Wei Tian *received his B.S. degree in Mathematics from Shandong University in 2001, M.S. degree in System Engineering from Xi'an Jiaotong University, China, in 2004, and Ph.D. degree from the Illinois Institute of Technology, Chicago, in 2011. He is a visiting scientist at the Robert W. Galvin Center for Electricity Initiative at IIT. His research interests include power system restructuring and long-range planning.*

Mohammad Shahidehpour *is the Bodine Chair Professor and Director of the Robert W. Galvin Center for Electricity Initiative at the Illinois Institute of Technology. He is the recipient of the 2011 Innovation Award from the Association of Electrical and Computer Engineering Department Heads.*

Zuyi Li *received his B.S. degree in Electrical Engineering from Shanghai Jiaotong University in 1995, M.S. degree in E.E. from Tsinghua University, China, in 1998 and Ph.D. degree in E.E. from IIT in 2002. Presently, he is an Associate Professor in the ECE Department at IIT.*

This study was funded in part by the U.S. Department of Energy, grants nos. DE-EE 0002979 and DE-EE 0001380.000.

Analysis of 2030 Large-Scale Wind Energy Integration in the Eastern Interconnection Using WINS

A simulation of the 2030 load forecast in the Eastern Interconnection suggests that large-scale wind energy integration will have a major impact on the hourly commitment and dispatch of gas and coal units, especially at off-peak load hours. While fuel price alterations will have major impacts on the system production cost, load variation will have a larger impact and potential carbon costs will have the greatest impact.

Wei Tian, Mohammad Shahidehpour and Zuyi Li

I. Introduction

Wind energy is an important component of the future energy production portfolio throughout the world. In the United States, wind energy is expected to provide 20 percent of the U.S. energy production portfolio by 2030 [1–3]. However, the electricity market requires a detailed simulation of the economics and the adequacy of the energy production portfolio before large-scale wind energy can be integrated into existing power systems.

The U.S. Eastern Interconnection is the largest interconnection in the world with more than 5,000 generating units and about 70,000 branches. The National Renewable Energy Laboratory (NREL) initiated a study in 2008 to examine the impact of 20–30 percent wind

 1040-6190/$–see front matter doi:/10.1016/j.tej.2011.09.002

energy integration in the Eastern Interconnection [4]. The western wind and solar integration study in 2007 examined the operational impact of 35 percent renewable energy penetration [5]. The impact of wind energy integration on power system operations is analyzed further in [6,7,15]. An hourly unit commitment and economic dispatch model for analyzing large-scale power system operations was represented in [8]. A follow-up optimization-based security-constrained unit commitment (SCUC) model [16–18] was presented in [9] which took into account the intermittency and volatility of wind power generation and transmission network constraints.

In this article, we focus on large-scale wind energy integration in the Eastern Interconnection in 2030. The wind energy sites are analyzed and the impact of large-scale wind energy integration on existing generation resources and production costs is studied. Fuel price sensitivity, wind energy production sensitivity, load growth sensitivity, carbon cost sensitivity, and load management strategies are considered and analyzed for large-scale wind energy integration.

The rest of the article is organized as follows. Section II describes the proposed methodology, assumptions, and relevant evaluation metrics. Section III presents the wind energy integration study results for the Eastern Interconnection. The conclusions drawn from the study are provided in Section IV.

II. Methodology for Wind Energy Integration

A. WINS

At the Illinois Institute of Technology (IIT), we had developed over the years an efficient decision tool called POMS (POwer Market Simulator) [10] for the day-ahead scheduling of large-scale power systems. The expansion of POMS, which is referred to as WINS (Wind INtegration Simulator), is considered in this study to support the collaborative planning, analysis, and implementation of large-scale wind energy integration in the United States. The WINS architecture is depicted in Figure 1. WINS applies unit commitment to simulate large-scale wind energy integrations in the hourly power system operation. The application of WINS in this article analyzes the impact of large-scale wind energy integration in the year 2030 on production costs, unit commitment, and dispatch of generation resources in the Eastern Interconnection. For the purpose of this energy adequacy study, we do not consider transmission constraints in this article. We use the wind data given in [4]. A brief description of the wind data is given in [12]. The wind forecast uncertainty is simulated in this article by

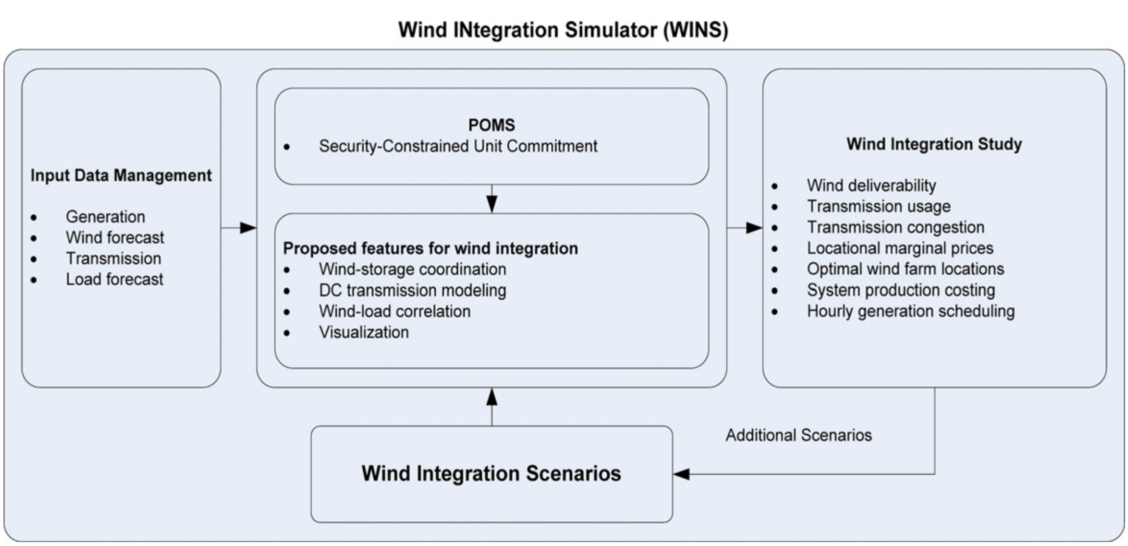

Figure 1: Framework of WINS

 1040-6190/$–see front matter doi:/10.1016/j.tej.2011.09.002

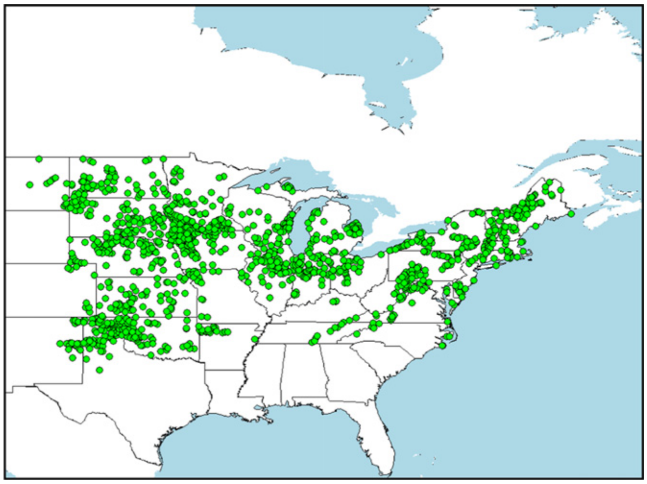

Figure 2: Potential Wind Sites in the Eastern Interconnection

sensitivity analyses applied to the wind energy integration Scenarios.

B. Input data

It is estimated that approximately 225 GW of wind power generation is required to supply 20 percent, and 330 GW is required to supply 30 percent, of the total energy by 2024 in the Eastern Interconnection [4]. In this article, we utilize the land-based time series wind simulation results [4]. The potential land-based wind sites in the Eastern Interconnection are shown in **Figure 2** for about 580 GW of wind power generation capacity. The figure shows that there are potential wind energy sites with rich wind resources in the central part of the United States. In this study, we consider a 1.28 percent annual load growth rate which is based on the MTEP 08 (MISO Transmission Expansion Planning) assumptions. The hourly load distribution shown in **Figure 3** is based on the MISO's hourly load profile in 2007. In Figure 3, peak loads appear in July and August. The power flow solution is used for calculating the hourly load distribution at each bus. Fuel prices are assumed to increase at an annual rate of 4 percent for oil and gas, 2 percent for coal, and 3 percent for nuclear fuel based on the fuel price given in 2008 [13].

C. Evaluation metrics

The evaluation criteria and metrics used in our simulations are defined as follows.

1. Wind Energy Availability

The available wind energy is treated as dispatchable in WINS simulations. Here,

(1) $P_A = \sum_{t=1}^{T}\sum_{i=1}^{NG} p_i^{\max} w_{it}$ where T represents the number of hours in a period (e.g., one year), NG represents the number of wind generators/farms, $p_i^{\max}$ is the

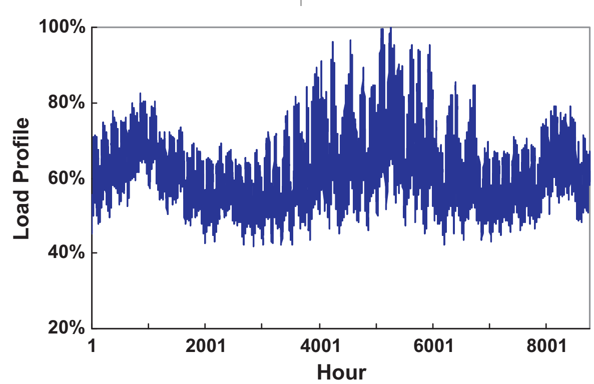

Figure 3: Annual Hourly Load Profile

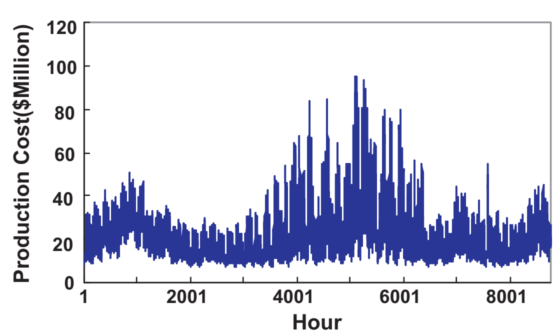

Figure 4: Hourly Production Cost Without Wind Integration

nominal capacity of wind generator/farm i, w_{it} represents the wind power generation i at time t, P_A represents the system wind energy availability in the given study period.

We assume the available wind energy is much less than the total system load in the Eastern Interconnection. Therefore, the total available wind energy is to be dispatchable without any curtailment.

2. Percentage of Wind Energy Contribution

This metric (2) is to evaluate the percentage of wind energy contribution to the total energy utilized for supplying the load in the power system.

$$= \frac{\text{Wind Energy}}{\text{Total Energy}} \times 100\% \qquad (2)$$

III. Numerical Results

In this section, we utilize WINS to simulate the wind energy integration in the Eastern Interconnection of the United States based on the methodology presented in Section II.

A. Level of wind energy integration

We simulate the hourly power system operation using WINS for a given wind power capacity factor (CF). Four Scenarios are studied as follows.

Scenario 1: No wind energy integration is considered.

Scenario 2: Wind energy integration with a minimum CF of 40 percent is considered.

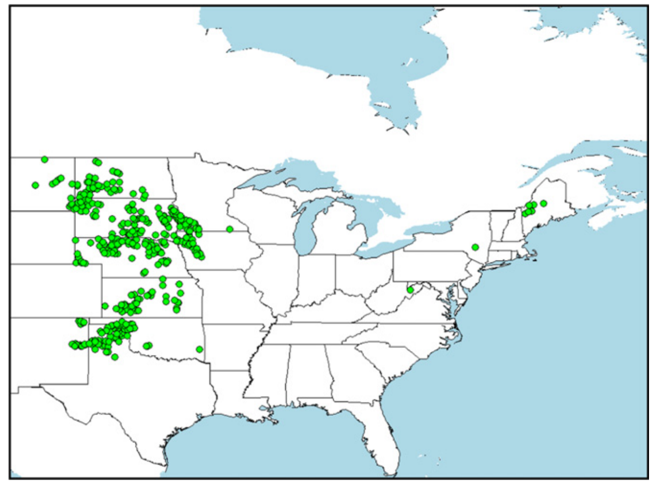

Figure 5: Potential Wind Sites with CF $\geq$40%

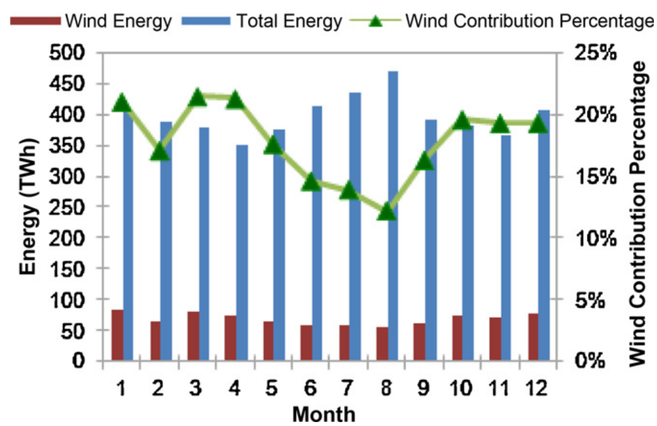

Figure 6: Monthly Wind Energy and its Contribution to Total Energy

Scenario 3: Wind energy integration with a minimum CF of 30 percent is considered.

Scenario 4: Wind energy integration in all potential sites is considered.

1. No Wind Integration

This is the base case in which the hourly loads will be served by fossil fuel and hydro units. Figure 4 shows the hourly production cost which is $217.5

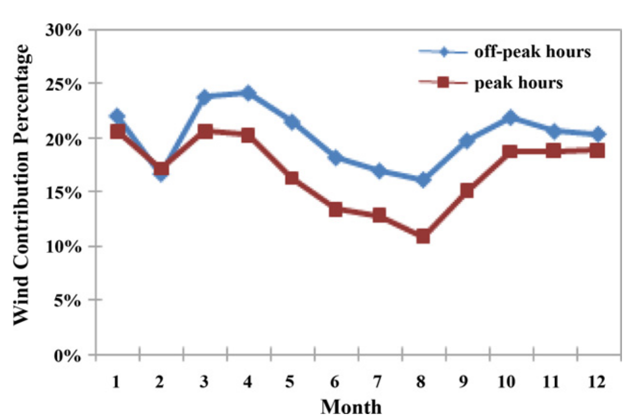

Figure 7: Wind Energy Contribution at Peak/Off-Peak Hours

 1040-6190/$–see front matter doi:/10.1016/j.tej.2011.09.002

billion per year with an average production cost of $45.64/MWh. The production cost will not change linearly with the hourly load fluctuations. Hydro units will have zero costs and be scheduled first to serve hourly loads or reserves; then cheaper units such as nuclear, coal, and large oil will be committed as loads pick up, and finally expensive units such as gas and oil will be committed to supply hourly loads. A higher production cost will occur at annual peak hours of 5,000–5,500 (i.e., July and August). The production cost at peak hours (6 AM–10 PM) will be $177.8 billion and the production cost at off-peak hours (11 PM–5 AM) will be $39.7 billion. The average production costs at peak/off-peak hours are $50.2/MWh and $32.5/MWh. The average production cost at peak load hours is higher when expensive generators are committed and dispatched.

2. Integration of Wind Energy Sites with a Minimum CF of 40 Percent

There are 399 such potential wind energy sites with a total wind generation capacity of 230.5 GW. The largest annual CF is 49 percent. Figure 5 shows the 399 potential wind energy sites in the Eastern Interconnection in which wind energy resources are mainly located remotely in the central region of the United States. The total available wind energy with a minimum 40 percent CF in that region is 845.2 TWh.

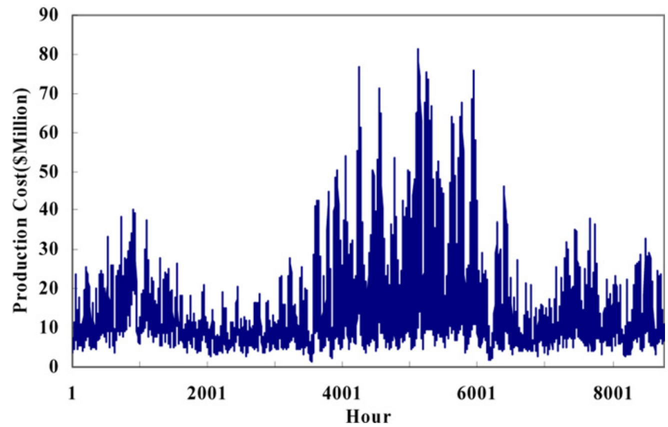

Figure 8: Hourly Production Cost in Scenario 2

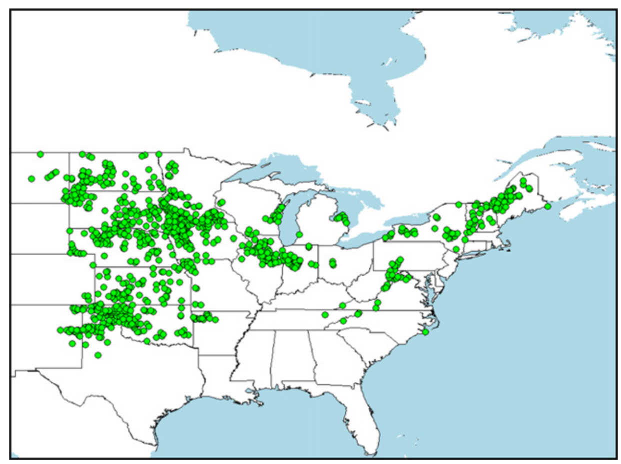

Figure 9: Potential Wind Sites with CF $\geq$30%

The 2030 energy forecast in the Eastern Interconnection is 4,783.2 TWh, which indicates that the potential wind energy is about 17.67 percent of the total energy production portfolio. We assume the wind energy has zero fuel cost and transmission congestion is not considered. So the entire available wind energy

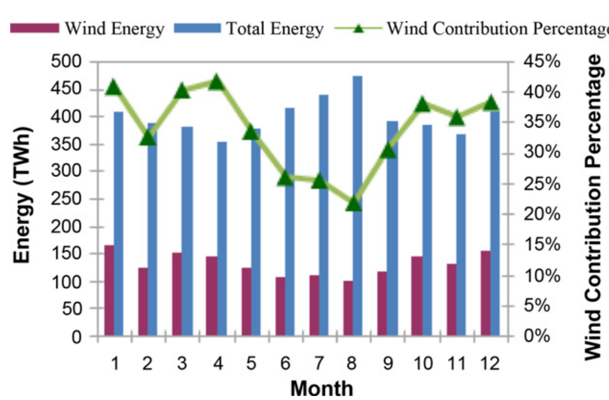

Figure 10: Monthly Wind Energy and its Contribution to Total Energy

will be dispatched to satisfy the hourly load. Figure 6 shows the monthly wind energy in 2030. The wind energy resources are mostly available in spring and winter; however, peak loads occur in summer. January has the highest level of available wind energy of 86.4 TWh, which amounts to 21.11 percent, of the total energy. March has the highest percentage for wind energy contribution (21.53 percent) because the load is lower than that of January. The available wind energy is scarce in August while the highest level of load occurs in this month. So August represents the month with the least available wind energy and the percentage of wind energy contribution (i.e., 57.5 TWh and 12.2 percent) to the total energy production portfolio.

Figure 7 shows the wind energy contribution at peak and off-peak hours. The figure shows that the wind is usually rich at night as compared with that in the daytime, especially in the summer. The hourly average wind energy at peak/off-peak hours are 2.27 TWh and 2.69 TWh in August, and the percentages of wind energy contribution are 10.88 percent and 16.22 percent, respectively. Figure 8 shows the hourly production cost. Compared to Figure 4, the production cost is lower when the large-scale wind energy is integrated. The annual production cost is $130.4 billion, which is about $87.1 billion less than that in Scenario 1. The annual average production cost decreases from $45.64/MWh to $27.25/MWh when the wind energy is integrated. Here, the production costs at peak/off-peak hours are $107.1 billion and $23.2 billion, and the average production cost at peak/off-peak hours are $30.1/MWh and $18.9/MWh respectively. The average production cost is lower in this Scenario at peak/off-peak hours.

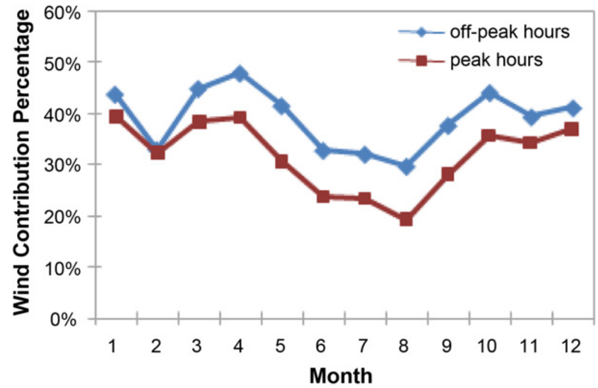

Figure 11: Wind Energy Contribution at Peak/Off-Peak Hours

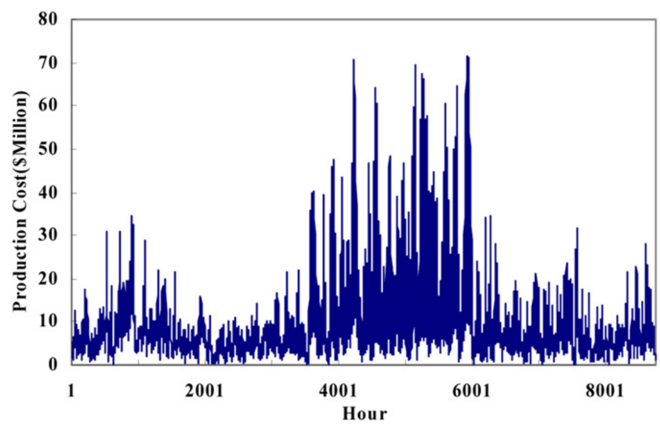

Figure 12: Hourly Production Cost in Scenario 3

3. Integration of Wind Energy Sites with a Minimum CF of 30 Percent

In this case, 972 wind sites are introduced in Figure 9 with a total

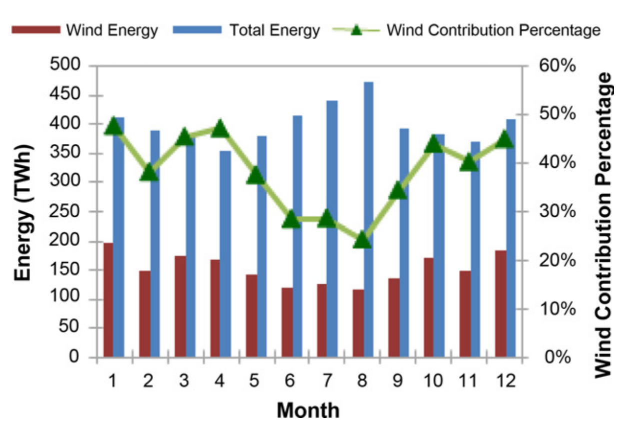

Figure 13: Monthly Wind Energy and its Contribution to Total Energy

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2011.09.002

capacity of 481.5 GW. Compared to Figure 5, additional wind energy sites located in Wisconsin, Illinois, Indiana, and other regions are considered in this Scenario. **Figure 10** shows that the annual wind energy contribution is 1,596 TW, which amounts to 33.37 percent of the total energy production portfolio. **Figure 11** shows the monthly wind energy contribution at peak/off-peak hours. Compared to the simulation results in Scenario 2, 573 additional potential wind energy sites with a total capacity of 251 GW are added here with a CF between 30 percent and 40 percent. In this case, the added wind generation capacity is 108.9 percent (i.e., 481.5 GW vs. 230.5 GW) while the added wind energy contribution is about 88.85 percent (i.e., 33.37 percent vs. 17.67 percent). The production cost in **Figure 12** is $86.8 billion with an average hourly production cost of $18.14/MWh. The average production costs at peak/off-peak hours are $20.33/MWh and $11.33/MWh, respectively.

4. Integration in All Potential Wind Energy Sites

There are 1,326 wind energy sites in the Eastern Interconnection with a total capacity of 580 GW. **Figure 13** shows the monthly wind energy production and wind energy contribution. The annual wind energy production is about 1,816 TWh and the annual percentage of wind energy contribution is about 38 percent. In this case, the minimum wind

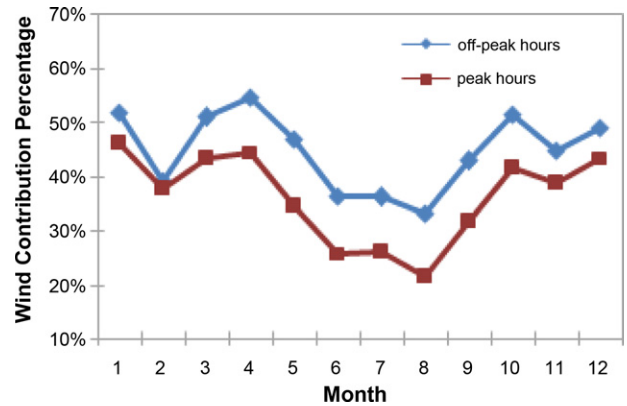

Figure 14: Wind Energy Contribution at Peak/Off-Peak Hours

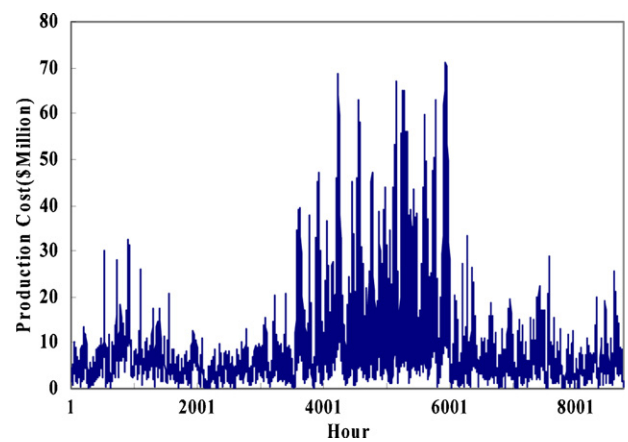

Figure 15: Hourly Production Cost in Scenario 4

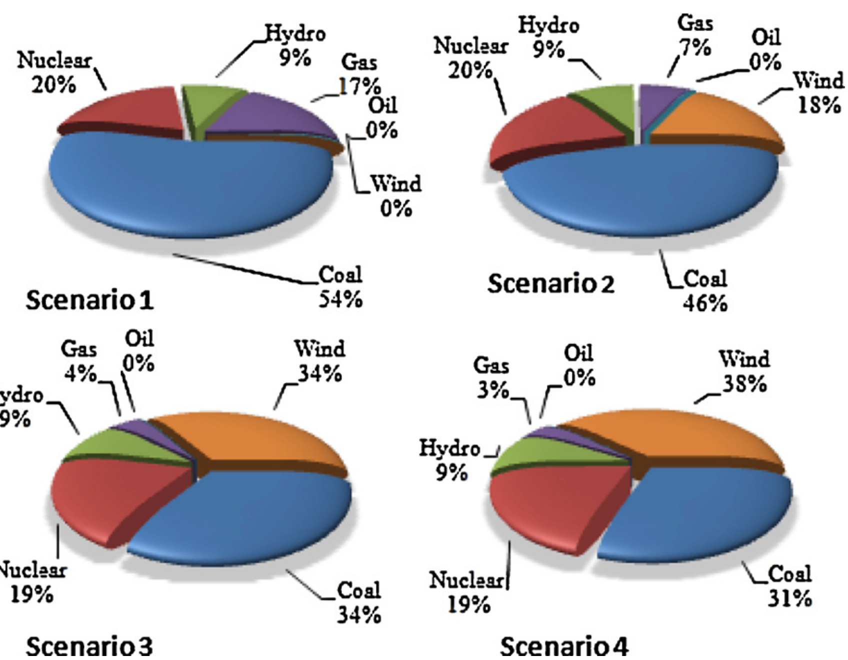

Figure 16: Energy Production Portfolios in Wind Integration Scenarios

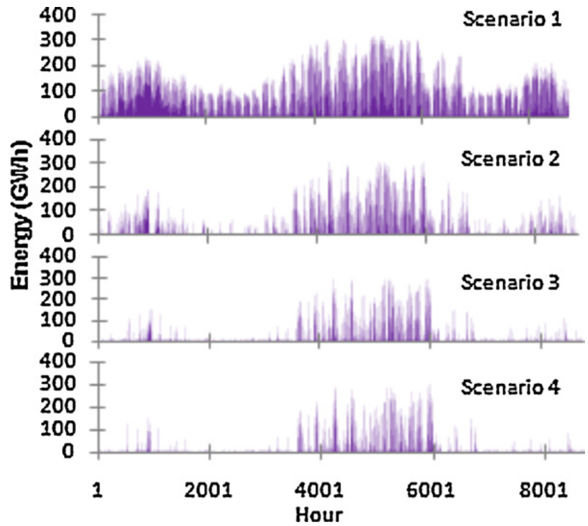

Figure 17: Energy Provided by Gas Units in Wind Integration Scenarios

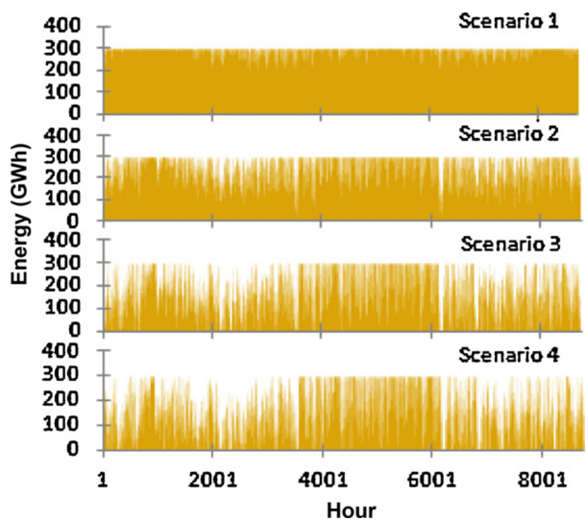

Figure 18: Energy Provided by Coal Units in Wind Integration Scenarios

energy contribution will be more than 20 percent of the system load. **Figure 14** shows the percentage of wind energy contribution at peak/off-peak hours. Here, the wind energy contribution to the total energy at peak hours in August is 21.33 percent, which is also the lowest period for the wind energy production. The wind energy in this period is 75.83 TWh as compared to 38.67 TWh in Scenario 2 and 68.52 TWh in Scenario 3. The annual production cost is $77 billion.

Figure 15 shows the hourly production cost with an average production cost of $16.1/MWh, and peak/off-peak average production costs of $18.19/MWh and $10.04/MWh, respectively. Compared to the simulation results in Scenarios 1–3, the production costs has dropped here as more wind energy sites are added. **Figure 16** shows the wind energy contribution in all four Scenarios. Here, the gas unit production has decreased as more wind energy is considered. Also, the energy supplied by coal units is lower as they are replaced by the integrated wind energy units. Figures 17–19 show the energy supplied by gas, coal, and wind units in four Scenarios. These figures show that wind energy will replace some of the fossil energy especially at off-peak hours in the Eastern Interconnection. **Figure 20** show the annual commitment results of existing power plants in four Scenarios, in which red dots represents the power plants in

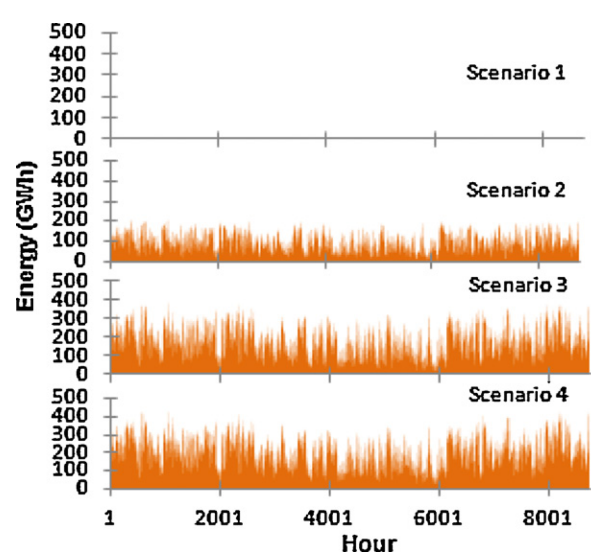

Figure 19: Hourly Wind Energy in Wind Integration Scenarios

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2011.09.002

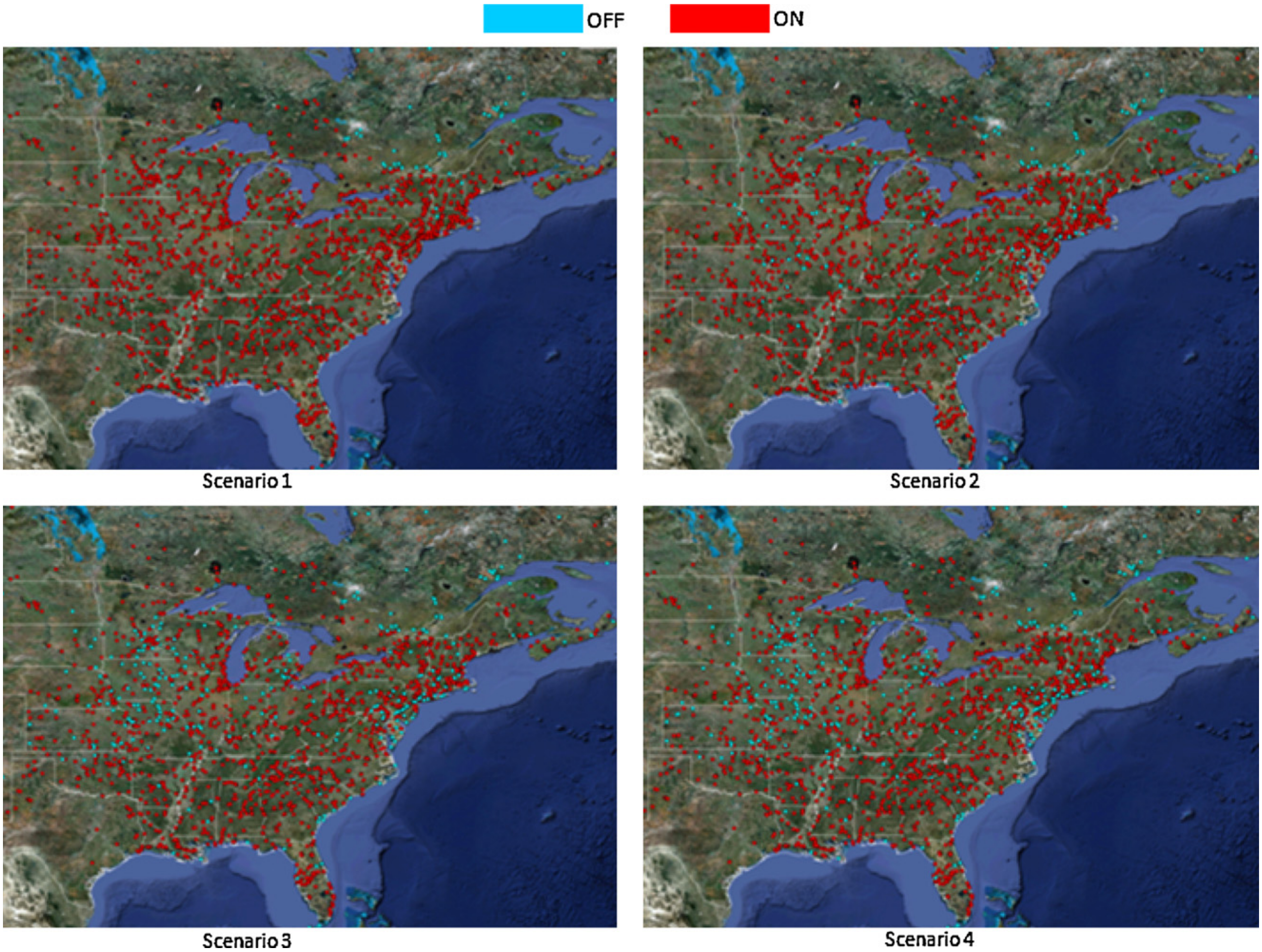

Figure 20: Unit Commitment Results in Wind Integration Scenarios

which at least one unit is committed for a minimum of one hour per year. Also, blue dots show the plants which will be off throughout the year as more wind energy is integrated in the Eastern Interconnection.

B. Sensitivity analysis

There are several uncertain energy factors in the Eastern Interconnection, including fuel prices, hourly wind speed [11], hourly loads, and carbon costs, which could have major impacts on the large-scale wind energy integration and the energy production portfolio. It is perceived that an accurate forecast for some of these factors might not be readily available. In this section, we apply sensitivity analyses, based on our simulation results given in Section A2, to study the impact of fluctuations in such factors on the wind energy integration and the annual energy production portfolio in the

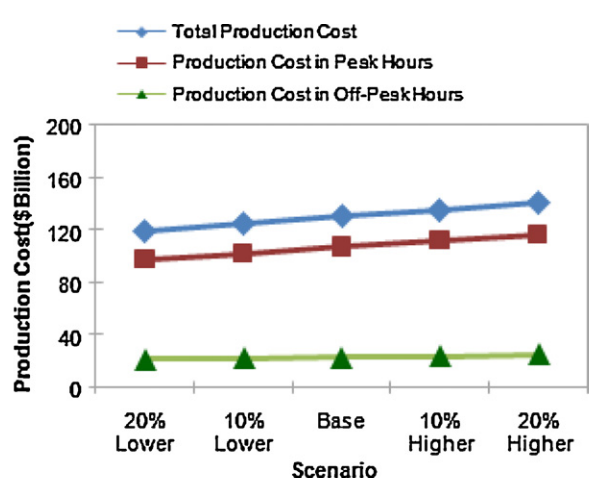

Figure 21: Production Costs in Fuel Cost Scenarios

  doi:/10.1016/j.tej.2011.09.002

Eastern Interconnection. The simulation results given in Section A2 are considered as the base case in this section.

1. Fuel Price Sensitivity

We apply the sensitivity analysis to the WINS simulation results for 2030, given in Section A2, in which the potential wind energy sites with a minimum CF of 40 percent and a total energy contribution of 17.67 percent (which is close to the expected 20 percent wind contribution in 2030) were considered. The following four Scenarios would consider the impact of fuel price forecast.

Scenario 5: Actual fuel price is 20 percent lower than the forecast

Scenario 6: Actual fuel price is 10 percent lower than the forecast

Scenario 7: Actual fuel price is 10 percent higher than the forecast

Scenario 8: Actual fuel price is 20 percent higher than the forecast

As expected, the fuel price escalation has no impact on the wind energy dispatch since the wind energy has a zero price and will always be dispatched. However, the production cost in **Figure 21** will increase as fuel prices increase. The increase in fuel price at peak hours will have a more pronounced impact on the production cost as more expensive units will be committed.

2. Wind Energy Production Sensitivity Analysis

We apply the sensitivity analysis to the 2030 simulation results in Section A2. Four Scenarios are studied as follows.

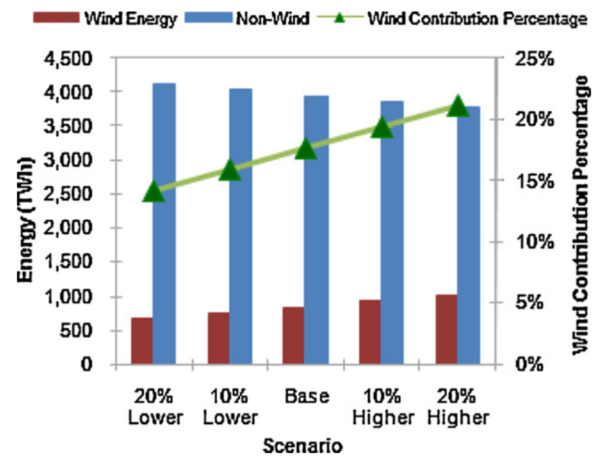

Figure 22: Wind/Non-Wind Energy in Wind Energy Scenarios

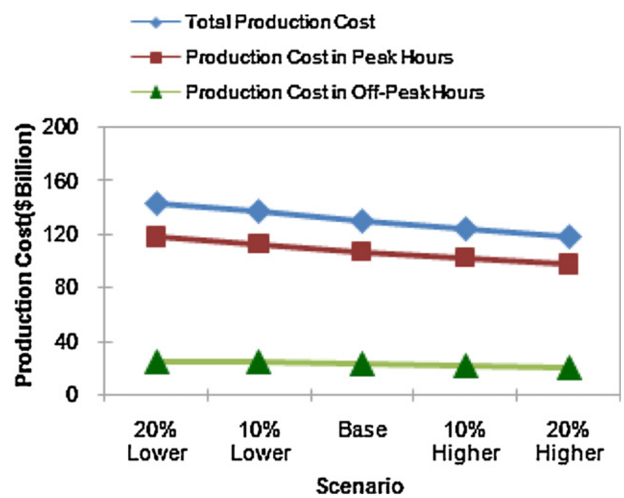

Figure 23: Production Cost in Wind Energy Production Scenarios

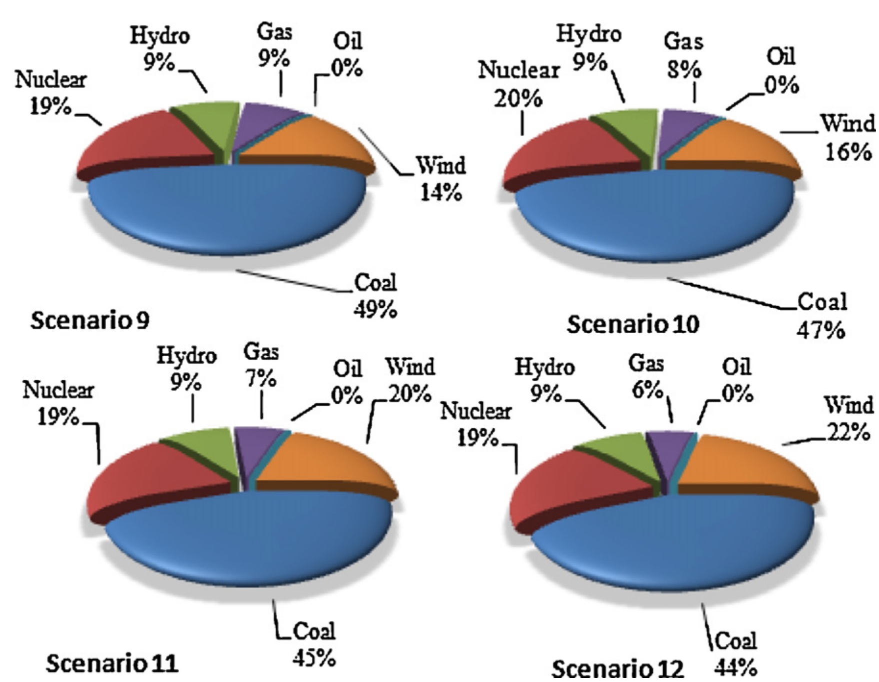

Figure 24: Energy Production Portfolios in Wind Energy Production Scenarios

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2011.09.002

Scenario 9: Actual wind energy production is 20 percent lower than the forecast
Scenario 10: Actual wind energy production is 10 percent lower than the forecast
Scenario 11: Actual wind energy production is 10 percent higher than the forecast
Scenario 12: Actual wind energy production is 20 percent higher than the forecast

Figure 22 shows that the wind energy contribution to the total energy production is about 20 percent when the actual wind energy is 10 percent higher than that in the base case. Figure 23 shows that the total production cost decreases with the added wind energy production. Again, the production cost is more sensitive to the wind energy production at peak hours. Figure 24 shows the energy production portfolios in all four Scenarios. The energy produced by gas and coal units will decrease as the wind energy production is higher. Similar to that in Figure 22, the wind energy contribution is increased from 14 percent to 22 percent. The unit commitment and hourly generation dispatch show a similar pattern as that in Section A2.

3. *Load Sensitivity Analysis*

In this section, we study the impact of load forecast errors on the WINS base case simulation results in Section A2. We do the sensitivity analysis based the load forecast in 2030. Four Scenarios are studied as follows.

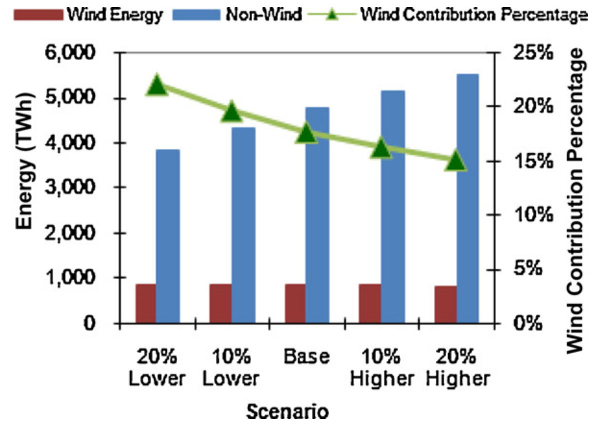

Figure 25: Wind/Non-Wind Energy in Load Scenarios

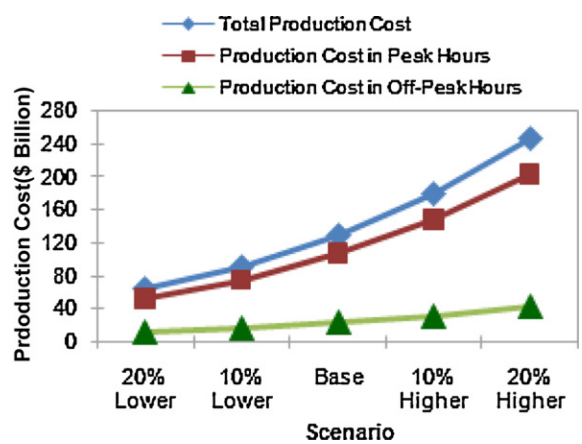

Figure 26: Production Cost in Load Scenarios

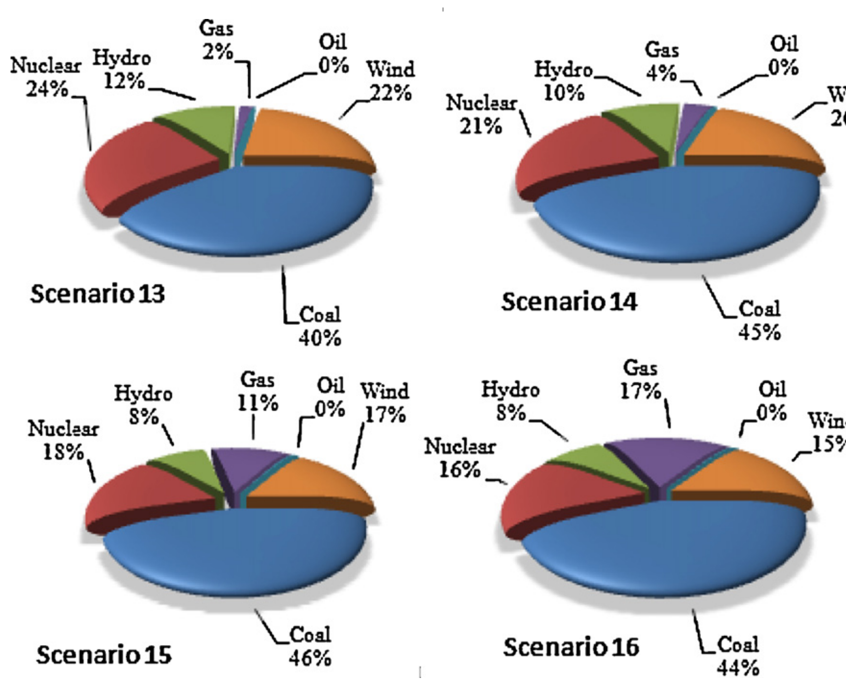

Figure 27: Energy Production Portfolios in Load Variation Scenarios

Scenario 13: Actual load is 20 percent lower than the forecast
Scenario 14: Actual load is 10 percent lower than the forecast
Scenario 15: Actual load is 10 percent higher than the forecast
Scenario 16: Actual load is 20 percent higher than the forecast

The wind energy contribution, depicted in Figure 25, shows a 19.62 percent contribution to the total energy production in Scenario 14 when the actual load is 10 percent lower than the forecast. The wind energy contribution will decline as the actual load escalates because the additional load will be served by other types of units. The production costs in Figure 26, as compared to those in Sections B1 and B2, show that the system load will have the largest impact on production costs. Here, the production cost increases a lot between Scenarios 13 and 16. The production cost at peak hours is more sensitive to load variations.

Figure 27 shows the energy contribution in the given four Scenarios. The nuclear, hydro, and wind unit with their inexpensive fuel will supply much of the hourly load. However, their contributions will decline as the system load increases. Compared with the base case in Section A2, the energy contributions by gas and coal units, especially those supplied by gas units, will decrease as we reduce the system load. Furthermore, the contribution of gas units to the energy production portfolio will increase from 7 percent in the base case (A2) to 11 percent in Scenario 15 and 17 percent in Scenario 16 as we increase the system load, which means that the additional load is mainly supplied by gas units.

Figures 28 and 29 show the hourly energy supplied by gas and coal units. In Figure 28, the energy supplied by gas units has increased as compared to that in Scenarios 13–14 especially at peak hours. In Scenario 13, gas units are mainly committed and dispatched at peak hours. Figure 30 shows that the load variation would have the largest impact on the commitment and the dispatch of generating units as compared to the fluctuation in fuel price or wind energy production. The commitment based on Scenarios 13–14 shows that many of the existing units will never be committed as hourly loads are lowered. On the other hand, almost all existing units will be committed when the hourly loads are higher than the forecast in Scenarios 15–16. The results indicate that the load management could introduce

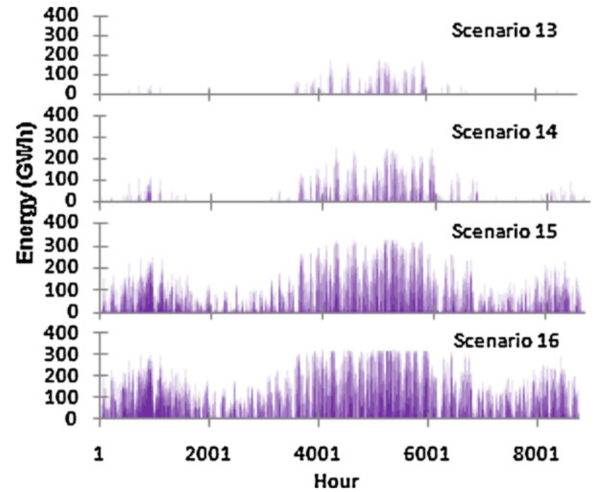

Figure 28: Hourly Energy Provided by Gas Units in Load Variation Scenarios

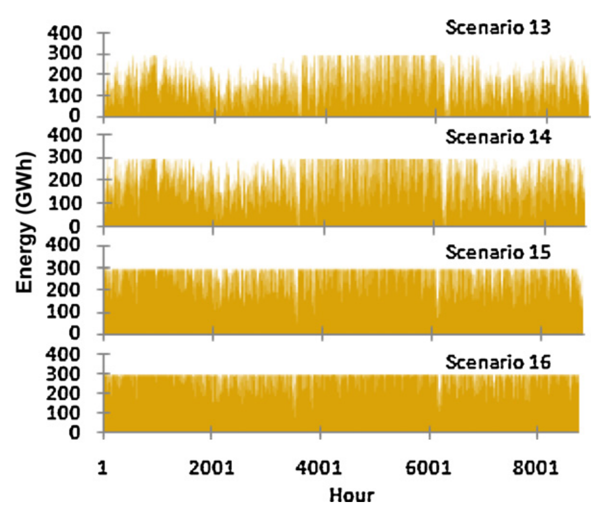

Figure 29: Hourly Energy Provided by Coal Units in Load Variation Scenarios

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2011.09.002

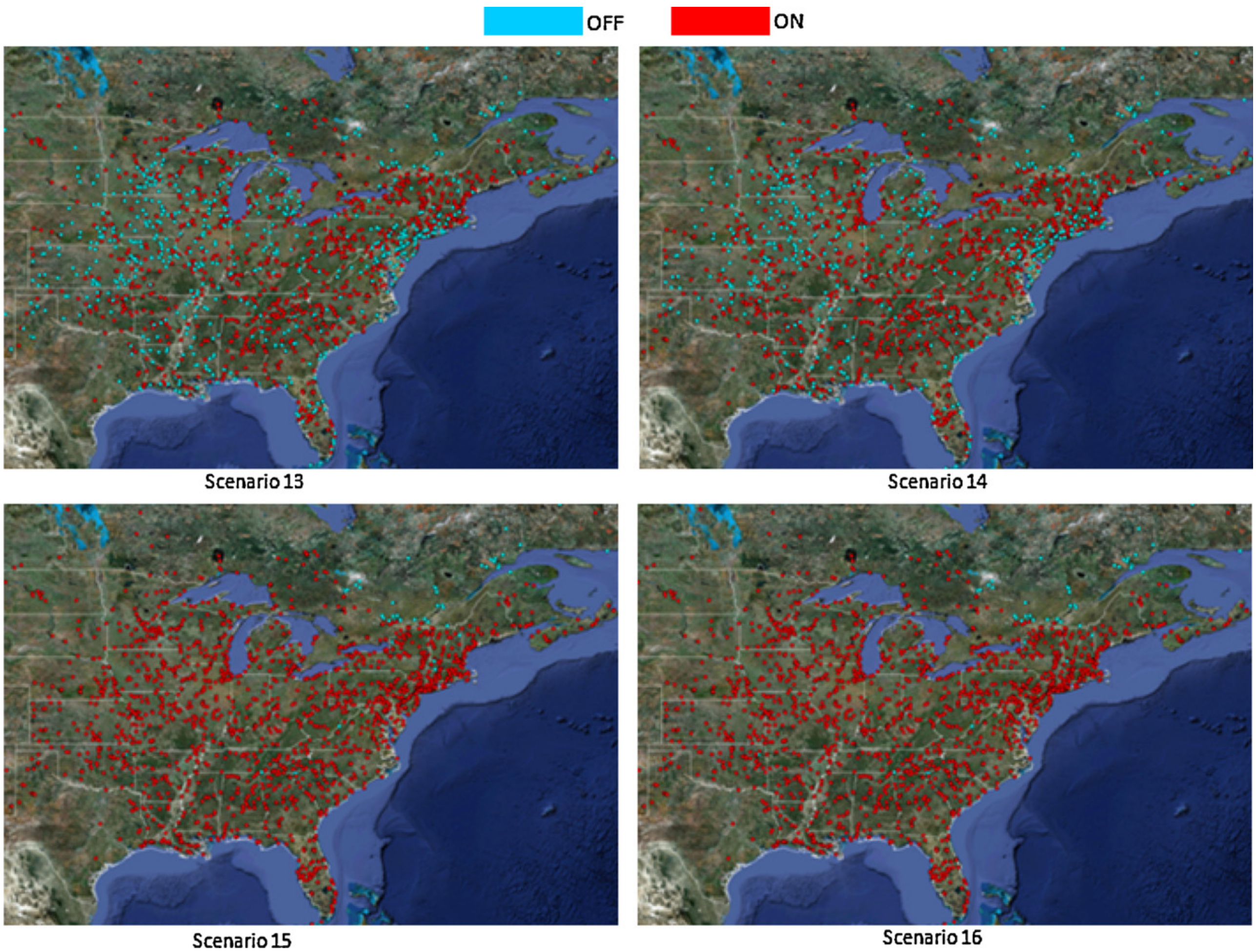

Figure 30: Unit Commitment Results in Load Variation Scenarios

large incentives for improving the system operation bottlenecks and decreasing the operation costs.

4. Carbon Cost Sensitivity Analysis

Higher carbon cost can be used as an incentive for promoting the development of clean, efficient or environmentally friendly power generation portfolios [14]. The carbon cost data given in [14] is considered here as the low-carbon-cost Scenario. The high carbon cost Scenario would consider a carbon cost that is doubled. In this section, we consider wind energy sites with CF $\geq$40% and CF $\geq$30% for

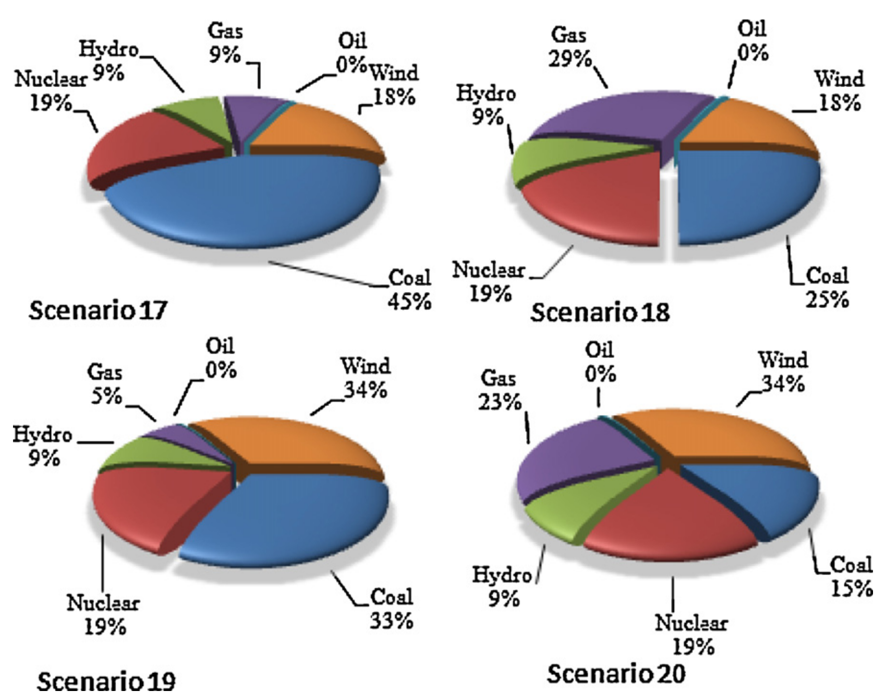

Figure 31: Energy Production Portfolios in Carbon Cost Scenarios

analyzing the following four Scenarios.

Scenario 17: Low carbon cost is considered with a minimum CF of 40 percent for wind units

Scenario 18: High carbon cost is considered with a minimum CF of 40 percent for wind units

Scenario 19: Low carbon cost is considered with a minimum CF of 30 percent for wind units

Scenario 20: High carbon cost is considered with a minimum CF of 30 percent for wind units.

The variations in carbon cost will not change the wind energy contribution to the energy production portfolio. However, the total production cost will be much higher when we apply a higher carbon cost. The production costs for four Scenarios are $406.8 billion, $638 billion, $285.7 billion, and $448 billion. The average production cost at peak/off-peak load hours are $89.5/MWh and $71.7/MWh in Scenario 17, and $140/MWh and $113.5/MWh in Scenario 18.

Figure 31 shows the energy production portfolios in carbon cost Scenarios in which the high carbon cost will have a major impact on the energy supplied by gas and coal units. Since coal prices are lower than gas prices, the energy supplied by coal units does not change much in the low-carbon-cost Scenarios. The energy supplied by gas units increases from 9 percent in Scenario 17 to 29 percent in Scenario 18 while that of coal decreases from 45 percent to 25 percent. Similar results are obtained in Scenarios 19 and 20 when we consider wind units

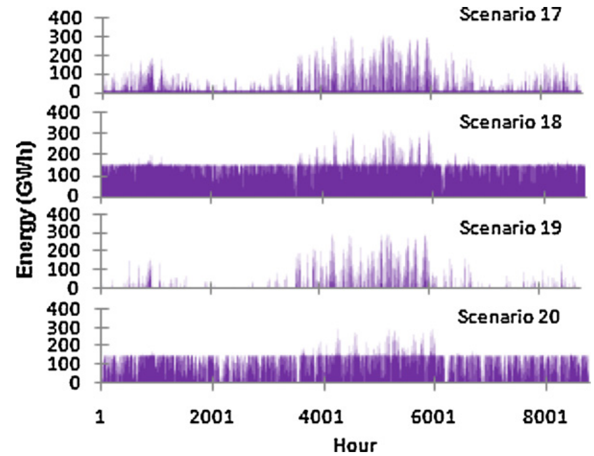

Figure 32: Energy Provided by Gas Units in Carbon Cost Scenarios

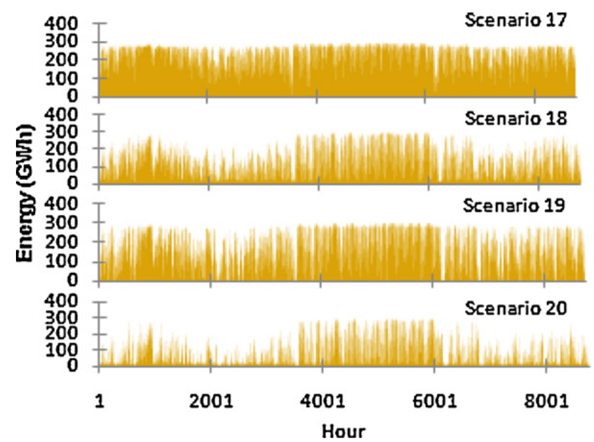

Figure 33: Energy Provided by Coal Units in Carbon Cost Scenarios

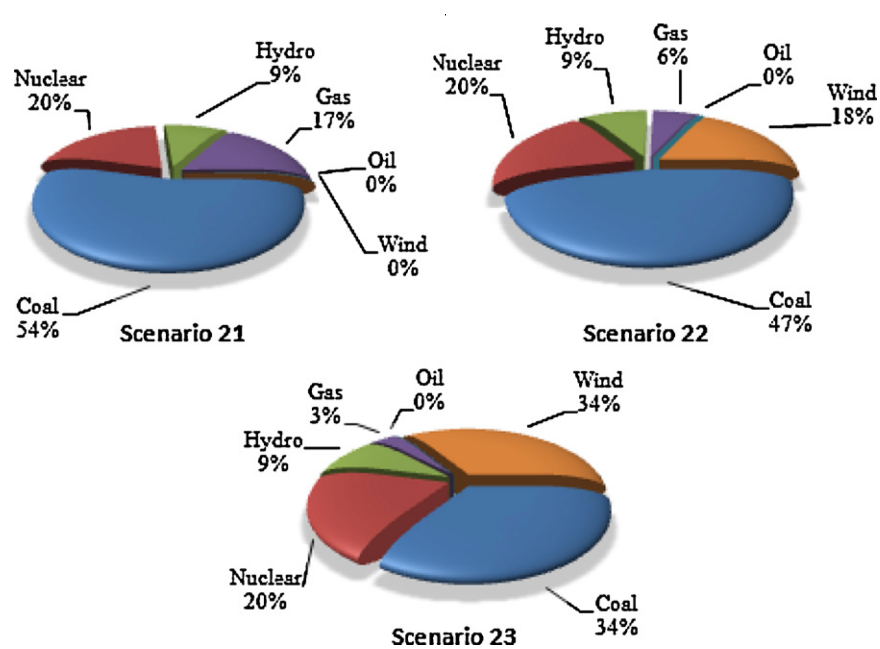

Figure 34: Energy Production Portfolios in Load Shedding Scenarios

 1040-6190/$–see front matter , doi:/10.1016/j.tej.2011.09.002

with a minimum CF of 30 percent. Figures 32 and 33 show the hourly energy supplied by gas and coal units, which are consistent with that of Figure 31. Here, gas units would be committed and dispatched in most hours when we consider high carbon costs.

C. Load management by introducing load shedding

As presented in Section B3, the hourly load variations would have a major impact on the WINS simulation results. In this section, we consider load shedding as an option to manage the system operation more efficiently at peak hours. For instance, if the hourly load were higher than 80 percent of the annual peak load, we would set it at 80 percent. Three Scenarios are considered as follows.

Scenario 21: Wind energy is not considered when load shedding is applied

Scenario 22: Wind energy with a minimum CF of 40 percent is considered when load shedding is applied

Scenario 23: Wind energy with a minimum CF of 30 percent is considered when load shedding is applied

Figure 34 shows the energy production portfolios for the three load shedding Scenarios. **Figures 35–37** show that the load shedding will alter the unit commitment as compared to those in Figure 20. Here, more gas units are turned off at peak hours when load

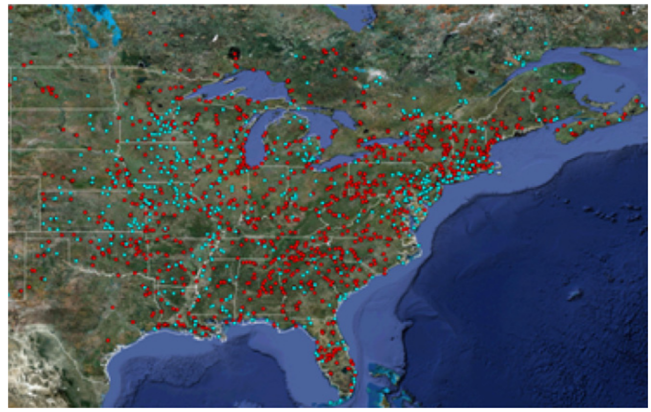

Figure 35: Unit Commitment Results in Scenario 21

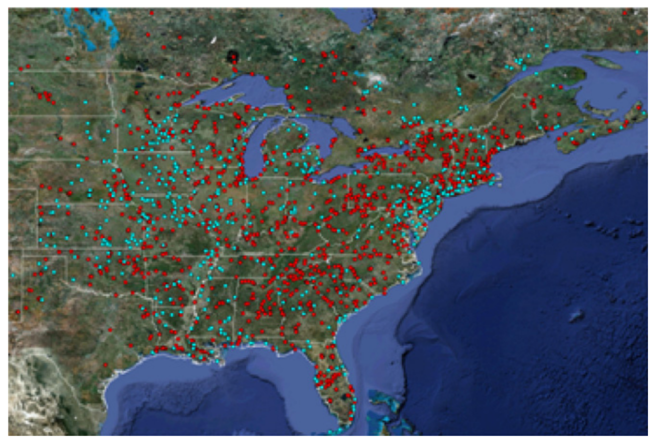

Figure 36: Unit Commitment Results in Scenario 22

shedding is applied. Here, there are about 1,200 gas units which would never be committed again when load shedding is considered as compared to those of the Scenarios 1, 2, and 3 in Section A. These results are similar to those for load variation analysis given in Scenarios 13 and 14 (Section B3). **Figure 38** shows the hourly energy supplied by gas units in which the gas unit dispatch is lower because of the load shedding at peak hours.

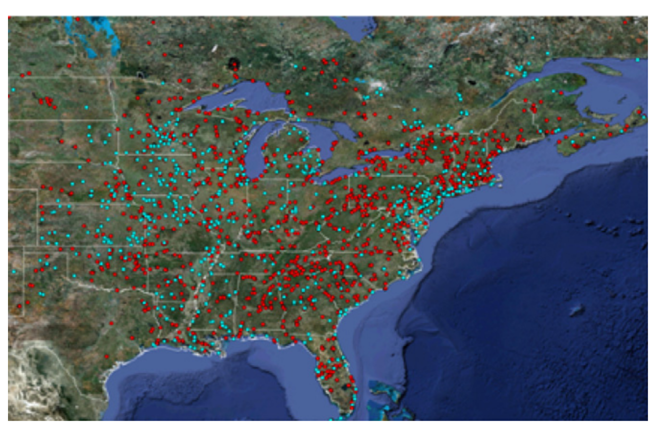

Figure 37: Unit Commitment Results in Scenario 23

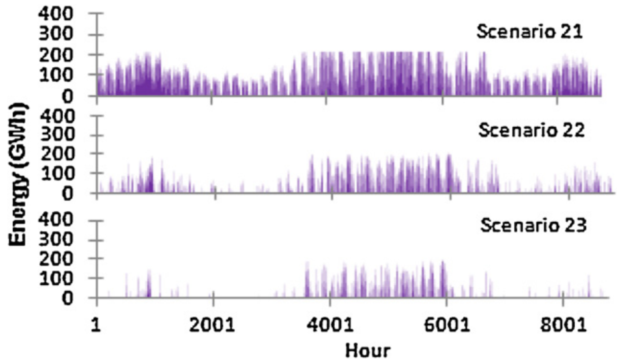

Figure 38: Energy Provided by Gas Units

Load shedding has almost no impact on the hourly dispatch of coal units, as coal units are committed to serve the base load.

IV. Concluding Remarks

In this article, a comprehensive large-scale wind energy integration analysis is considered

Table 1: Summary of Simulations in All Scenarios

Scenarios	Wind Capacity (GW)	Wind Energy (TWh)	Wind Energy Contribution (%)	Production Cost ($ Billion)	Average Production Cost ($/MWh)
No wind	0	0	0	217.5	45.64
$CF \geq 40\%$	230.5	845.2	17.67	130.4	27.25
$CF \geq 30\%$	481.5	1,596	33.37	86.8	18.14
All Wind	580	1,816	38	77	16.10
Fuel price sensitivity					
20% lower	230.5	845.2	17.67	118.9	24.87
10% lower		845.2	17.67	124.7	26.06
10% higher		845.2	17.67	135.7	28.36
20% higher		845.2	17.67	141.7	29.63
Wind gen. sensitivity					
20% lower		676.1	14.14	143.7	30.03
10% lower		760.6	15.9	136.8	28.59
10% higher		929.7	19.44	130.4	25.99
20% higher		1014	21.20	124.3	24.80
Load sensitivity					
20% lower		845.2	22.07	64	16.73
10% lower		845.2	19.62	91.6	21.27
10% higher		845.2	16.29	178.5	34.65
20% higher		845.2	15.12	245.9	44.54
Carbon cost sensitivity					
Low carbon cost with 40% wind	230.5	845.2	17.67	406.8	84.97
High carbon cost with 40% wind	230.5	845.2	17.67	638	133.3
Low carbon cost with 30% wind	481.5	1,596	17.67	285.7	69.68
High carbon cost with 30% wind	481.5	1,596	17.67	448	93.59
Load management					
No wind energy with load shedding	0	0	0	208.7	44
Min 40% CF wind with load shedding	230.5	845.2	17.81	123	25.9
Min 30% CF wind with load shedding	481.5	1,596	33.53	80.6	16.97

 1040-6190/$–see front matter doi:/10.1016/j.tej.2011.09.002

which is based on the simulation of the 2030 load forecast in the Eastern Interconnection of the United States. The wind energy integration simulation results and their sensitivities are summarized in **Table 1**. Here, transmission constraints are not considered when studying the wind energy production portfolios because the 2030 wind integration sites are not specified in the proposed wind energy data. Accordingly, the contribution of wind energy to the five Scenarios listed in Table 1 is about 20 percent or higher.

The 2030 simulation results show that large-scale wind energy integration will have a major impact on the hourly commitment and the dispatch of gas and coal units, especially at off-peak load hours, since the wind energy is generally rich at such hours. More gas and coal units will be replaced by wind energy as wind units at candidate wind sites are integrated into the grid, and the system production cost will decrease along with the wind energy integration. The fuel price sensitivity simulation shows that fuel price alterations will have major impacts on the system production cost. However, load variation will have a larger impact on the simulation results. Potential carbon costs will have the largest impact on simulation results. Here, production costs will rise significantly with increasing the carbon costs, and more gas units and fewer coal units will be committed and dispatched as carbon costs increase. Peak load shaving and demand response will have a major impact on the hourly commitment and dispatch of gas units because peak loads are mainly supplied by gas units. Also, load deferrals and smoothing out the daily load profile by introducing Smart Grid technologies (e.g., storage) will notably improve the economics and enhance the operation of power systems.■

References

[1] U.S. Department of Energy, 2009 Wind Technologies Market report, Aug. 2010, at http://www1.eere.energy.gov/windandhydro/pdfs/2009_wind_technologies_market_report.pdf

[2] U.S. National Renewable Energy Laboratory, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, at http://www.nrel.gov/docs/fy08osti/41869.pdf

[3] International Energy Agency, *IEA Wind Energy Annual Report 2009*, July 2010, at http://www.ieawind.org/AnnualReports_PDF/2009.html

[4] Eastern Wind Integration and Transmission Study, at http://www.nrel.gov/wind/systemsintegration/ewits.html

[5] Western Wind and Solar Integration Study, at http://www.nrel.gov/wind/systemsintegration/wwsis.html

[6] B. Parsons, M. Milligan, B. Zavadil, D. Brooks, B. Kirby, K. Dragoon and J. Caldwell, 2004, *Grid Impacts of Wind Power: A Summary of Recent Studies in the United States*, Wind Energy, 7 at 87–108.

[7] J.C. Smith, M.R. Milligan, E.A. DeMeo and B. Parsons, Aug. 2007, *Utility Wind Energy Integration and Operating Impact State of the Art*, IEEE Trans. Power Syst., 22 (3) at 900–908.

[8] M. Shahidehpour, H. Yamin and Z. Li, Market Operations in Electric Power Systems (New York: Wiley, 2002).

[9] J. Wang, M. Shahidehpour and Z. Li, Aug. 2008, *Security-Constrained Unit Commitment with Volatile Wind Power Generation*, IEEE Trans. Power Syst., 23 (3) at 1319–1327.

[10] W. Tian, Z. Li and M. Shahidehpour, Transmission Congestion Analysis in the Eastern Interconnection Using POMS, in: Proc. IEEE Power Eng. Soc. General Meeting, Minneapolis, July 26–29, 2010.

[11] Argonne National Lab, Wind Power Forecasting: State-of-the-Art, 2009, at http://www.dis.anl.gov/pubs/65613.pdf.

[12] J.E. Schmidt, A Statistical Analysis of Wind Power in the Eastern Interconnect of the United States, in: Proc. IEEE Power Eng. Soc. General Meeting, Minneapolis, July 26–29, 2010.

[13] Midwest ISO Planning, at http://www.midwestiso.org/page/Expansion+ Planning.

[14] U.S. Department of Energy, Fuel and Energy Source Codes and Emission Coefficients, at http://www.eia.doe.gov/oiaf/1605/coefficients.html.

[15] A. Tuohy, P. Meibom, E. Denny, M. and and O'Malley, May 2009, *Unit Commitment for Systems with Significant Wind Penetration*, IEEE Trans. Power Syst., 24 at 592–601.

[16] L. Wu, M. Shahidehpour and T. Li, May 2007, *Stochastic Security-Constrained Unit Commitment*, IEEE Trans. on Power Syst., 22 (2) at 800–811.

[17] Y. Fu, M. Shahidehpour and Z. Li, Aug. 2005, *Security-Constrained Unit Commitment with AC Constraints*, IEEE Trans. Power Syst., 20 (3) at 1538–1550.

[18] Y. Fu, M. Shahidehpour and Z. Li, May 2006, *AC Contingency Dispatch Based on Security-Constrained Unit Commitment*, IEEE Trans. Power Syst., 21 (2) at 897–908.