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NATIONAL RENEWABLE ENERGY LABORATORY

Impacts of Improved Day-Ahead Wind Forecasts on Power Grid Operations

September 2011

Richard Piwko and Gary Jordan
GE Energy Consulting
Schenectady, New York

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.

Subcontract Report
NREL/SR-5500-50907
November 2011

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NREL Technical Monitor: Debra Lew

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1 Background

With increasing penetration of wind generation on interconnected power systems, system operators are faced with increased levels of variability and uncertainty. Given that the power output of wind plants is a function of wind speed, the level of wind generation on a power system varies from hour-to-hour and from day-to-day. And given that wind speed is a function of the weather, the amount of wind that a power system operator can expect for the next day is subject to the level of uncertainty in weather-related forecasts for the next day.

Power system operators presently use day-ahead load forecasts to predict how much energy must be delivered for each hour of the next day. This forecast enables day-ahead commitment of generation resources, some of which may need many hours advance notice to be ready to generate power during the next day. Power systems with high penetrations of wind generation depend on day-ahead wind forecasts to predict how much of the wind power will be available for each hour of the next day. Combining wind forecast with the load forecast enables operators to commit the balance of the generation fleet to economically and securely serve load on the next day.

Forecasts are not perfect. Load forecasting is a very mature science since power system operators have been using day-ahead load forecasts in their security constrained unit commitment (SCUC) processes for several decades. Day-ahead hourly load forecast errors are typically in the range of 1% to 3%[1]. State-of-the-art (SOA) wind forecasts typically have errors in the range of 15% to 20% mean absolute error (MAE) for a single wind plant[2].

Previous large-scale wind integration studies have demonstrated that using day-ahead SOA wind power forecasts for unit commitment can dramatically improve system operation by reducing overall operating costs, reducing unserved energy, and reducing spilled energy (wind curtailment), while maintaining required levels of system reliability. This study analyzed the potential benefits of improving the accuracy (reducing the error) of day-ahead wind forecasts on power system operations, assuming that wind forecasts were used for day ahead security constrained unit commitment.

The following wind forecasts were considered:

- State-of-the-art (SOA) wind forecasts, based on mesoscale simulation methods
- SOA with 10% improvement
- SOA with 20% improvement

---

[1] CAISO publishes historical information on load forecasts and other operational data at http://oasishis.caiso.com/

[2] ISO-NE report, "Technical Requirements for Wind Generation Interconnection and Integration". Section 4 addresses Wind Generation Forecasting. http://www.iso-ne.com/committees/comm_wkgrps/prtcpnts_comm/pac/reports/2009/index.html

- SOA with 100% improvement (i.e., a perfect forecast)

When wind forecasts are lower than actual wind plant output, more conventional generation is committed in the day ahead than is actually needed during the day of operation. This means that the committed conventional generation will be operated at lower power output than planned, which would be a less efficient operating point for the system (primarily due to lower efficiency at lower power levels for thermal units). If the wind forecast error is large enough, it may be necessary to spill some of the excess wind (or other) generation.

When wind forecasts are higher than actual wind plant output, less conventional generation is committed in the day ahead than is actually needed during the day of operation. Turning on quick-start peaking units normally mitigates the shortage in committed generation, but this drives up system operating cost significantly because of their lower efficiency. If the wind forecast error is large enough, there is also a risk of operating reserve shortfalls or possibly load-shedding.

This study uses the WECC system as the basis for evaluating the operating cost impacts of improved day-ahead wind forecasts. In order to estimate the potential impacts for the entire US power grid, the WECC results are extrapolated according to the relative sizes of the WECC and US power grids, as measured by annual load energy.

2 Study Scenarios

The WECC system is used as the basis for this analysis, building on the In-Area scenario developed for the Western Wind and Solar Integration Study, WWSIS. Figure 2.1 shows the locations of wind generating plants assumed for this study. Red dots are "preselected" or existing wind generation plants at the time the study scenario was developed. Blue dots represent future wind plants that were added to provide the required level of wind generation for the I30 case with 30% wind energy in the Westconnect footprint (NV, AZ, NM, CO, WY) and 20% wind energy in the rest of WECC. Table 2.1 summarizes the wind plant capacities and wind energy penetration levels for the cases included in this study. The same data is shown graphically in Figure 2.2. The study considered WECC wind energy penetration levels of 3%, 10%, 14%, and 24%.

Additional information about the In-Area Scenario is included in the WWSIS final report[3].

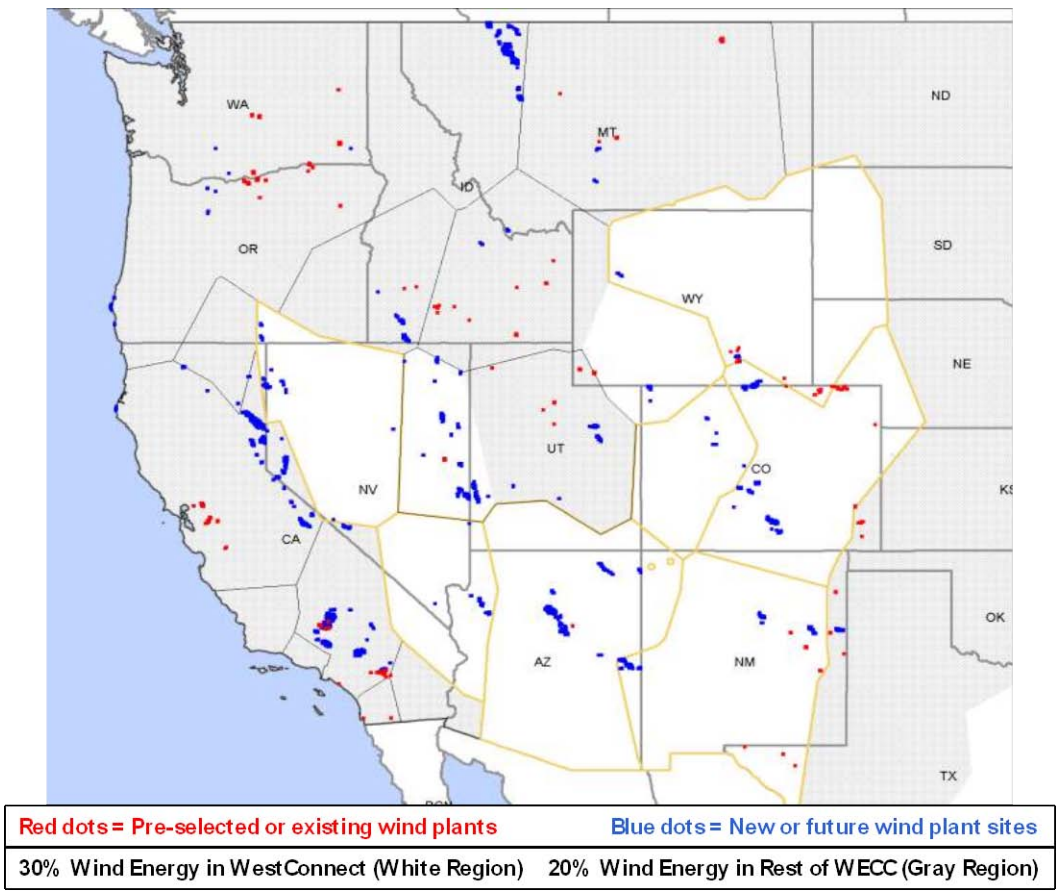

Figure 2.1: Wind sites for WWSIS 30% In Area Scenario, I30.

[3] NREL Report, "Western Wind and Solar Integration Study", http://www.nrel.gov/wind/systemsintegration/wwsis.html

Table 2.1: Total Wind Plant Capacity and Wind Energy Penetration for Study Scenario

Case Name	Case Code	Wind Capacity (MW)	Wind Energy (GWh)	Wind Energy Penetration for Study Footprint	Wind Energy Penetration for all of WECC
No Wind		0	0	0%	0%
Preselected	Pre	10,230	22,526	3%	3%
10% In-Area	I10	33,240	93,339	10%	10%
20% In-Area	I20	42,900	122,336	20%	14%
30% In-Area	I30	75,390	214,381	30%	24%

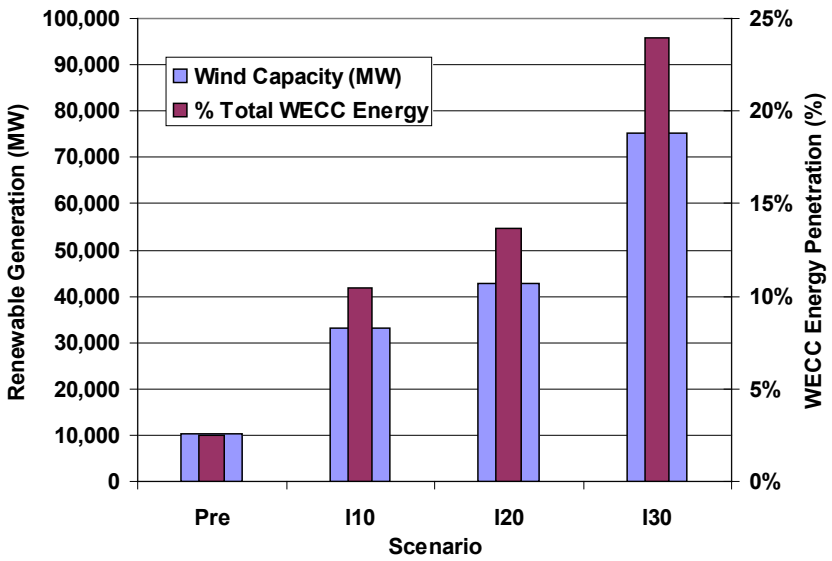

Figure 2.2: Total WECC wind generation and annual WECC wind energy penetration for study cases.

3 Analysis Approach

This study builds upon the methods and models developed during the WWSIS. The same Multi-Area Production Simulation (MAPS) model used to simulate hourly operation of the WECC system for the WWSIS was used for this study. Chapter 6 of the WWSIS report explains the details of that model.

The WWSIS used day-ahead SOA wind forecasts developed by 3-TIER for the purpose of that study. The dataset includes a separate day ahead wind forecast for each individual wind plant. The forecasts exhibited mean absolute errors in the range of 12% to 16% when aggregated on a state-by-state basis (i.e., calculated by aggregating the hourly day-ahead forecasts and hourly actual outputs for all wind plants in a given state). Section 5.6 of the WWSIS report shows more information about the SOA wind forecast data.

The primary objective of this study was to examine the impact of improving the SOA wind generation forecasts by 10% and 20%. This was done by modifying the day-ahead SOA wind generation forecasts used in the WWSIS by reducing the wind generation forecast error by 10% and 20% for each hour of the year, and then repeating the production simulations to evaluate impacts on overall WECC system operations. Wind generation and load profiles from three calendar years were analyzed (2004, 2005, and 2006).

Note that the wind generation forecast improvements are expressed in power (MW), not wind speed (meters/second). For typical pitch-controlled wind turbines, power output varies as the cube of wind speed over a significant portion of the power output curve (see Figure 3.1). In this region, small improvements in forecasted wind speed would lead to significantly larger improvements in wind power forecasts.

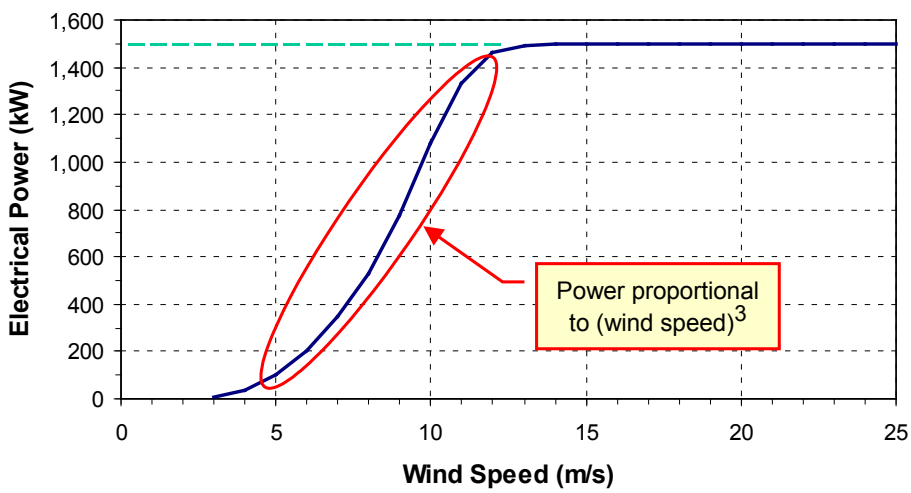

Figure 3.1: Example of Wind Turbine Power Output Curve

Figure 3.2 shows forecast and actual aggregated wind plant output for a region of Arizona with 1920 MW of wind generation, for the 30% In-Area Scenario, for two days

in January. The black curve represents the actual wind plant output. The red curve labeled "Base Forecast" represents the day-ahead SOA generation forecast provided by 3-TIER. The blue and green curves represent the SOA generation forecast with 10% and 20% less error respectively. Figure 3.3 shows the errors in each of the three wind generation forecasts, calculated as the difference between the forecast value and the actual value.

Figure 3.4 and Figure 3.5 show similar data for two days in June. Figure 3.6 shows a duration curve of the wind forecast error for all hours in a year. For 80% of the hours, the forecast errors are less than 500 MW. But for a few hours each year, at the positive and negative tails of the curves, forecast errors are in the range of 1500 MW.

In this study, the day-ahead unit commitment process assumed that the forecasted wind generation would be available, and committed other generation resources to cover the net load (load minus forecasted wind generation) plus reserves.

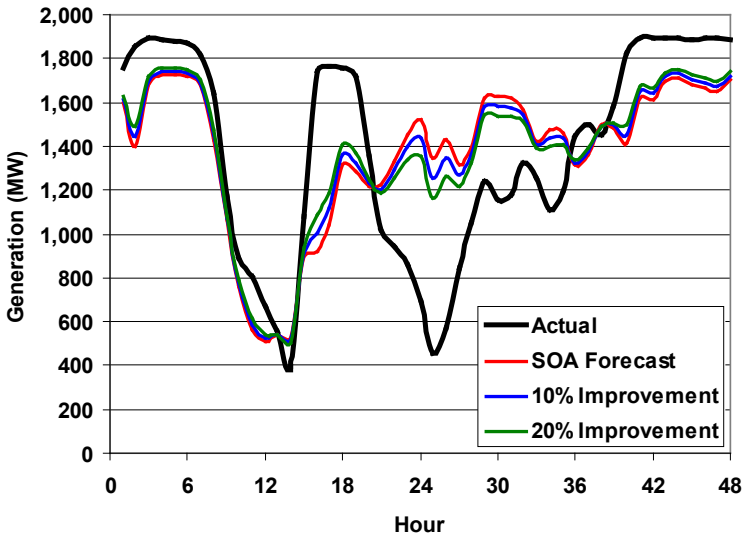

Figure 3.2: SOA and Improved Wind Forecasts for a Group of Wind Plants in Arizona; Two Days in January

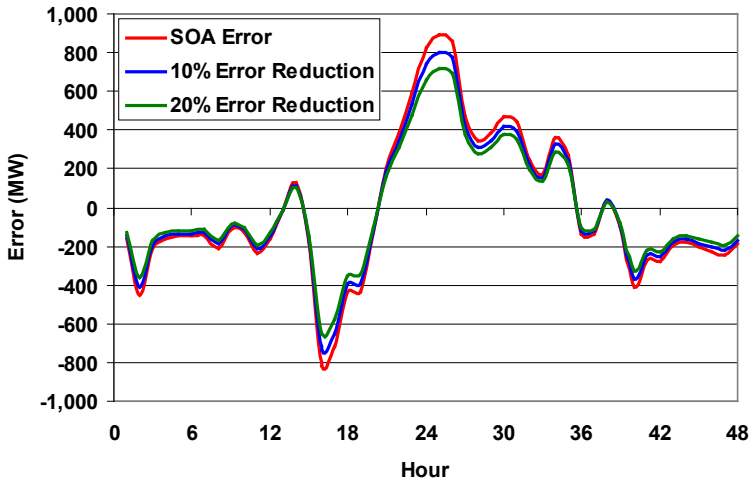

Figure 3.3: Wind Forecast Errors with SOA and Improved Wind Forecasts in Arizona, Two Days in January

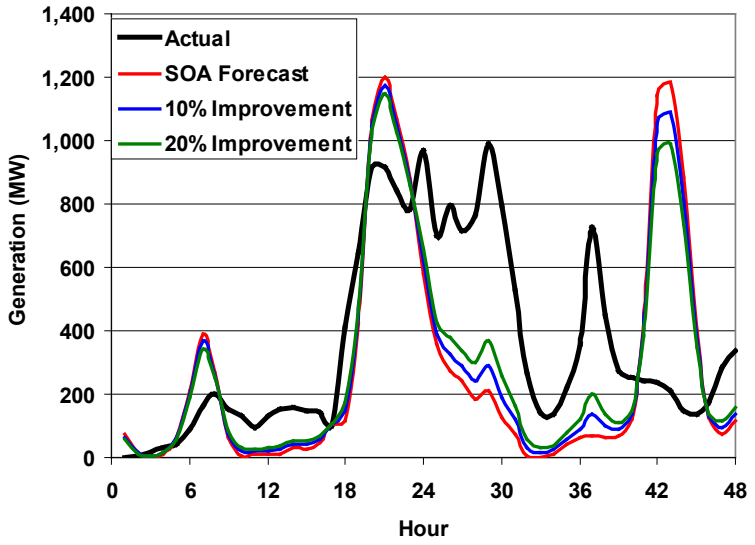

Figure 3.4: SOA and Improved Wind Forecasts for Wind Plants in Arizona; Two Days in June

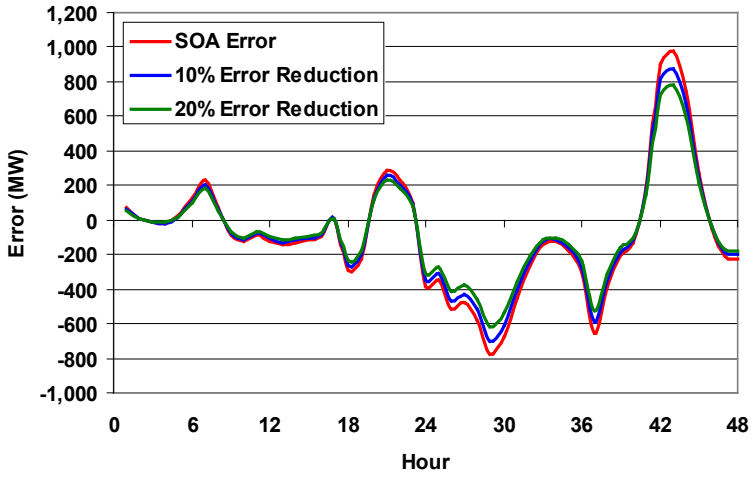

Figure 3.5: Wind Forecast Errors with SOA and Improved Wind Forecasts in Arizona, Two Days in June

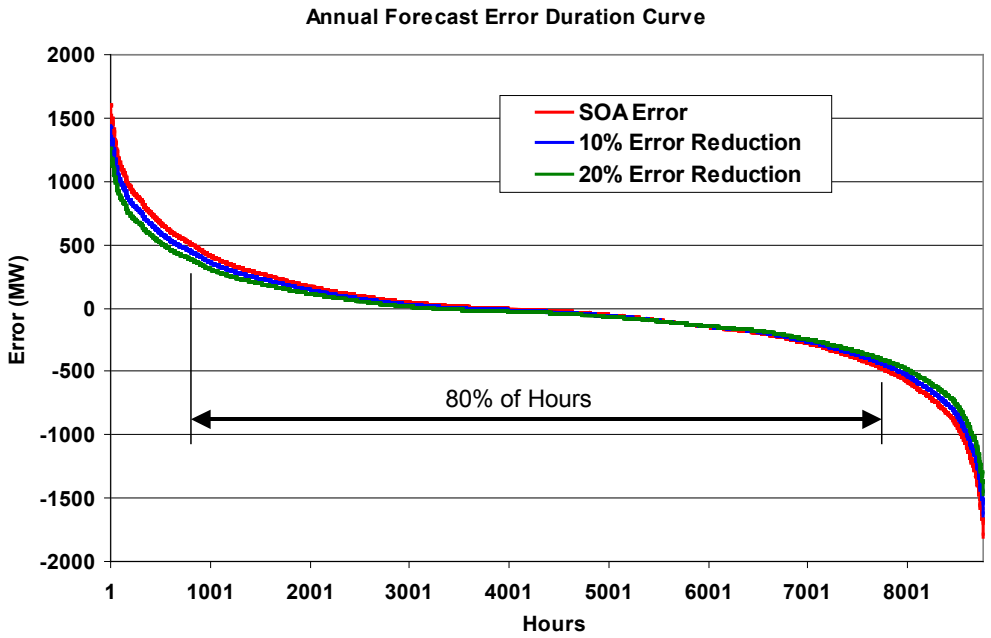

Figure 3.6: Annual Wind Forecast Error Duration Curves for a Group of Wind Plants in Arizona, SOA and Improved Forecasts, 2006 data.

4 Results

The potential benefits of improved day-ahead wind generation forecasts were evaluated with respect to three critical measurements: operating costs, unserved energy, and spilled energy.

Table 4.1 summarizes the production cost simulation cases from which the study results were derived. The first three characters of the Case Code refers to the amount of wind generation, as defined in Table 2.1. The remaining characters refer to the type of wind forecast; 10% improvement, 20% improvement, or perfect (i.e., 100% improvement).

Table 4.1: Key to Simulation Case Assumptions and Codes

Case Code	Case Assumptions
Pre m10	Preselected wind generation, modified SOA wind forecast with 10% less error
Pre m20	Preselected wind generation, modified SOA wind forecast with 20% less error
Pre P	Preselected wind generation, perfect wind forecast
I10 m10	10% In-Area Scenario, modified SOA wind forecast with 10% less error
I10 m20	10% In-Area Scenario, modified SOA wind forecast with 20% less error
I10 P	10% In-Area Scenario, perfect wind forecast
I20 m10	20% In-Area Scenario, modified SOA wind forecast with 10% less error
I20 m20	20% In-Area Scenario, modified SOA wind forecast with 20% less error
I20 P	20% In-Area Scenario, perfect wind forecast
I30 m10	30% In-Area Scenario, modified SOA wind forecast with 10% less error
I30 m20	30% In-Area Scenario, modified SOA wind forecast with 20% less error
I30 P	30% In-Area Scenario, perfect wind forecast

4.1 Operating Costs

For this analysis, operating costs include the variable costs associated with operating the WECC power system for a year, including fuels costs, unit start-up costs, and unit variable operation and maintenance (O&M) costs. Operating costs exclude capital costs, debt service costs, and other fixed costs.

Figure 4.1shows the annual operating cost savings for the WECC system with improved forecasts, relative to operation using a SOA wind forecast, for increasing levels of wind energy penetration, and for three years of operation. It shows the savings in operating costs for a 10%, 20% and 100% improvement to the day-ahead wind generation forecast. The data for the 100% improved, or perfect, forecast shows the maximum possible benefit to the WECC operating cost from wind forecasts. Although a perfect wind forecast is not realistically possible, the data serves as a calibration for the amount of benefit gained from more realistic levels of forecast improvements.

Figure 4.2 shows the same information as Figure 4.1, but without the perfect forecast. If we consider the cases with 14% WECC wind energy penetration, the results show:

- A 10% improvement in day-ahead wind generation forecast yields an average of $28M savings in annual operating costs.
- A 20% improvement in day-ahead wind generation forecast yields an average of $52M savings in annual operating costs.

With 24% wind energy penetration in WECC, the results show:

- A 10% improvement in day-ahead wind generation forecast yields an average of $100M savings in annual operating costs.
- A 20% improvement in day-ahead wind generation forecast yields an average of $195M savings in annual operating costs.

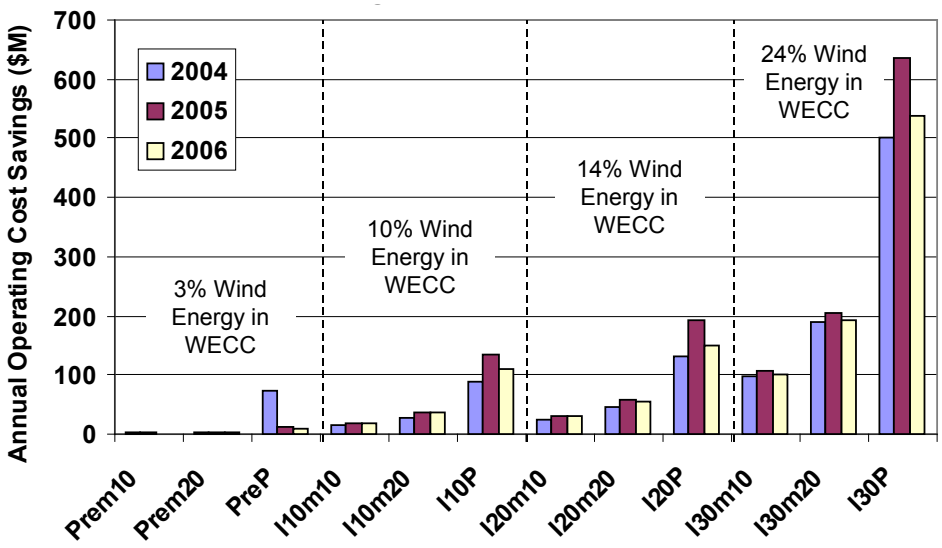

Figure 4.1: WECC Operating Cost Savings with Improved Wind Generation Forecasts (Relative to SOA Wind Forecast).

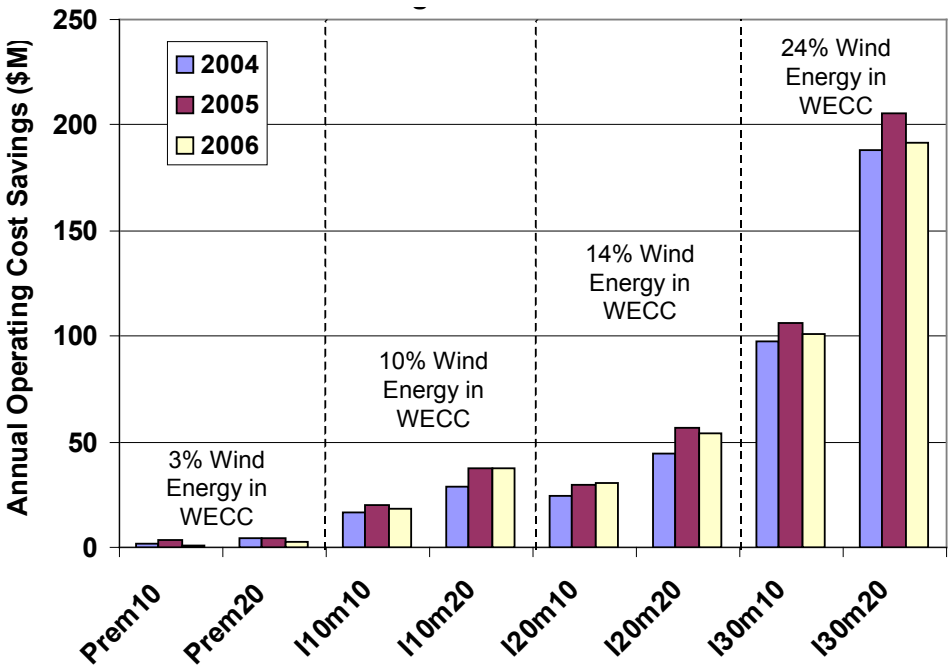

Figure 4.2: WECC Operating Cost Savings with Improved Wind Generation Forecasts (Relative to SOA Wind Forecast).

These same results are also plotted in Figure 4.3 and Figure 4.4. These figures show average annual operating cost savings as a function of forecast improvement. Figure 4.3 is scaled to 100% improvement (perfect wind forecast). Figure 4.4 is scaled to 30% forecast improvement to show higher resolution. A critical observation here is that the slope of the curves becomes lower as the level of forecast improvement increases, indicating that there is a diminishing benefit for greater forecast improvements. The initial 10% or 20% improvements in wind forecasts provide the greatest relative benefits. Further improvement will provide diminishing marginal benefits, approaching the perfect forecast.

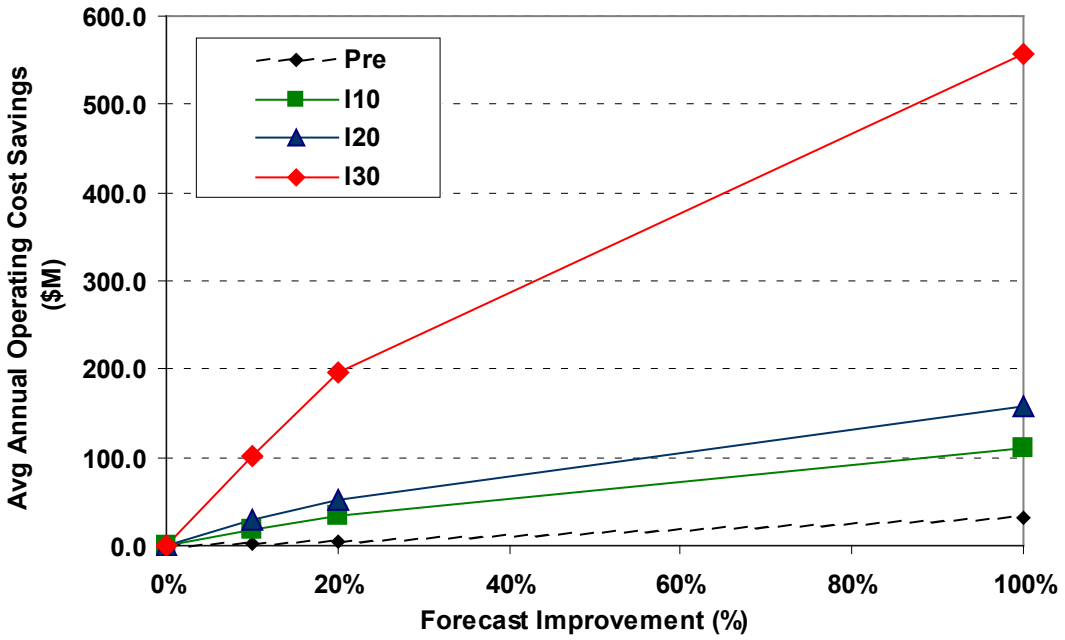

Figure 4.3: Average Annual Operating Cost Savings as a Function of Wind Generation Forecast Improvement Relative to SOA

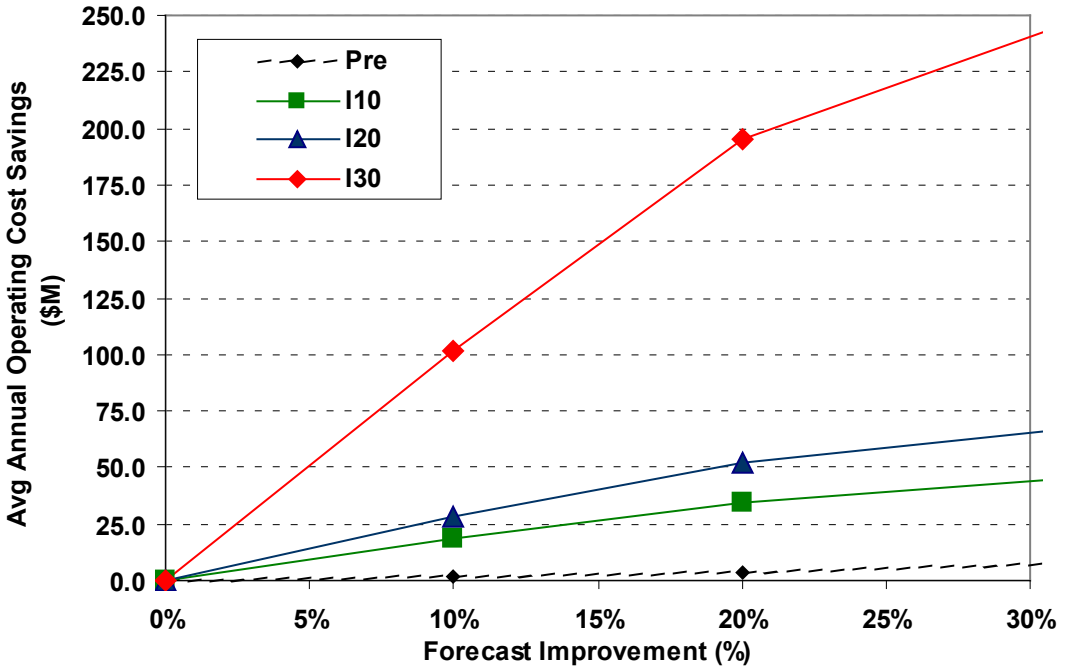

Figure 4.4: Average Annual Operating Cost Savings as a Function of Wind Generation Forecast Improvement Relative to SOA

4.1.1 Extrapolation to Entire US Power Grid

According to historical data for year 2009 in the Ventyx database, annual energy demand for WECC was 714 TWh and annual energy demand for the entire USA was 3836 TWh. Therefore, the WECC system serves slightly less than 20% of the total US electrical energy demand.

Assuming that the operational characteristics of the WECC system are generally representative of other operating areas in the USA, it would seem reasonable to roughly estimate the operating cost impacts of improved day-ahead wind forecasts on the entire USA by multiplying the WECC results by a factor of 5.

With 14% wind energy penetration in the US, extrapolation of the WECC results implies that:

- A 10% improvement in day-ahead wind generation forecast yields an average of $140M savings in annual operating costs.
- A 20% improvement in day-ahead wind generation forecast yields an average of $260M savings in annual operating costs.

With 24% wind energy penetration in the US, extrapolation of the WECC results implies that:

- A 10% improvement in day-ahead wind generation forecast yields an average of $500M savings in annual operating costs.
- A 20% improvement in day-ahead wind generation forecast yields an average of $975M savings in annual operating costs.

4.2 Operating Reserve Shortfalls

A shortfall in operating reserve occurs when there is insufficient generation available to serve the load and meet operating reserve requirements. When a reserve shortfall occurs, there is still adequate generation to serve the load, but there is not enough generation to supply all required reserves. The magnitude of the reserve shortfall is the cumulative shortage in reserve energy for all hours over a calendar year of operation. In a system that has adequate installed capacity margin, reserve shortfall events are extremely rare. When such an event does occur, a likely cause is a large error in the day-ahead forecast used for unit commitment. These events would typically develop in the following sequence:

- The day-ahead unit SCUC commits adequate generation to meet the forecast load for the next day using forecasted wind generation and other dispatchable generation resources. The commitment also includes required operating reserves.
- When the next day arrives, actual wind generation falls significantly below the forecasted level, or actual load is significantly above the forecasted load, or both.
- Quick start generation is committed and dispatched to fill the shortfall to the extent possible, but there is still not enough generation available to completely meet operating reserve requirements.

Study results indicate that improved day-ahead wind generation forecasts have no significant impact on reserve shortfalls if WECC wind energy penetration is below 14% because there were sufficient quick-start generators available to cover the forecast errors. With wind energy penetration of 24%, improved wind forecasts significantly reduce reserve shortfalls (see Figure 4.5). For the three calendar years analyzed, average annual operating reserve shortfalls would be reduced from 43 GWh to 24 GWh with a 10% wind forecast improvement. Reserve shortfalls would be further reduced to 15 GWh with a 20% wind forecast improvement.

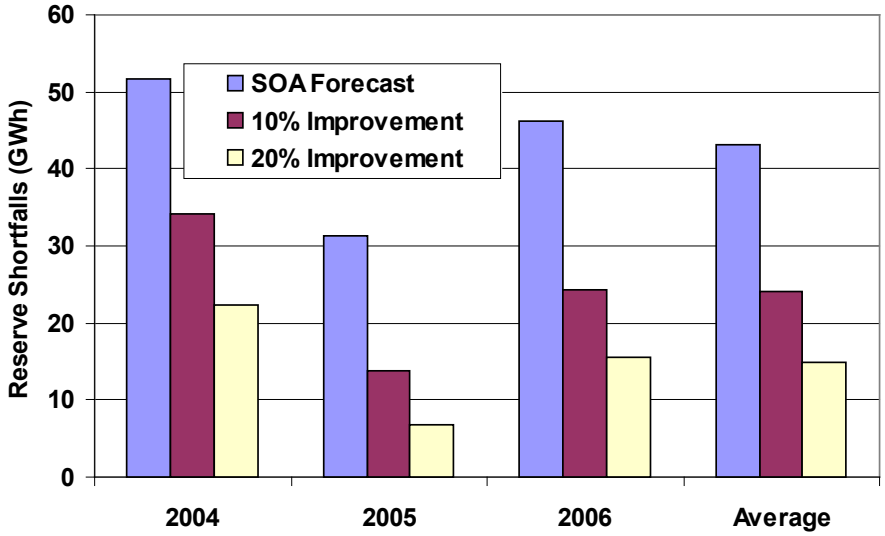

Figure 4.5: Reserve Shortfalls with Improved Wind Generation Forecasts, I30 Scenario

4.3 Spilled Energy

Spilled energy is a measure of generation that is available at no cost but cannot be used due to necessary restrictions on power system commitment and dispatch. For example, if thermal generation required to meet forecasted load on the next day is turned down to minimum load overnight, and wind generation in the overnight hours exceeds predicted levels, it may become necessary to spill (or curtail) excess generation. Most often, wind generation is curtailed in such circumstances.

Spilled energy may also be caused by congestion (i.e., generation in one area that cannot be delivered to load in another area due to transmission capacity limits). The results in this study include congestion on inter-area transfer paths. However, the system model does not include full transmission representation within balancing areas, so not all possible spilled energy due to congestion is captured in the analysis.

Study results indicate that improved day-ahead wind generation forecasts have no significant impact on spilled energy if WECC wind energy penetration is below 14%. With wind energy penetration of 24%, improved wind forecasts reduce the amounts of spilled energy (see Figure 4.6). For the three calendar years analyzed, average annual spilled energy would be reduced from 655 GWh to 628 GWh with a 10% wind forecast

improvement. It would be further reduced to 613 GWh with a 20% wind forecast improvement.

Figure 4.7 shows the percentage reduction in spilled energy relative to that with a SOA day-ahead wind generation forecast. Spilled energy is reduced by 4% with a 10% improvement in wind forecast. Spilled energy is reduced by 6.3% with a 20% wind forecast improvement.

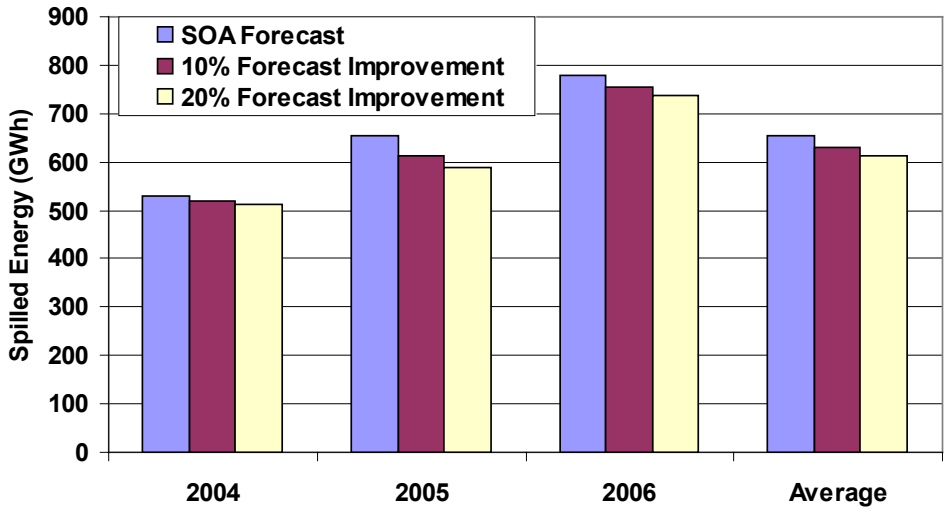

Figure 4.6: Spilled Energy with SOA and Improved Wind Generation Forecasts, I30 Scenario

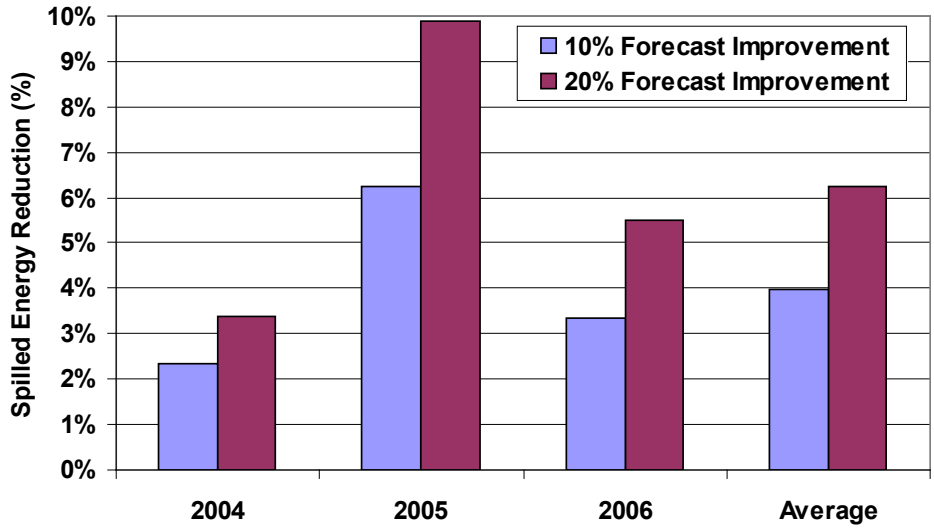

Figure 4.7: Reductions in Spilled Energy with Improved Wind Generation Forecasts, I30 Scenario

5 Key Findings

The study results show that improved day-ahead wind forecasts can significantly reduce operating costs and increase the reliability of large interconnected power systems. Even a relatively modest 10% improvement in wind generation forecasts would reduce WECC operating costs by about $28M per year with 14% wind energy penetration. For the entire US power system, the corresponding operating cost reduction would be about $140M per year.

The impacts are even greater at higher penetrations of wind energy. A 10% wind forecast improvement would reduce WECC operating costs by about $100M per year with 24% wind energy penetration. For the entire US power system, the corresponding operating cost reduction would be about $500M per year. These findings are summarized in Table 5.1.

Improved wind generation forecasts can reduce the amount of spilled energy by up to 6%, thereby increasing the overall energy efficiency of the power system. Improved wind forecasts also increase the reliability of power systems by reducing operating reserve shortfalls. A 20% wind forecast improvement could decrease reserve shortfalls by as much as 2/3 with 24% wind energy penetration.

Table 5.1: Annual Operating Cost Reductions due to Improved Day-Ahead Wind Generation Forecasts

Day-Ahead Wind Generation Forecast Error Reduction	Wind Energy Penetration	WECC Annual Operating Cost Reduction ($M)	Estimated US Annual Operating Cost Reduction ($M)
10%	14%	$28M	$140M
20%	14%	$52M	$260M
10%	24%	$100M	$500M
20%	24%	$195M	$975M

6 Future Work

The study results suggest several areas that could warrant further exploration:

1. This study assumed that wind power forecasts were improved by the same percentage in all hours of the year. But what if it was possible to obtain bigger improvements for periods with the biggest forecast errors? Large forecast errors lead to most of the problems and costs with system operations, so reducing the largest errors would be very beneficial.
2. In general, over-forecasting wind power causes more severe problems for system operations than under-forecasting wind power. When wind is over-forecast (predicting more wind power than actually occurs), the power grid experiences a shortage in unit commitment and expensive peaking units are turned on to fill the gap. There is also the risk of reserve shortfalls. Would it be possible to improve wind forecasts such that over-forecast errors are reduced by greater amount? What would be the value of such an improvement?
3. Wind forecast providers are moving towards ensemble forecasts and other methods that enable confidence bands to placed around forecast values. How would improved wind forecasts techniques affect those confidence values? And how could the forecast confidence data be used in the unit commitment process?

A Addendum – Examination of Climatology Forecast

Although climatology-based wind generation forecasts are not often (if ever) used for day-ahead unit commitment and real time power system operations, the effectiveness of climatology forecasts was investigated as part of this study. The results are reported in this addendum. The information in this addendum builds upon the study cases and simulation results presented in the main report.

Climatology forecasts are based on trends, and therefore provide an expectation of what should happen based on historical records of what has normally happened in the past. For the purpose of this analysis, it was assumed that wind generation followed daily trends, and that those trends are different for different months of the year.

Climatology forecasts were derived from the three years of "actual" wind data for all the wind plants included in this study. This was done by calculating the average hourly wind plant output for each month of the year. For example, a climatology forecast of a selected plant was calculated by averaging the hourly profiles for all the days in January. The colored lines in Figure A.1 show the output for that plant for all days in January. The heavy black line shows the hourly average plant output, which represents one method for calculating a climatology forecast for the month of January.

Figure A.2 shows the results of applying the same method to the wind plant output data for three years. It shows that the average January daily output profiles are similar for years 2004 and 2005, but that 2006 is significantly different.

For the purpose of this analysis, climatology-based wind forecasts were calculated as the average hourly plant output for each wind plant, for each of the three years of wind data. Figure A.3 shows those forecasts for an example wind plant for all 12 months of the year. For each month, the plot shows the average daily output profile that was subsequently used in production simulations as the climatology-based forecast for that wind plant. These types of profiles were calculated for each year of wind data.

Figure A.4 shows a duration curve of hourly forecast errors for an entire year for the example wind plant. The red curve is for the state-of-art (SOA) wind generation forecast based on mesoscale simulation techniques. The 10% and 20% improved SOA forecasts are also shown in blue and green respectively. The climatology forecast is represented by the black line. It has significantly higher errors than the other forecasts, except at the extremes.

Figure A.5 shows operating cost savings if WECC uses a climatology-based wind forecast for day-ahead unit commitment, relative to operating with no wind forecast (i.e., day-ahead unit commitment assumes there will be no wind generation available the next day). The figure shows that with 3% wind energy penetration, the climatology forecast reduces operating costs by about $175M per year. With 24% wind energy penetration, the operating cost savings grow to about $3.8B per year.

Figure A.6 shows a similar comparison, but for the SOA forecast relative to the climatology forecast. With 3% wind energy penetration, using a SOA wind forecast for unit commitment saves about $6M in annual operating costs compared to using a climatology forecast. If wind energy penetration increases to 14%, the operating costs savings grow to about $175M per year. And with 24% wind energy penetration, the operating cost savings grow to an average of $730M per year.

Figure A.7 shows a comparison of how SOA and climatology forecasts affect reserve shortfalls and spilled energy. Spilled energy is about 30% lower with the SOA forecast as compared to the climatology forecast. Reserve shortfalls are about 85% lower with the SOA forecast as compared to the climatology forecast.

In general, the results of this analysis indicated that:

- Using climatology-based wind forecasts for day-ahead unit commitment can significantly reduce variable operating costs, as compared to assuming there will be no wind generation the next day.
- SOA mesoscale simulation based wind generation forecasts can reduce variable operating costs even further.
- Because SOA forecasts are uniquely derived for each day of operation, they perform dramatically better than climatology forecasts in reducing reserve shortfalls and spilled energy.

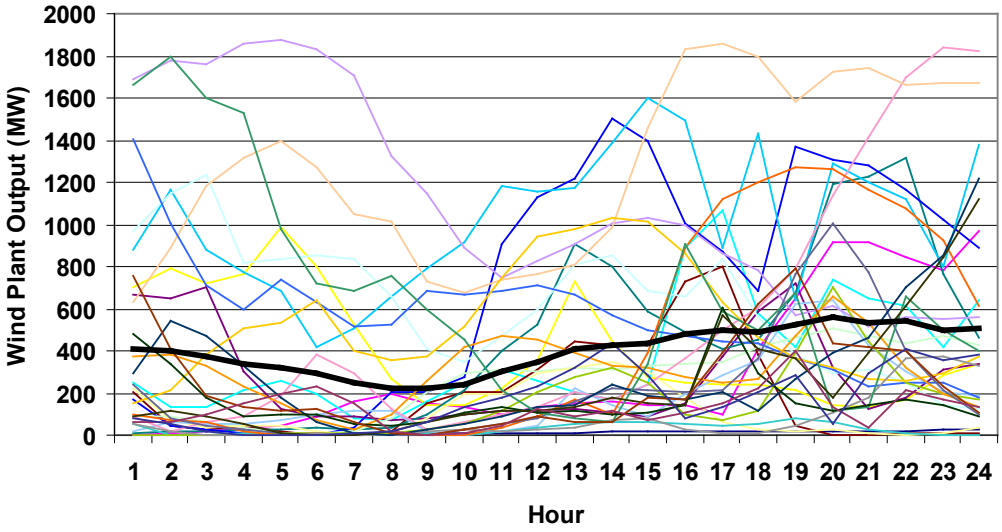

Figure A.1: Wind plant output for all days in June 2006, and average daily output profile.

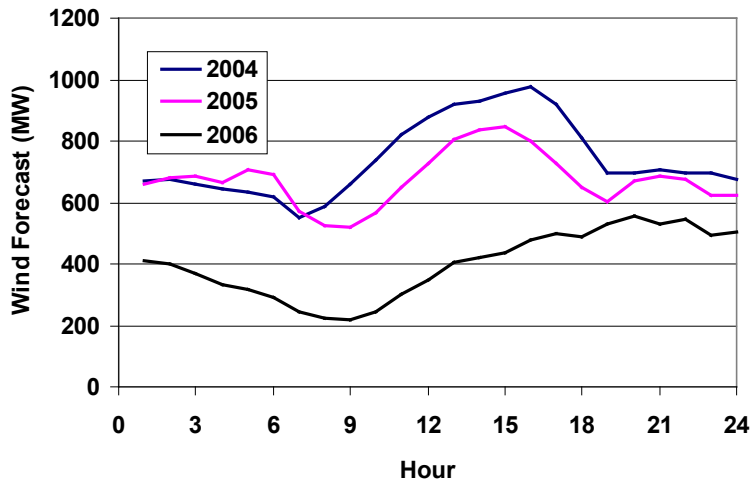

Figure A.2: Wind Plant Climatology Forecast Profiles for June.

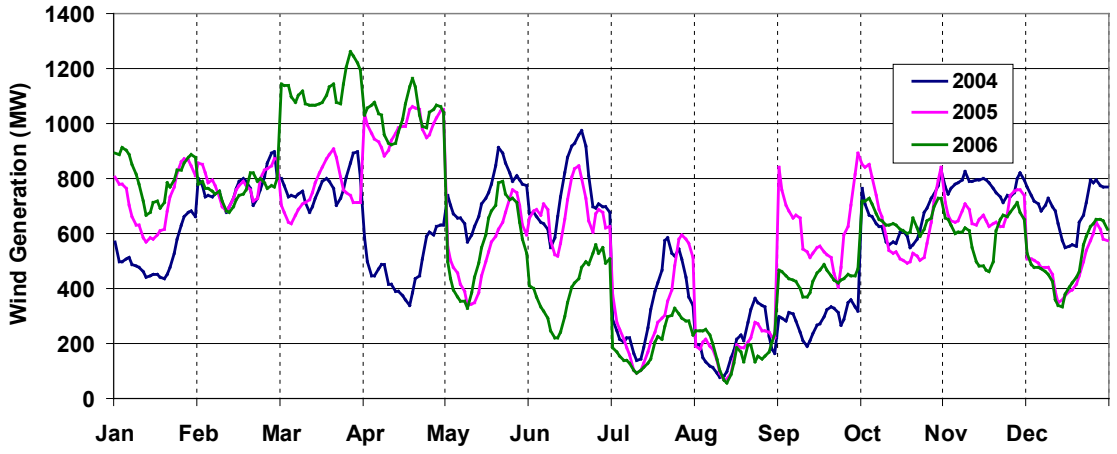

Figure A.3: Wind Plant Climatology Forecasts for 12 Months

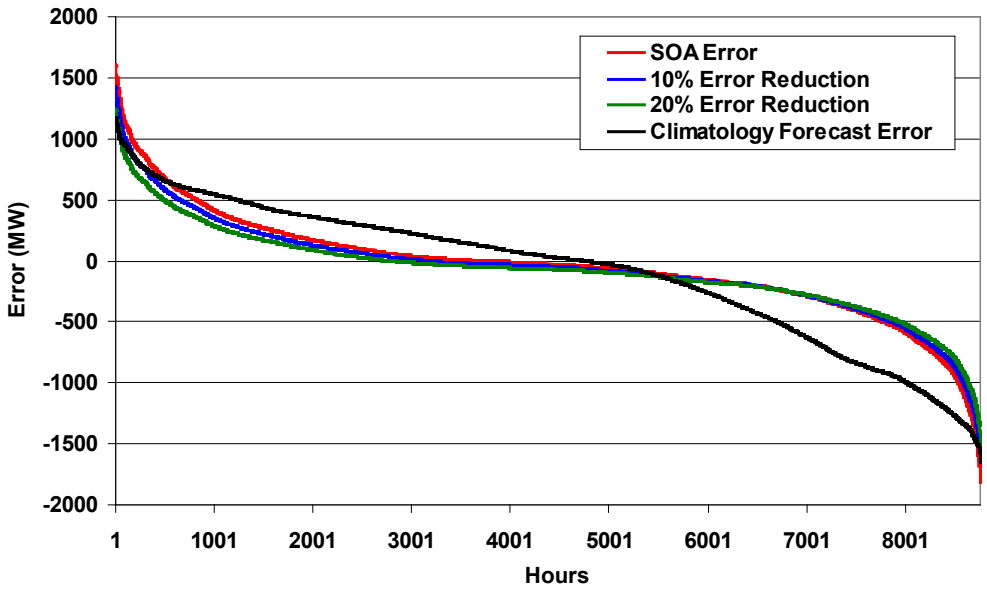

Figure A.4: Forecast Error Duration Curve for SOA and Climatology Forecasts

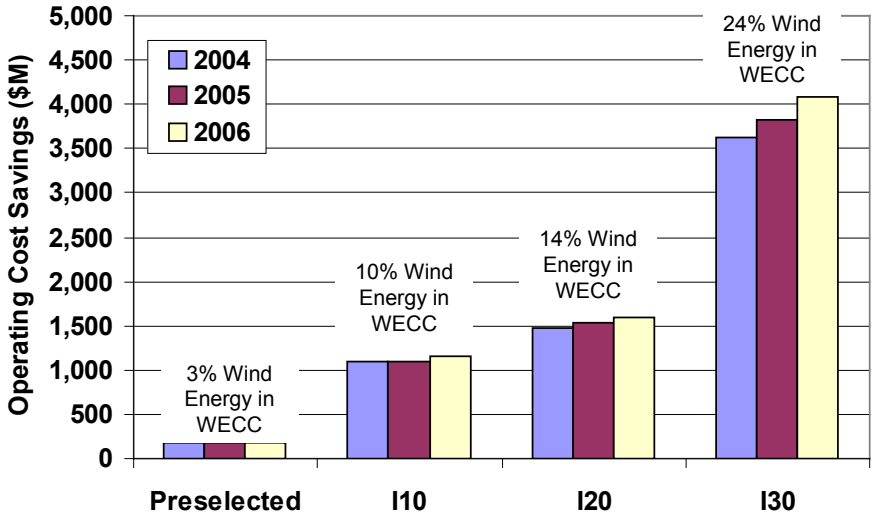

Figure A.5: WECC Operating Cost Reductions for Using Climatology Wind Forecast relative to No Wind Forecast

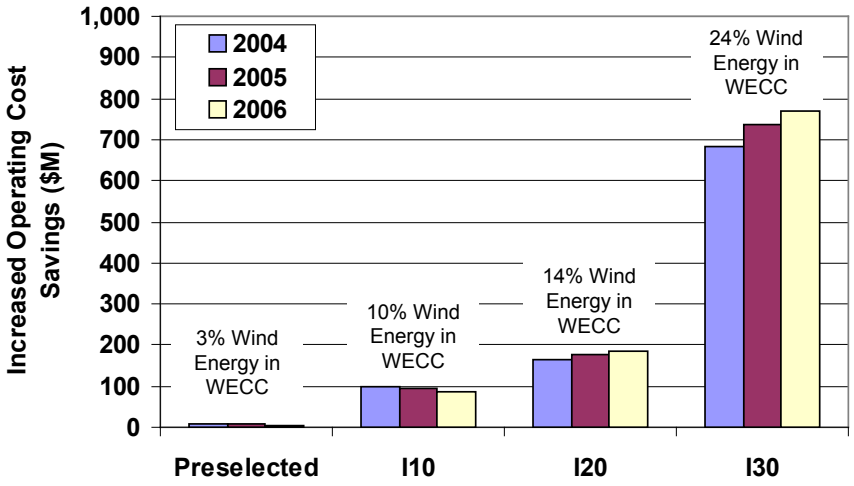

Figure A.6: WECC Operating Cost Reductions for Using SOA Wind Forecast relative to Climatology Wind Forecast

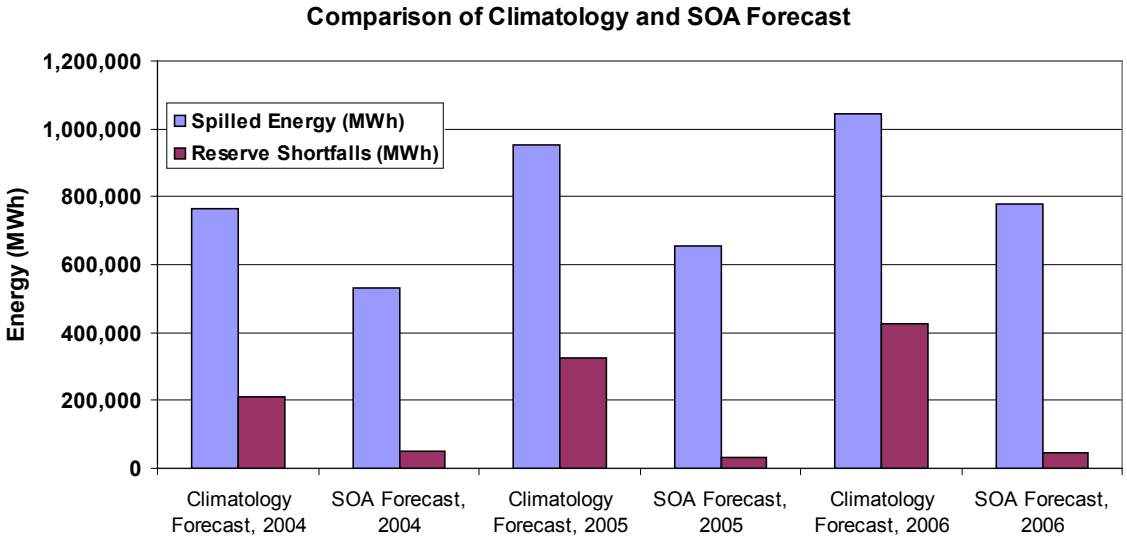

Figure A.7: Spilled Energy and Reserve Shortfalls for System Operation with Climatology vs. SOA Wind Generation Forecast