Wind Power Forecasting and Electricity Market Operations

by

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Abstract

In this paper we give a brief overview of wind power forecasting models and how they are used in power system and electricity market operations. We focus on the organized electricity markets in the United States, where several independent system operators (ISOs/RTOs) have recently introduced wind power forecasting systems as part of their operations. We find that wind power forecasting is already used for a number of important applications. However, as the amount of wind power capacity is rapidly increasing, there is a need to better integrate wind power forecasting into different parts of power system operations, from determination of operating reserve requirements to unit commitment and dispatch decisions. It is also important that wind power forecast providers tailor their products to meet the specific needs of the system operators.

1 Introduction

Different countries and regions are introducing policies aimed at lowering the environmental footprint from the energy sector and increasing the use of renewable energy. In the United States, a number of initiatives have been taken at the state level, from renewable portfolio standards (RPS) and renewable energy certificates (REC) (Wiser and Barbose, 2008), to regional greenhouse gas emission control schemes. Within the U.S. federal government, new energy and environmental policies and goals are also currently being crafted, and these are likely to substantially increase the use of renewable energy. The European Union is trying to implement its ambitious 20/20/20 targets by 2020, which aim at reducing greenhouse gas emissions by 20% (compared to 1990), increasing the amount of renewable energy to 20%, and reducing the overall energy consumption by 20% through energy efficiency (EU 2008).

With the current focus on energy and the environment, efficient integration of renewable energy into the electric power system is becoming increasingly important. In a recent report, the U.S. Department of Energy (DOE) describes a model-based scenario, where wind energy provides 20% of the U.S. electricity demand in 2030 (DOE 2008). The report discusses a set of technical and economic challenges that have to be overcome for this scenario to unfold. A large-scale introduction of wind power causes a number of challenges for electricity market and power system operators who will have to deal with the variability and uncertainty in the wind power generation in their scheduling and dispatch decisions. Wind power forecasting has been identified as an important tool to address the increasing variability and uncertainty, and to more efficiently operate power systems with large wind power penetration. In this paper, we discuss how wind power is currently handled in power system and electricity market operations. In particular, we focus on how the information from advanced wind power forecasting tools are being used in the day-ahead and real-time operations. Based on a survey of existing practices and procedures among selected system operators (ISO/RTOs[1]) in the United States, we identify important areas of improvement.

The paper has the following structure: First, we briefly describe the main inputs, methodologies, and results from state-of-the-art wind power forecasting models. We then give an overview of the main procedures involved in short-term power system operations, focusing on the organized ISO/RTO markets in the United States. A discussion on how the operational procedures and tools can benefit from wind power forecasting is then provided, with an overview of the current status among selected system/market operators in the US. We conclude by identifying important areas of improvement to achieve a more efficient use of advanced wind power forecasting in power system and electricity market operations.

2 Wind power forecasting

As the amount of wind power has reached high levels in some countries, particularly in Europe, there has been a continuous improvement of wind power forecasting models over the last decade (Ernst et al. 2007). A number of wind power forecasting providers have emerged, and there is competition to provide the best forecasts to the electric power industry. There are several different groups of forecast users in the industry, including generation companies and utilities, market analysts and traders, and power system and electricity market operators. In this paper we focus on the use of wind power forecasts for power system and market operations.

A wind power forecasting model typically uses input data from different sources, including results from numerical weather prediction models (NWPs), SCADA data describing the real-time state of the wind power plants and local real-time meteorological conditions, and additional information about the characteristics of the wind power plants and the nearby terrain and topography. Wind power forecasting models can be categorized into physical and statistical models. The physical approach (Figure 1) includes a model describing the physical relationship between wind speed, atmospheric conditions, local topography, and the output from the wind power plant. In contrast, the statistical approach (Figure 2) does not aim at describing the physical steps involved in the wind power conversion process, but rather estimates a statistical relationship between relevant input data (for weather and wind power plants) and the wind power generation. Modern advanced wind power forecasting models are often based on a combination of the physical and statistical approaches. The performance of wind power forecasts and the forecast accuracy depends on the availability of good NWP forecasts, the complexity of the terrain, and the availability of real-time weather and power plant data. In general, the forecasting error increases with the forecast horizon. However, there can be large differences in forecasting errors between wind power plants at different locations.

Wind power forecasting models are continuously being improved with the goal to increase the accuracy of the forecasts. Ongoing research areas include ensemble forecasting, uncertainty estimation of wind power generation, and forecasting of ramping events. An overview of wind power forecasting with examples of applications in power system operations can be found in Ernst et al. (2007). For a detailed review of state of the art wind power forecasting we refer to INESC (2009).

[1] The terms ISO (Independent System Operator) and RTO (Regional Transmission Organization) are used interchangeably in the United States.

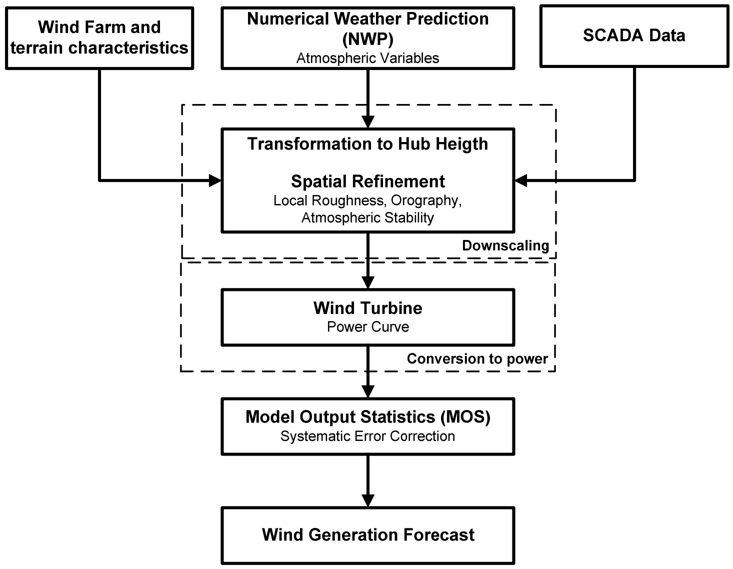

Figure 1 The main steps of the physical approach in wind power forecasting (INESC Porto, 2009).

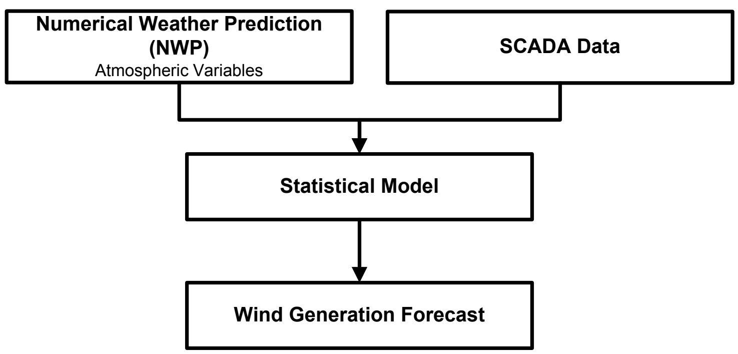

Figure 2 The main steps of the statistical approach in wind power forecasting (INESC Porto, 2009).

3 Power system and electricity market operations

In this section we outline the main steps typically involved in the short-term operation of power systems. Our discussion is based on the operation of ISO/RTO markets in the US, where different regions of the country have seen a considerable degree of convergence in their electricity market design over the last several years. A table summarizing market operation and the current state of wind power forecasting for the Midwest ISO (MISO), New York ISO (NYISO), PJM, Electric Reliability Council of Texas (ERCOT), and California ISO (CAISO) is provided in the appendix (Table A1).

3.1 Market operations timeline

A typical timeline for the operation of the market is shown in Figure 3. The procedures and timeline are based on the current rules in the MISO market. However, other markets are operated in a similar way, as summarized in Table A1. The main steps in the market operations, including determination of reserve requirements, day-ahead (DA) operations, and real-time (RT) operations, are discussed below. In the next section we discuss how wind power forecasting can be used in the different parts of market operations.

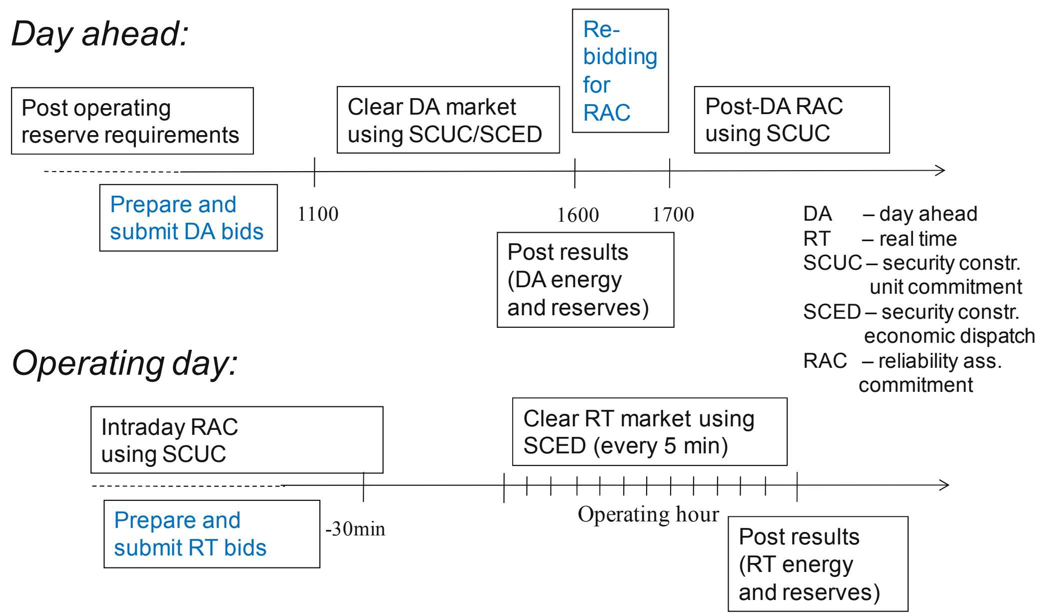

Figure 3 Market operations timeline for Midwest ISO.

3.2 Reserve requirements

It is necessary to maintain a certain amount of operating reserves in order to run the power system in a reliable and secure manner. The operating reserves are typically categorized into several types depending on how quickly they can respond to changes in the system (Figure 4). The regulating reserve responds immediately to generation adjustment needs in the system, and is usually provided by generating units with automatic generation control (AGC) responding to frequency deviations in the network. The contingency reserves need to be able to respond within 10 minutes, and are used to respond to contingencies that may occur, such as forced outages of generators or transmission lines. The contingency reserve can be split into spinning and supplemental (non-spinning) reserves. Note that it is common in U.S. markets that both generation and demand resources can provide operating reserves.

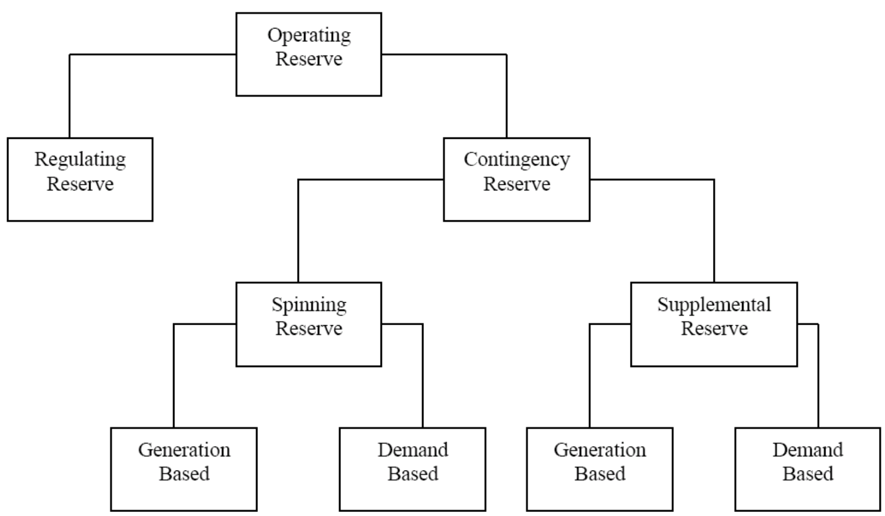

Figure 4 Typical categories of operating reserves (Source: MISO 2009).

The requirements for operating reserves in U.S. power systems are based on standards determined by the North American Reliability Council (NERC 2009a). The ISO/RTOs are required to maintain sufficient regulation to meet NERC's criterion for area control error (ACE). The ACE is a measure for the deviation between scheduled and realized exchange from a balancing authority area and is defined as "the instantaneous difference between net actual and scheduled interchange, taking into account the effects of Frequency Bias including correction for meter error" (NERC 2009a). The requirement for contingency reserves is usually based on the N-1 rule, i.e. sufficient contingency reserve must be held to cover "the loss of generating capacity due to forced outages of generation or transmission equipment that would result from the most severe single contingency" (NERC 2009a). In addition, at least half of the contingency reserve must be spinning. These are the minimum requirements set by NERC. However, regional variations exist and some ISO/RTOs use more stringent requirements for their operating reserves. In systems with large and congested networks it is also common to specify regional reserve requirements, in addition to the system-wide criteria. It is also interesting to note that some markets have introduced a demand curve for different types of operating reserves rather than the traditional fixed requirements.

Operating reserve requirements may be updated to accommodate changes in the system conditions. The update frequency varies between different markets (seasonal, monthly, and daily updating). However, the requirements for the next operating day must at least be posted before the operation of the DA market starts.

3.3 Day-ahead operations

At the DA stage, market participants (demand and supply) must submit their bids to the ISO/RTO by a certain deadline. The actual bidding deadline varies between different markets, as shown in Table A1. The bids of the market participants must reflect how much energy and operating reserves they can provide. Information on unit commitment constraints (ramping rates, start-up costs/times, minimum down-time, etc. for generating units) is also provided to the ISO/RTO.

The clearing of the DA market for energy and reserves is a two-stage procedure. First, a security constrained unit commitment (SCUC) is run to commit resources in the DA market. The objective of the SCUC is to minimize the operating costs while meeting the total demand bid into the market. The SCUC algorithm considers the unit commitment constraints. Hence, the optimization problem includes integer variables. Mixed integer linear programming (MILP) is typically used to solve the resulting large-scale SCUC problem. The next step in the market clearing is to run a security-constrained economic dispatch (SCED) algorithm, based on the commitment schedule from the SCUC. The SCED is formulated as a linear programming routine, and locational marginal prices (LMPs) are derived from the energy balance constraints in each of the transmission nodes. Note that the LMPs cannot be derived from the SCUC optimization, since it is a mixed integer problem. Transmission constraints are also sometimes simplified or omitted from the SCUC formulation, in order to be able to solve the problem in a reasonable time. In contrast, the transmission constraints are always included in the SCED formulation, although usually with a simplified linear representation (DC-OPF).

In most U.S. markets, the SCUC/SCED procedure co-optimizes energy and operating reserves. The output from the DA market clearing therefore includes schedules for energy and operating reserves. In addition, LMPs are derived for each transmission node, and market clearing prices are also calculated for each category of operating reserves. The prices are used in the financial settlement of the DA market. Note that most intermittent resources are currently not bidding into the DA market, but are being treated as price-takers in the RT market.

After the clearing of the DA market and before the start of the operating day, the ISO/RTO usually performs a revised commitment with focus on reliability. The Post-DA reliability assessment commitment

(RAC) is also performed with SCUC. However, the demand bids which are used to clear the DA market are now replaced with the forecasted load for the next day. The ISO/RTO may therefore decide to change the commitment schedule from the DA market clearing based on the results from the RAC. Rules are usually in place to make sure that committed generating resources recover all their operating costs. This may sometimes require side-payments in addition to the regular payments based on the market clearing prices, in order to recover no-load costs, start-up costs, etc.

3.4 Real-time operations

During the operating day, the RAC is repeated as needed in order to adjust the commitment to accommodate changes in the operating conditions (forced outages, deviations from forecasted loads, etc.). At the same time, market participants can bid their remaining resources into the RT market. The deadline for submitting bids to the RT market varies quite widely between different markets (Table A1)[2]. During the operating hour, the ISO/RTO uses SCED to dispatch the system. At the same time, RT prices for energy (LMPs) and operating reserves are calculated. The frequency of the RT dispatch is now 5 minutes in most ISO/RTO markets (Table A1). The variations in load which are not taken care of by the 5-minute dispatch signals are handled through regulation reserves and AGC. Therefore, if wind power adds more variability and uncertainty in the very short term, it may be necessary to increase the amount of regulation reserves in the system.

Conventional power generation sources are typically penalized if they deviate from their RT dispatch signals. However, so far renewable generation such as wind power has not been given dispatch signals from the ISO/RTO. Wind power has therefore typically been exempt from RT deviation penalties, and the majority of the wind power generation is settled at the RT price. However, this may change as the ISO/RTOs are working on improving the integration of wind power into their operating procedures for the DA and RT markets.

4 Wind power forecasting in operations

In this section we discuss to what extent wind power forecasts are currently used in electricity market operations and identify important areas of improvement. A brief summary of the current status and developments of wind power forecasting among selected U.S. ISO/RTOs is provided in Table A1.

4.1 Current status

There is a relatively short history of wind power forecasting among ISO/RTOs in the United States. CAISO was the first ISO/RTO to start using wind power forecasting for system operation when they introduced forecasting as part of their Participant Intermittent Resource Program (PIRP) in 2004 (Blatchford 2008). MISO, NYISO, and ERCOT all introduced centralized wind power forecasting in 2008, whereas PJM is implementing their forecasting system in 2009.

Wind power forecasting is used for different purposes, as summarized in Table A1. The planning horizon ranges from several days ahead to real-time operations. In our review, we found areas of application from transmission outage planning, transmission security and peak load analysis, to reliability unit commitment, hour-ahead market bidding, and real-time commitment and dispatch. The wind power forecasts are used as input to some of the procedures for system and market operations outlined in Section 3. However, the ISOs/RTOs have limited experience in this area so far and are continuously working on improving and automating the use of wind power forecasting in DA and RT operations.

A common problem is to get sufficient real-time weather and wind power generation data of good quality. This is important input to improve the wind power forecast quality. Some ISO/RTOs are therefore

[2] Some ISO/RTOs, like NYISO and CAISO, also have a formal hour-ahead market.

introducing mandatory data reporting requirements for wind power producers, with penalties for non-compliance.

4.2 Areas for improvement

The need for wind power forecasting in power system operations is obviously dependent on the amount of wind power capacity in the system. However, given the rapid increase in wind power generation in many areas of the United States, it is quickly becoming important to efficiently utilize the information provided by advanced wind power forecasting models. Some important areas for improving the use of wind power forecasting in power system operations are briefly discussed below, with focus on the elements of market operation discussed in Section 3. The need for a revision of current operating procedures and integration of wind power forecasting into system operation to integrate more renewable energy have also been emphasized in a recent report by NERC (NERC, 2009b).

Operating reserves
The additional uncertainty and variability caused by an increasing penetration of wind power generation raises the question of whether current requirements for operating reserves are adequate. The need for regulation services may increase due to the short-term variations in wind power generation, although the short frequency of RT dispatch (5 min) in most ISO/RTO markets reduce the magnitude of variations that must be handled through regulation services. An increase in slower starting reserves may be necessary to be able to counter large-scale wind power down-ramping events. Ongoing research is addressing the optimal determination of reserve requirements under high penetration of wind power (Ortega-Vazquez and Kirschen 2009). Since wind power forecasting models now are being able to produce probabilistic estimates for the wind power generation, one could potentially use the uncertainty information from the forecast in determining the operating reserves requirements. Consequently, the operating reserve requirement could depend on the forecasted level and uncertainty in wind power generation for the next day. This would require that operating reserve requirements are determined more frequently and closer to real-time than what is typically the case today.

Among ISO/RTOs in the United States, it is interesting to note that ERCOT is already considering wind power penetration and forecasting uncertainty in their determination of requirements for regulation and non-spinning reserves (ERCOT 2009c and Maggio, 2009). ERCOT is currently the ISO/RTO with the highest share of wind power (Table A1).

Unit commitment
Unit commitment decisions are obviously of major importance to maintain reliability and cost efficiency in the power system. The generation from wind power plants and the information in wind power forecasts should therefore be efficiently integrated into the unit commitment problem. Traditionally, this is formulated as a deterministic optimization problem. However, the additional uncertainty from wind power generation makes it relevant to consider alternative formulations. Several different approaches have been proposed in recent literature to address uncertainty in wind power generation in the unit commitment problem (e.g. Bart et al. 2006, Bouffard and Galiana 2008, Wang et al. 2008, Ruiz et al, 2009, Tuohy et al. 2009). Preliminary results indicate that such models can play an important role in reducing costs while maintaining system security under increased uncertainty and variability. However, more research is needed into developing and testing stochastic models for unit commitment, and how wind power forecasting errors (magnitude and phase errors) are likely to influence reliability and cost in the power system. In addition, it is important to consider the close interaction between operating reserve requirements and unit commitment policy.

So far, U.S. ISOs/RTOs are apparently focusing on how to integrate the information in wind power forecasts into the reliability commitment. This is obviously important to address reliability, and the reliability commitment will also influence RT prices. However, it is also important to integrate the information in wind power forecasts into the DA market clearing. Wind power will have an increasing impact on the marginal cost of electricity and this should be properly reflected in the DA market clearing, where most of the energy is settled. An important challenge is how to consider the uncertainty information in the wind power forecast in the DA operating procedures. An interesting approach is taken by ERCOT, which is currently using an 80% exceedance forecast for wind power generation as input to their DA resource planning procedures (Maggio 2009).

Dispatch

Efficiently integrating wind power into RT dispatch is also important. Short-term wind power forecasts, which have relatively low uncertainty, should be taken into account in the ISO/RTOs' RT SCED. At the same time, it is important that the ISO/RTO is able to control the generation from wind power plants and enforce curtailment of wind power generation in situations where this is needed, either from an economic or reliability perspective. Modern wind power plants include a number of features which makes them appear similar to conventional dispatchable power plants, including reactive power contribution, voltage regulation, disturbance ride-through, grid frequency response, smoothing wind ramps, and controlled start-up/shut-down. It will be increasingly important that system operators take advantage of these features in RT dispatch and operations.

The U.S. ISO/RTOs are working on integrating wind power forecasts into their dispatch procedures. CAISO is already requiring wind power plants participating in the Participating Intermittent Resource Program (PIRP) program to bid into their hour-ahead market according to a short-term wind power forecast. Rules are also in place to limit the deviation charges for wind power. An interesting development takes place in NYISO, which is introducing new rules to incorporate wind power in their SCED (Gonzales et al. 2008, Swider 2009). With the new rules, wind power plants will be required to bid into the RT market as flexible units. During unconstrained hours, wind power plants can operate freely. However, in constrained situations wind power plants will be directed to reduce output when the clearing price at their location falls below their economic bid. Penalties will be introduced for exceeding the dispatch instructions. The new procedure will make sure that the economic preferences of the wind power producers are reflected in the SCED. It will also contribute to a more efficient dispatch overall, and reduce the need for using out-of-market actions to maintain system reliability. Other ISO/RTOs should consider similar measures to improve the handling of wind power resources in the RT dispatch.

5 Conclusions

Wind power forecasting will serve as an important tool to improve the efficiency and reliability of power systems with a large share of wind power. ISO/RTOs in the United States are currently working on integrating wind power forecasts into their operating procedures, and wind power forecasting is already used for a number of important applications. However, as the amount of wind power capacity is rapidly increasing, there is a need to better integrate wind power forecasting into different parts of power system operations, from determination of operating reserve requirements to unit commitment and dispatch decisions. It is also important that wind power forecasting models are capable of addressing the needs of the system operators, including forecasts of severe weather alerts and ramping events, and stochastic wind power forecasts.

Appendix

Table A1 Overview of market operation and wind power forecasting in five U.S. electricity markets.

	MISO	NYISO	PJM	ERCOT	CAISO
Peak load	109,157 MW (7/31-2006)	33,939 MW (8/2-2006)	144,644 MW (8/2-2006)	62,339 MW (8/17-2006)	50,270 MW (7/24-2006)
Installed capacity	Ca.127,000 MW	Ca.39,000 MW	Ca.163,000 MW	Ca.71,000 MW	Ca.58,000 MW (incl. imports)
Wind capacity (at end of 2008)	Ca. 4,000 MW	Ca. 1275 MW	Ca. 2050 MW	Ca. 8000 MW	Ca. 2500 MW
Pricing and congestion mngt.	LMP	LMP	LMP	Zonal (trans. to LMP)	LMP
Reserve requirements	- Based on NERC standards. - Demand curve for reserves. - Zonal res. reqs. - Demand can participate in all markets. - Reqs. updated daily. - Published 2 days ahead. - Wind not directly considered.	- Based on NERC standards. - Demand curve for reserves. - Zonal res. reqs. (3 zones) - Demand can participate in all markets. - Reqs. updated monthly. - Wind not directly considered.	- Based on NERC standards. - Regulation: 1 % of peak load (hrs. 5-24), 1% of valley load (hrs. 0-5). - Zonal res. reqs. - Demand can participate in reserves markets. - Wind not directly considered.	- Using own reqs., similar to NERC. -System-wide reqs. - Updated monthly. - Wind and forecast error considered for regulation and non-spinning.	- Based on WECC criteria and NERC standards. - Regional reqs. enforced (up to 8 regions). - Published 2 days ahead. - Wind not directly considered.
DA market	Energy + regulation, spinning, supplemental reserves co-optimized	Energy + regulation, spinning, supplemental reserves co-optimized	Energy + supplemental reserves co-optimized	No Energy, but regulation, spinning, supplemental, replacement reserves	Energy + regulation, spinning, supplemental reserves co-optimized
RT market	Energy + regulation, spinning, supplemental reserves co-optimized.	Energy + regulation, spinning, supplemental reserves co-optimized.	Energy + regulation, spinning reserves co-optimized.	Energy balancing market. 15 min freq.	Energy + regulation, spinning, supplemental reserves co-optimized.
Market timeline	DA offers due: 11am DA results: 4pm Re-bidding due: 5pm RT offers due: OH -30 min	DA offers due: 5 am DA results: 11 am RT offers due: OH -75 min	DA offers due: noon DA results: 4pm RT offers due: 6pm DA	DA bids due (reserves): 1pm/4pm DA results (reserves): 1.30pm/6pm RT offers due: OH -60 min	DA offers: 10am DA results: 1pm RT offers: OH - 75 min
RT dispatch frequency	5 min	5 min	5 min	15 min	5 min
Unit commitment procedure	Yes. SCUC used DA, post-DA, and intra-day, as needed.	Yes, SCUC used DA and 75 min before RT (results 45 min before RT).	Yes. SCUC used DA, reliability UC post-DA and intra-day, as needed.	No. Will be introduced with nodal market.	Yes. SCUC used DA, HA, and for RT operations.

Wind forecasting	In operation since 2008: - 90+ nodes included. - Transmission outage coordination. - Wind impact tool for ramp event impact on flowgates. -Transmission security and peak load analysis. - Input to reliability UC.	In operation since 2008: - DA forecast twice daily (4am, 4pm). - RT forecast every 15min. - Reliability pass of DA SCUC. - Real time commitment and dispatch. - Wind plants required to provide met data to NYISO.	Forecasting system is being introduced in 2009: - Four types of forecasts (short, medium, long, ramp).	In operation since 2008: - Updated hourly. - 80% exceedance forecast used for DA planning.	Introduced in 2004: - Next hour, next day, extended. - Part of PIRP. - Used in HA market, as PIRP participants must bid forecast. - Wind plants required to provide met data to ISO.
Wind forecasting developments	- Automated procedure for use in market operations (UC etc.). - Required participant provision of DA forecasts.	- Wind plants required to bid into RT markets (DA optional). -Bids included in RT dispatch to improve efficiency. - Penalties for exceeding base points. - Ramping alert system. - More/better data from plants. - Evaluating needs for operating reserves.	Planned use: - Reliability assessment (DA and RT). - Unit commitment (DA and RT). - Ancillary services (regulation, contingency).	- To be fully integrated in DA and RT operations in new nodal design, to be introduced end of 2010.	- Improving data quality. - Improving forecast quality. - Integrate forecast into MRTU, incl. DA operations.
Imbalance settlements for wind power	Settled at RT price. No deviation penalties.	No penalties for deviation from schedule in RT (3300 MW exempt from penalties).	Wind usually settled at RT price.	Settled at real-time zonal energy price. No deviation penalties.	Deviations netted over month at av. price. No deviation penalty (PIRP).
Sources	MISO (09), McMullen (09), DeMeo et al. (07).	NYISO (08a), NYISO (08b), Swider (09), Medelson (08), Gonzalez et al. (08).	Patil (09), PJM (09), DeMeo et al. (07).	ERCOT (09a, 09b, 09c), Maggio (09), DeMeo et al. (07).	CAISO (09), Blatchford (08), Loutan and Hawkins (07), Makarov et al. (09), DeMeo et al. (07).

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