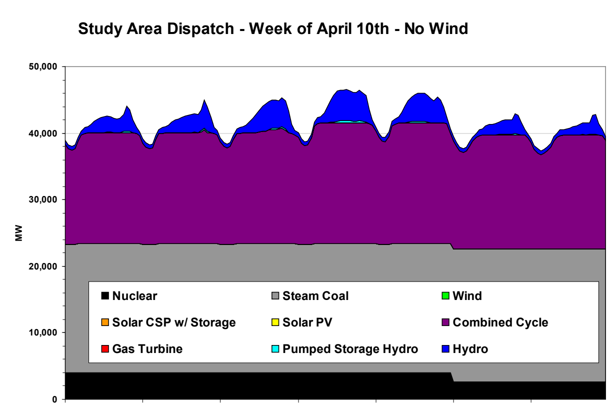


Fig. 2. Example of dispatch from April; no wind.

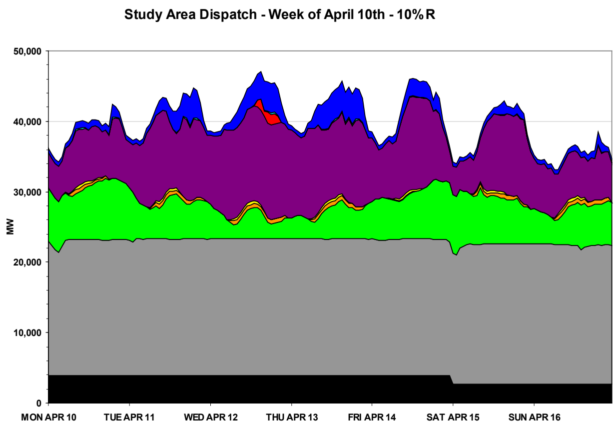


Fig. 3. Example of dispatch from April; 10% penetration.

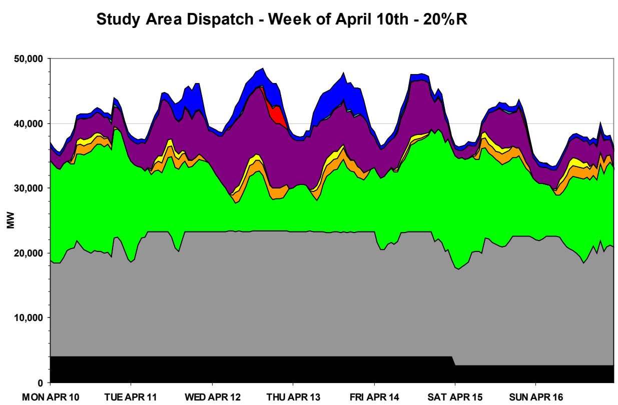


Fig. 4. Example of dispatch from April; 20% penetration.

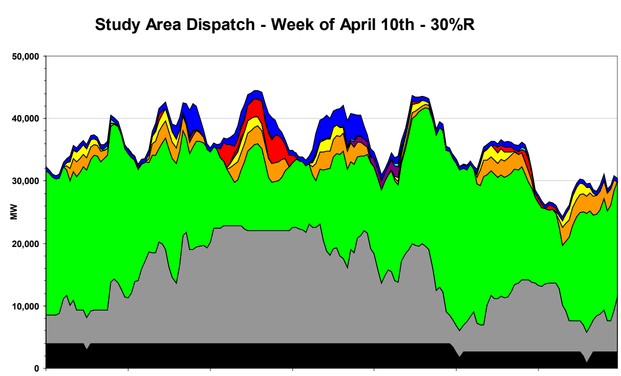


Fig. 5. Example of dispatch from April, 30% penetration.

The impact of the displaced generation on production costs at higher penetrations of wind and solar power can be seen in Fig. 6. The scenarios represented on the graph represent (a) pre-selected sites with perfect forecast (approximately the current installed capacity), (b) in-area, 10%, 20%, and 30% wind penetration respectively with perfect forecast, with similar scenarios for representative forecast errors. The I2020R case in Fig. **6**shows the impact of a reduction in forecast errors compared to the representative forecast error cases.

Fig. **6** shows that as renewable penetration increases, production cost savings also increase because of the reduction in fuel burned. In addition, we can see that larger forecast errors reduce the savings from wind and solar. As renewable penetration increases, the *incremental* saving in production cost decreases. This is consistent with the findings of the change in economic dispatch: at relatively low penetrations, the primary displaced fuel is natural gas. But as renewable penetrations increase enough to displace coal generation, the production savings from coal are less than the production savings from gas.

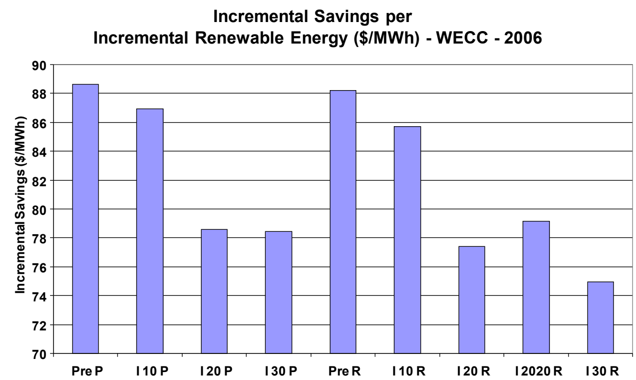


Fig. 6. Impact of renewable energy on production cost savings for the WWSIS.

Corresponding to the reduction in fuel and operating cost, the reduction in emissions was calculated. Fig. 7 shows this impact for the cases that include representative forecast errors (the perfect forecast cases do not appear here). As would be expected, the incremental decrease in coal generation at higher penetrations results in increasing per-unit reductions in carbon and other emissions.

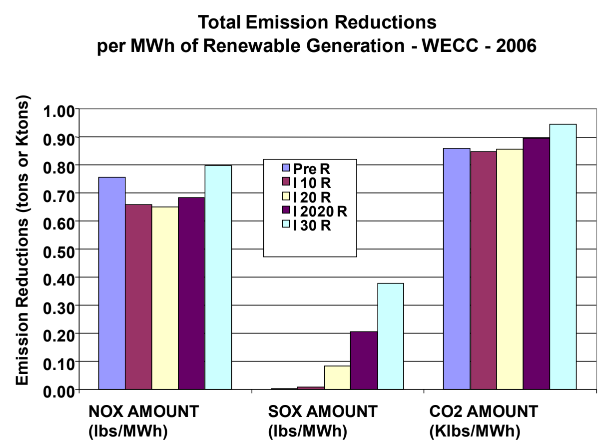


Fig. 7. Total emission reductions per MWh of renewable generation..

This study is scheduled to be completed in early 2010, and additional results and insights are forthcoming. However, conclusions to date indicate:

- Up to 20% penetration of wind power can be accommodated with no significant operational issues.
- 30% wind power is more challenging.
- Production costs and emissions decline with increasing renewable penetration.

- Based on the value of unserved energy, responsive load would appear to be easily justified as an economic option to help manage variability.
- The need for additional storage is not apparent from study results.
- Little differences in operational impacts have been found between alternative geographic cases at given penetration rates.
- Forecasts have value and forecast accuracy has an influence on operational savings.
- Operational impacts appear to be sensitive to the penetration in the rest of the interconnection.

B. EWITS

The EWITS expands work done by the JCSP by evaluating additional wind scenarios and developing supporting high-voltage transmission buildout scenarios. The study footprint is shown in Fig. 8.

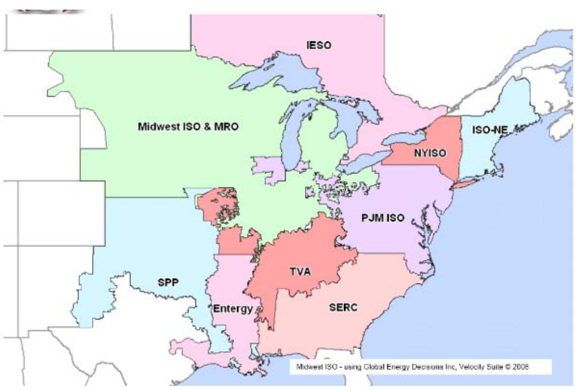


Fig. 8. EWITS study footprint (excludes IESO).

The study considers four scenarios (all penetrations are relative to annual energy in the study footprint):

1. 20% high-capacity factor wind, all onshore, results in significant wind use in the western portion of MISO and more transmission development than other 20% cases
2. 20% hybrid with some offshore. This scenario is the closest match to the JCSP and therefore provides a common reference
3. 20% wind with aggressive offshore and less onshore wind
4. 30% wind, aggressive onshore and offshore.

A key objective of this study was to evaluate the wind integration cost, similar to other studies done in the United States. This approach compares production cost with wind to production cost with a flat-block daily energy-equivalent to wind. However, it was determined that this approach does not work in studies with large wind penetrations because of the large, artificial ramp that occurs at midnight between the daily flat blocks. At low wind penetrations and in small footprints, this impact is not believed to be significant, but the EWITS analysis found such large impacts as to judge the method as invalid for the study.

Separate work [2] characterized these impacts and also showed that using the daily block proxy resource also introduces differences in value that are an artifact of the proxy resource. Fig. 9 shows the correlation of wind production and locational marginal prices (LMP) (see [2]). Using fixed LMPs and the wind data from EWITS, the value differential was shown to improve with alternative flat block proxies, but was still an issue as shown in Fig. 10

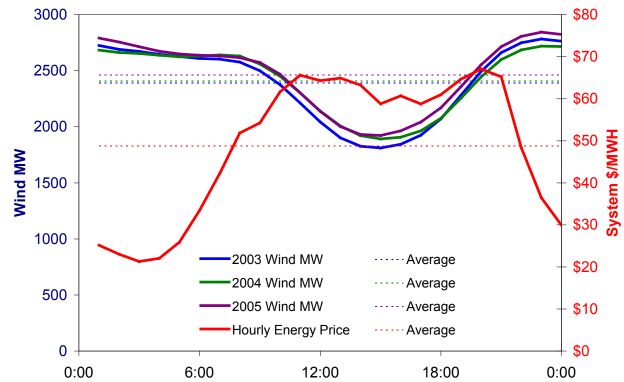


Fig. 9. Example of LMP profiles over 3 years and negative correlation with wind [2].

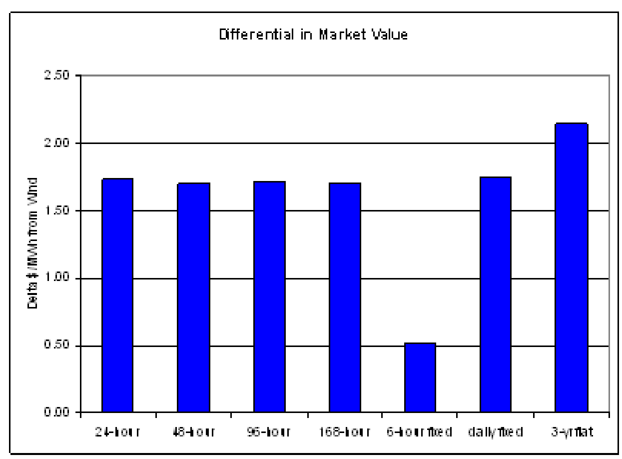


Fig. 10. Using different rolling average and fixed block definitions yield a differential in value of wind compared to the proxy. [2]

As a result of these and other discussions, the decision was made to explore a set of alternative cases to estimate the integration cost of wind, as follows:

- Ideal wind case. No day-ahead wind forecast error, and no incremental operating reserve driven by wind. Only load forecast error and uncertainty have any impact on operating reserve.
- Intermediate wind case. Uses day-ahead forecast errors, but has no incremental reserve requirement because of wind. This case allows us to estimate a cost of uncertainty.
- Actual wind case. This adds an incremental reserve requirement that is driven by wind power needs.

Although the wind penetration of the various scenarios is expressed relative to annual energy of the footprint, the various regions do not have the same penetration because of the way the individual sites were ranked and selected (best wind with various constraints on onshore, offshore, etc.; see Fig. 11).

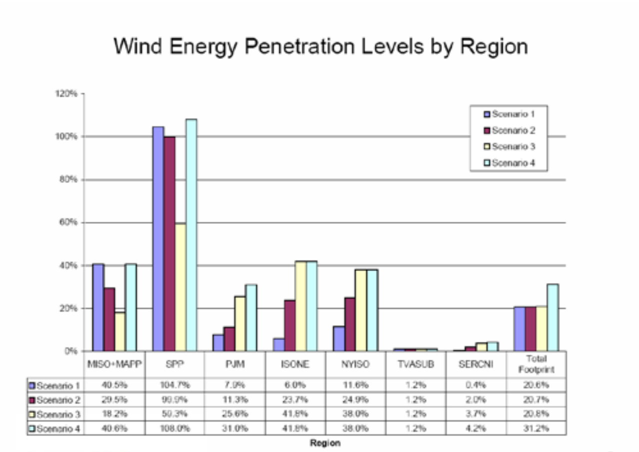


Fig. 11. Wind penetration varies by region.

The impact that wind has on market prices is similar to what has been found so far in the WWSIS. As the wind penetration increases, LMPs decline generally as a function of wind penetration, as shown in Fig. 12. It is clear that LMPs follow a similar downward trend but in some cases increase significantly at the 30% penetration case. At this penetration level it becomes somewhat difficult to trace all of the impacts of wind's variability and uncertainty because generators may respond to wind (and load) variations that occur in another region, subject to relative prices and costs.

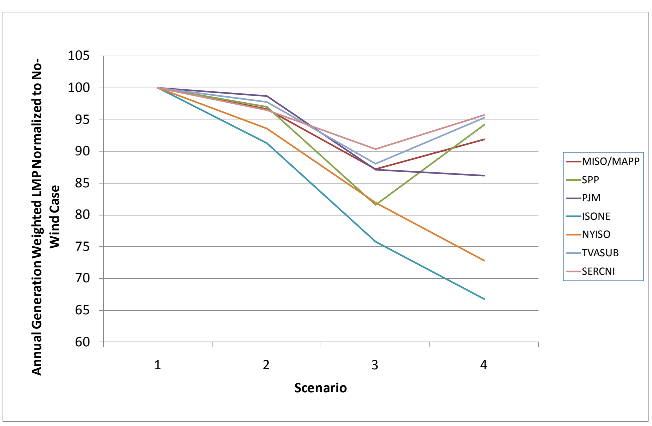


Fig. 12. Relative change in locational marginal prices by region and wind penetration level in the EWITS (preliminary).

EWITS also is performing an extensive analysis of wind capacity value, using the effective load carrying capability (ELCC) metric. Because EWITS also contains a transmission expansion component, the sensitivity of system adequacy and wind ELCC to the transmission assumptions will be explored in some detail. Cases under evaluation include:

- Stand-alone, isolated transmission zones
- Without transmission overlay (existing transmission)
- Infinite tie limits (copper sheet)

Preliminary results show a significant sensitivity of wind capacity value to transmission limits—as the transmission capability expands, the overall system is better able to take advantage of the geographic and time diversity of a larger footprint, increasing the relative wind ELCC. Of at least equal importance is the conclusion that a well-developed transmission system can defer or avoid new generation additions, resulting in a more efficient and cost-effective power system.

III. Summary

Both of the large-scale wind integration studies that are currently underway in the United States will be completed by early 2010. Emerging conclusions indicate that 20% wind energy penetration can be managed, but the role of wind forecasting is important to meet this objective. Additional transmission will be needed to deliver wind power to market, and storage appears to be unnecessary to achieve this penetration. Results for the 30% case appear to be more challenging, and as the studies move forward we anticipate more analysis will be done to achieve a better understanding of the operational challenges and potential solutions. High penetrations of wind reduce spot energy prices and production costs. Both analyses also show that carbon emissions are reduced, but that the level of reduction is a function of the displaced generation. The higher wind penetration cases tend to offset more coal than the lower penetration rates, consistent with an economically rational dispatch process.

IV. References

[1] D. Lew, M. Milligan, G. Jordan, L. Freeman, N. Miller, K. Clark, R. Piwko, "How do Wind and Solar Power Affect Grid Operations: The Western Wind and Solar Integration Study," in *Proc. 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms,* to appear.

[2] M. Milligan and B. Kirby, "Calculating Wind Integration Costs: Separating Wind Energy Value from Integration Cost Impacts," in *Proc. WindPower 2009.* Available online at http://www.nrel.gov/docs/fy09osti/46275.pdf

[3] D. Corbus, M. Schuerger, and B. Zavadil, Eastern Wind Integration and Transmission Study – Preliminary Findings" in *Proc. 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms,* to appear.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
September 2009	Conference Paper	

4. TITLE AND SUBTITLE
Large-Scale Wind Integration Studies in the United States: Preliminary Results; Preprint

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
M. Milligan, D. Lew, D. Corbus, R. Piwko, N. Miller, K. Clark, G. Jordan, L. Freeman, B. Zavadil, and M. Schuerger

5d. PROJECT NUMBER
NREL/CP-550-46527

5e. TASK NUMBER
WER9.5550

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-550-46527

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
The National Renewable Energy Laboratory is managing two large regional wind integration studies on behalf of the United States Department of Energy. These two studies are believed to be the largest ever undertaken in the United States.

15. SUBJECT TERMS
Wind; solar; resource data; integration; grid studies; WWSIS; EWITS; transmission; power system operation; reserve requirements.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)