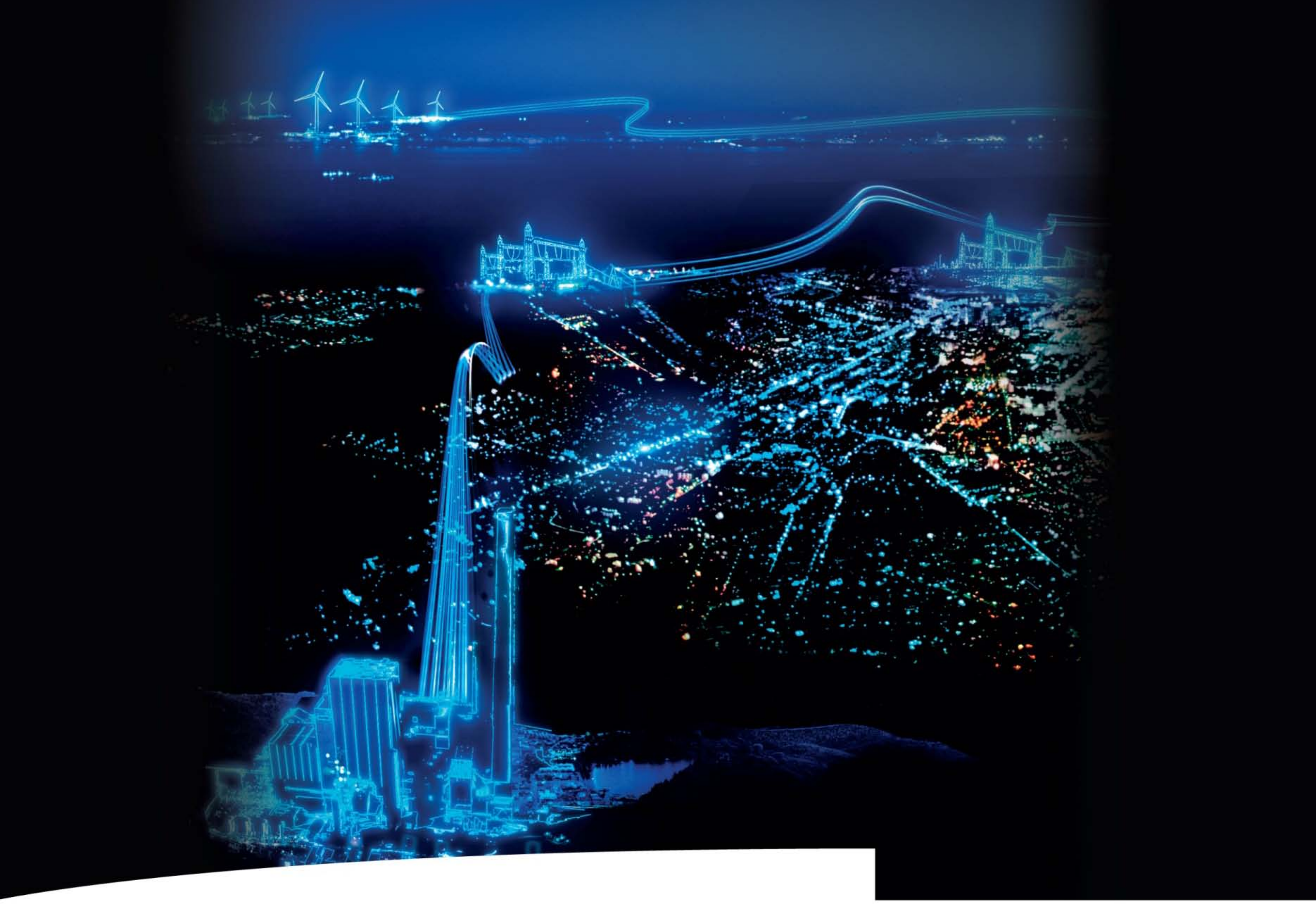

Strategies and Decision Support Systems for Integrating Variable Energy Resources in Control Centers for Reliable Grid Operations

Global Best Practices, Examples of Excellence and Lessons Learned

Lawrence E. Jones

NOTICE

The submitted manuscript has been offered by an employee of Alstom Grid Inc., a subcontractor of the U.S. Government under Award Number DE-EE0001375.

DISCLAIMER

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FOREWORD

A variety of studies have recently evaluated the opportunities for the large-scale integration of wind energy into the U.S. power system. These studies have included, but are not limited to, “20 Percent Wind Energy by 2030: Increasing Wind Energy’s Contribution to U.S. Electricity Supply”, the “Western Wind and Solar Integration Study”, and the “Eastern Wind Integration and Transmission Study.” Each of these U.S. based studies have evaluated a variety of activities that can be undertaken by utilities to help integrate wind energy.

The integration of wind energy into the power grid introduces additional variability and uncertainty into grid operations beyond that created by system load. It has been said by some in the utility industry that the integration of large amounts of wind energy into the power grid requires a paradigm shift in how the grid is operated. The following report provides an evaluation of how system operations worldwide are changing in response to increases in wind penetration. It provides unique insights into what has worked well, what has not, and how operators see the future of their responsibilities changing as we introduce more wind into the grid.

While there is no “silver bullet” solution to successful wind integration that applies to all power systems, experience from actual operators provides some of the most valuable feedback on how operations are changing, what tools are needed and which actions are providing the most benefit. This report constitutes the first time grid operators from across the globe have provided consolidated feedback on how wind energy is affecting them and what concrete measures are being taken to manage the system in the face of the increased challenges posed by the increased variability and uncertainty presented by wind generation. The U.S. Department of Energy is pleased to support this project through the American Recovery and Reinvestment Act, to enable such valuable information to be provided to the utility industry as a whole.

Charlton Clark

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy

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Gathering research data and pulling together such a global sample of utilities for this project took the work of many dedicated individuals.

Utilities and their Representatives

This report would not have been possible without the participation and contribution of the utilities and personnel who dedicated time and resource to complete the lengthy questionnaire, and provide additional relevant information about their decision support tools, processes and procedures for managing wind energy in their control room. The important contribution of the following individuals and their companies is hereby acknowledged:[1]

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Richard Candy, Rosalette Ungerer	ESKOM, South Africa
Lisa Dangelmaier	Hawaii Electric Company, USA
Alain Forcione, Richard Mailhot, André Robitaille	Hydro Quebec, Canada

[1] The list is sorted based on the first character of the utility's name, beginning with numbers and followed by characters. The corresponding list of individuals is sorted based on the first letter of the last name of each person.
[2] Previously employed by 50Hertz.

Rich Bauer — Idaho Power, USA

Bill Henson, John Norden — ISO New England, USA

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Eric King, Bart McManus, Jodi Obradovich[4] — Bonneville Power Administration, USA

Jens Møller Birkabæk, Henning S. Christensen, Thomas Krogh — Energinet, Denmark

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[3] Ajay N. Maharaj was employed by Transend Networks when the survey was conducted. In September 2010 he joined the Power and Water Corporation in Darwin, Northern Territory, Australia.

[4] Jodi Obradovich is employed by Pacific Northwest National Laboratory (PNNL) but was working on a project at BPA at the time of the visit.

Jon O’Sullivan Eirgrid, Ireland

Claudine D’Annunzio, John Dumas, Coleen Frosch, David Maggio ERCOT, USA

David Edelson, Allen Hargrave, Emilie Nelson, John Ravalli New York ISO, USA

José-Luis Mata, Pablo Martin Muñoz, Miguel de la Torre Red Eléctrica de España, Spain

These individuals participated in, on average, five hour interviews during which they and several of their colleagues generously shared their expertise and lessons learned in integrating wind energy into utility control center and grid operation. Their perspectives and the support from their organizations made it possible to correlate the best practices identified to the questionnaire findings.

Industry Advisory Committee

Thanks to the members of the voluntary Industry Advisory Committee (IAC) for their input to the development of the questionnaire, review of draft versions of this report and their insights on various aspects of the project:

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EXECUTIVE SUMMARY

ES.1 Introduction

Electricity generated from variable energy resources (VER), with wind being the leading source, is developing rapidly worldwide—and is only expected to increase further. The stats say it all: about 194.4 gigawatts (GW) of installed wind capacity worldwide was operable at the end of 2010, a 22% increase compared to 2009. The U.S. alone accounts for more than 40 GW of total installed capacity. In its landmark 2008 report *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, the U.S. Department of Energy (DOE) examined a scenario and found it feasible that wind power can contribute 20% to the U.S. electricity supply by 2030 if challenges identified in that report are addressed.

Nevertheless, effectively integrating a large amount of wind energy into current and future power grids is still a prominent issue for grid operators, regulators and the electricity industry today. In response to DOE's solicitation for proposals that address the potential challenges and solutions to realizing a scenario of "20% Wind Energy by 2030," researchers at Alstom Grid Inc. endeavored to investigate and identify the best ways in which to guide operational strategies, business processes and control room tools that support this overall objective.

To accomplish this, the Alstom Grid Inc. investigators surveyed 33 operators of electric power systems in 18 countries about wind integration, their operating policies, best practices, examples of excellence, lessons learned and decision support tools now in place. The power systems represented in this report have different network topologies, mix generation and load profiles, and a range of penetration levels of wind generation. Further, the combined amount of wind power capacity referenced in this report is 141 GW or 72% of the total installed capacity in the world. The power grids are located in varying geographies with diverse weather regimes and many of the utilities surveyed operate under dissimilar regulatory frameworks, and in regulated or deregulated electricity markets.

The power grids represented in this report have a combined total of 141GW of installed wind capacity or 72% of the installed wind capacity in the world.

Garnering participation from these worldwide utilities with high penetration levels of wind generation was crucial to meeting the research project's objectives. Having a unique and diverse set of respondents was also a prerequisite when gathering insights about wind integration practices. Figure 1 shows the total installed wind capacity of several countries and regions represented by utilities that participated in the survey.

As noted above, special emphasis was placed on how these utilities incorporate wind forecast information into operating policies, strategies, processes and decision support tools which dispatchers use in the daily operations of electric power grids. The current approach of electric utility control centers and ways in which these tactics have evolved are reflected in the findings. The survey also focuses on those control centers that have experienced fast rates of wind penetration in the past decade.

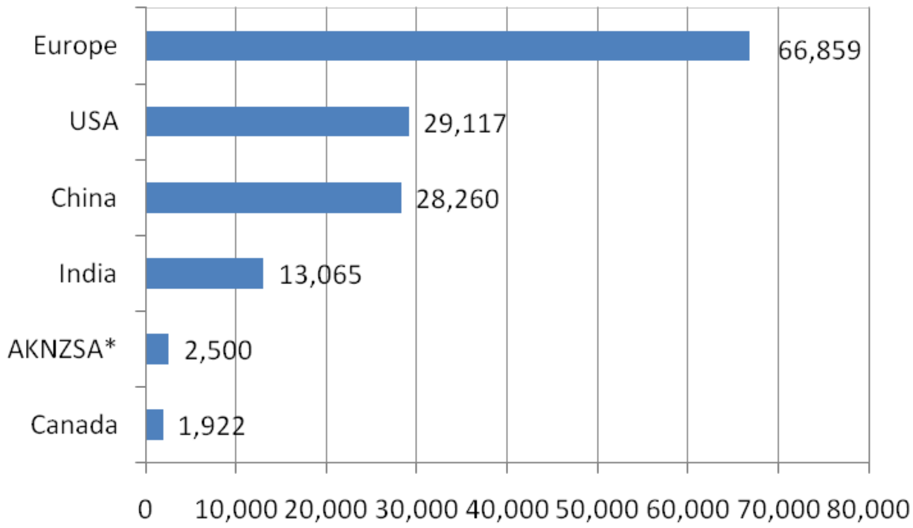

Figure 1. Distribution of Installed Wind Capacity (MW) in the Survey by Regions & Countries[6]

This report provides utilities with recommendations and examples of success stories aimed at informing the design of decision support tools, solutions and strategies for integrating more wind energy into their own power systems. The findings help to increase the industry-wide understanding of the operational impacts of wind integration and how wind power forecast is being used today. The identified practices from a broad group of utilities can be a foundation to fast-tracking the training of dispatchers. This report could also inform the formulation of regulatory policies for wind energy, as well as aid in the establishment of future operating procedures and practices for managing wind integration in the control room environment.

This willingness to consider what others have done and share operational success stories was clearly demonstrated by the respondents, considering the amount of time they allowed their staff to spend completing the questionnaire, as well as the quality and level of details provided. This project clearly indicated that more utilities are interested and open to using industry best practices and examples of excellence from their peers as the starting point for developing and deploying their own solutions.

[6] AKNZSA is short for Australia, Korea, New Zealand and South Africa.

ES.2 Methodology

Three complementary methods were used in the study: a questionnaire was developed, grid operators control centers were visited and a survey of existing literature was conducted.

In the first method, questions were grouped under one of the following seven categories: organizational; wind forecasting; integration of wind forecast; decision support systems and tools; processes and procedures; wind energy information; and training. Thirty-four out of more than sixty utility companies responded to the survey.

On-site visits to control centers of three grid operators in the U.S. and three in Europe comprised the second method of gathering information. The utilities visited in the U.S. were Bonneville Power Administration (BPA), Electric Reliability Council of Texas (ERCOT), and the New York Independent System Operator (NYISO). The European grid operators visited were Eirgrid, Ireland; Energinet, Denmark; and Red Eléctrica España (REE), Spain. The visits allowed the investigators to further explore some of the survey questions through in-depth interviews of operators and other control center personnel, as well as to see first-hand successful implementation of decision support tools and processes that demonstrate examples of excellence.

Grid operators who were not visited are also featured in this report. They have demonstrated exemplary efforts in their successful deployment of software systems and tools, as well as processes to support wind integration in control centers. They are 50Hertz Transmission GmbH in Germany, Alberta Electric System Operator (AESO) in Canada and RTE in France.

The third method in the study incorporated a survey of existing literature about tools, processes and procedures that utilities around the world have deployed to support the integration of wind, solar and other variable energy resources in general. This report presents the first-known research based on such a global sampling of grid operators.

Participants in the Survey

33 grid operators from 18 countries, which include:

12 European Transmission Systems Operators

9 members of the Association of Very Large Power Grid Operators

6 U.S. Regional Transmission Organizations/Independent System Operators

4 U.S. Transmission Utilities

4 Canadian Transmission System Operators

3 German Transmission System Operators

2 Australian Transmission System Operators

1 Transmission System Operator from China, India, Korea, New Zealand and South Africa, respectively

1 European Power Grid Monitoring and Coordination company

ES.3 Wind Penetration Levels

The challenges, issues, costs and other factors associated with integrating wind generation are closely related to the penetration level of wind power in a given system. A penetration level commonly used is the Wind Generation Penetration Level (WGPL), defined as the ratio of the total installed wind power capacity to the total installed generation in the system. Figure 2 shows a list of the survey respondents who represent systems that range from the highest wind generation penetration levels to the lowest. This diverse sampling of system operators captures a broad set of perspectives and experiences, as well as some common themes.

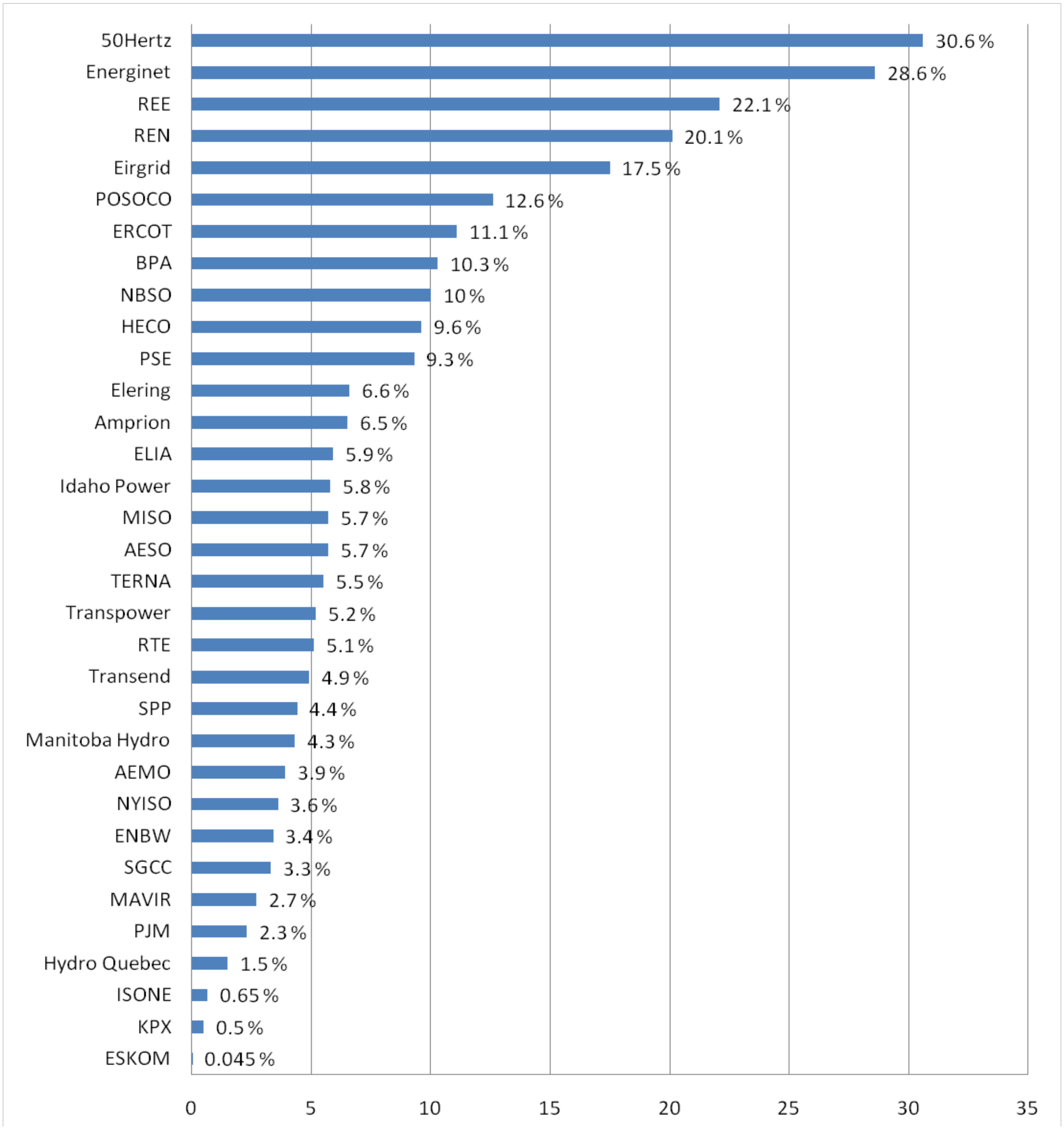

Figure 2. Wind Generation Penetration Level (%)

ES.4 Nine Current Best Practice Tools and Decision Support Systems

This report identifies and describes nine current best practice tools and decision support systems grid operators in the U.S. and Europe use to integrate and manage wind energy, as well as, in several cases, solar energy. The tools are:

- Dispatch Decision Support Tool (DDST) at the Alberta Electric System Operator, Canada
- Integrated Curtailment and Re-Dispatch System (iCRS) at the Bonneville Power Administration, USA
- Wind Security Assessment Tool (WSAT) at Eirgrid, Ireland
- Nordic Operational Information System (NOIS) at Energinet, Denmark
- Drift Planlægnings System at Energinet, Denmark
- Ercot Large Ramp Alert System (ELRAS) at the Electric Reliability Council of Texas, USA
- Generación Eólica Máxima Admisible en el Sistema (GEMAS) at Red Eléctric de España, Spain
- Centro de Control de Régimen Especial (CECRE) at Red Eléctric de España, Spain
- Insertion de la Production Eolienne dans le Système (IPES) at RTE, France

Current and emerging best practices are discussed in the report. The best practices are put under six different categories: tools, data, situational awareness, training, wind power forecasting and processes/procedures.

This collection of practices is an excellent starting point to further expand the general requirements for the development of new or enhancement of existing tools for wind integration. While certain aspects of these practices have been identified, it is important to note that the survey responses reflect the current views of the grid operators in an otherwise very dynamic and changing environment. The practices therefore offer important guidance in helping grid operators, policymakers and other industry stakeholders determine how to proceed with integrating high levels of wind energy. Application of these best practices must always be examined in the proper context. This examination should consider the differences in the power system and the electricity market within which it operates.

ES.5 Highlights of Some of the Key Findings

ES.5.1 Wind Power Forecasting

Wind power forecast is the most important pre-requisite for successfully integrating wind energy into power systems. Predictability of wind plant output is the key to managing uncertainty. The accuracy or error of the wind forecast is of paramount concern for a grid operator. The error affects the level of confidence that operators place in the data, how it may be integrated or not, and how it is used in the control room.

94% of grid operators say that integrating a significant amount of wind will largely depend on the accuracy of the wind power forecast

ES.5.2 Centralized wind forecasting program is best for reliable grid operations

A broad agreement among operators exists today that, in order to effectively integrate wind energy into power system operations, centralized forecasting is the current best approach for reliably operating power grids with wind generation. Therefore, grid operators around the world are acquiring centralized wind forecasting systems and services. Eighty percent of respondents in this study have implemented some form of centralized wind forecasting system or are in the process of putting one in place. A few grid operators still rely on decentralized wind power forecasting, but even in those cases, a transition to the centralized approach seems inevitable. Since completing the survey, important new developments at one U.S. operator of a regional grid and electricity market have emerged that suggest a move towards a hybrid approach, comprised of both centralized and decentralized forecasting. The hybrid approach is currently the subject of preliminary discussions in other North American regions with electricity markets.

ES.5.3 Wind Forecasting Products

For many grid operators, Day-Ahead (DA) forecast has been the focus of much research attention. Tremendous improvements have been made to reduce the DA forecasting errors. However, as grid operators and researchers learn more about wind variability and the operational impacts of wind in different timescales, efforts are underway to continuously improve the accuracy and use of other forecast products. Figure 3, below, depicts how respondents rank the importance of several forecasting products in control room real-time operations. Two of the most highly ranked products, ramp and ensemble forecasting, receive special attention in this report, based on additional interviews with respondents and the results from the survey literature.

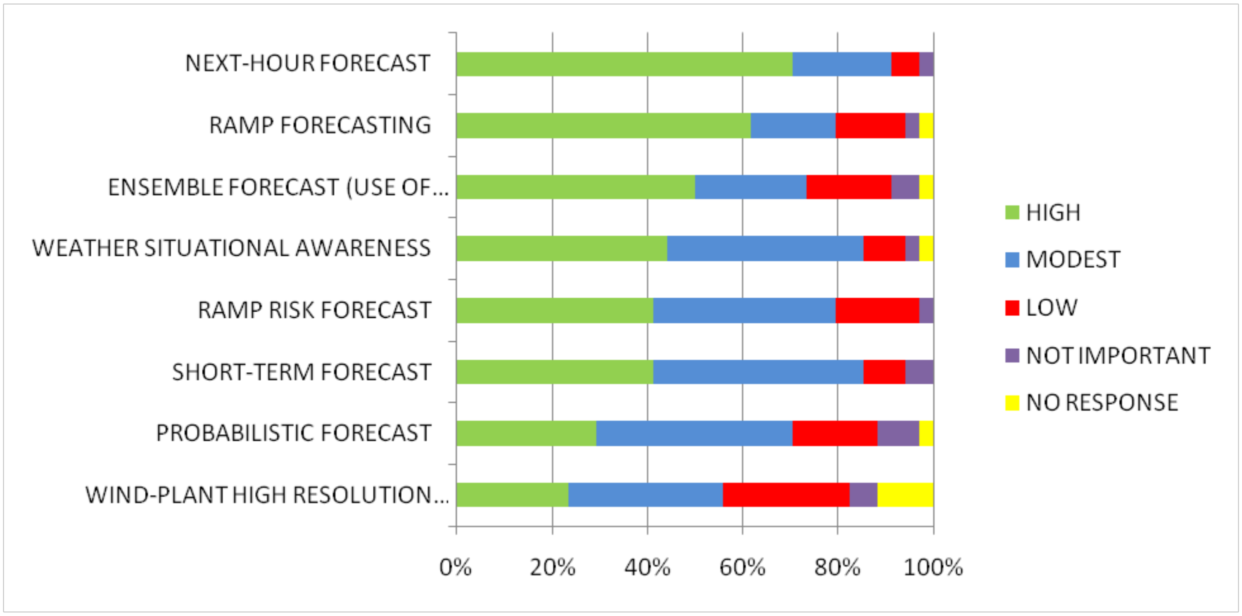

Figure 3. Importance of Wind Forecasting Products in Control Rooms

ES.5.4 Decision Support Systems and Operational Processes

In recent years, utilities in the U.S. and other parts of the world developed varying levels of expertise and knowledge in how to operate power grids with increasing amounts of wind power generation. While there may not be any insurmountable technical barrier to reaching the 20% wind energy by 2030 scenario described in the DOE report, the findings in this report suggest that such a scenario cannot be fully achieved without knowledgeable grid operators in control rooms equipped with the necessary decision support tools. Grid operators must be presented with accurate wind power forecast information in a useful and meaningful way. Ninety-four percent of respondents say that integrating wind energy will depend on the tools in the control room which is the nerve center for operating power systems. More and more grid operators no longer passively plan for high penetration of wind generation on their system. Rather, operators today already are at different stages in the deployment of decision support tools necessary to successfully integrate wind energy.

> *94% of grid operators agree or strongly agree that integrating wind energy depends on decision support tools in the control room*

The report addresses issues under the current operating conditions of utilities, but also ventures to anticipate conditions that could emerge as a result of meeting the 20% energy by 2030 scenario. It envisions different scenarios that could affect how control centers might look in the future, and the various decision support tools needed now or that will be available in the future.

ES.5.5 Integration of Wind Forecast in Decision Support Systems

With wind generation increasing in power systems, it is important to integrate wind forecast information with the strategies and decision support systems used in control room operations. The survey analysis highlights the different applications and processes that, when incorporated with wind power forecasts, are perceived to have the most value for integrating wind energy. Several grid operators are already implementing changes to the tools in their control rooms to cope with wind generation or they have plans to do so. Figure 4 shows the extent to which respondents have integrated wind forecast in different processes and tools, used in real-time operations.

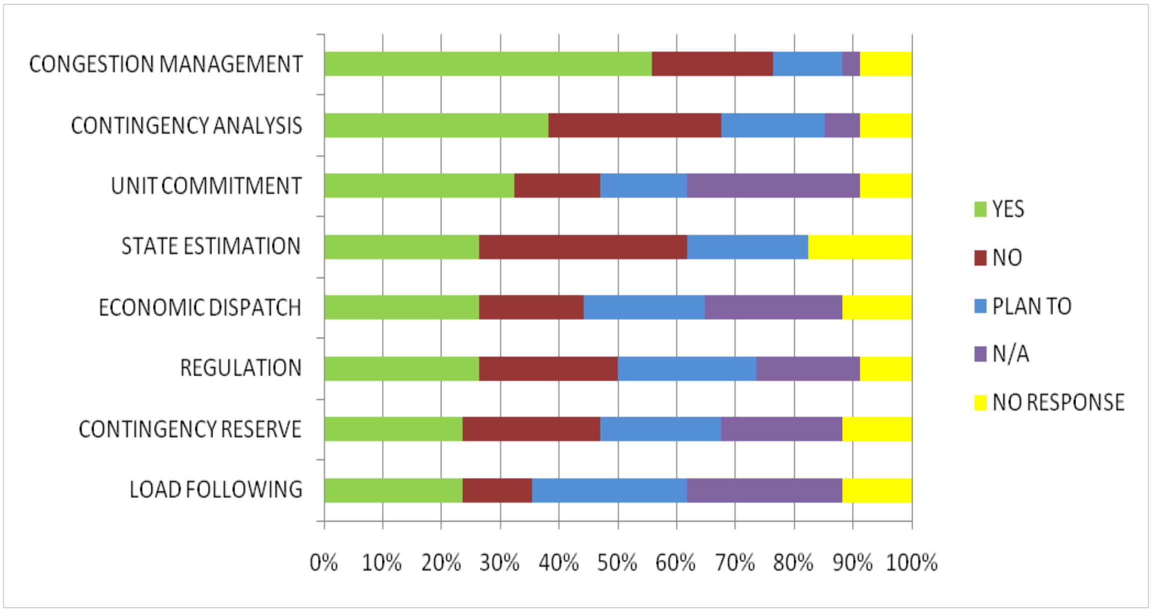

Figure 4. Integration of Wind Forecasts in Real-Time Applications and Processes

Congestion management is one of the most important functions of the grid operator. Higher penetration of wind power in the grid can introduce new patterns in the flow of power in the transmission and distribution networks. These unexpected flows could overload some transmission lines, causing new operational limits and congestion in the system. About 55% of the respondents have integrated wind forecast in their software tools or processes to manage congestion. Large RTOs/ISOs and TSOs that are interconnected to neighboring utilities were included in this percentage.

Twenty-five percent or more of all the respondents have incorporated wind forecast in real-time applications and processes for managing voltage stability, unit commitment (UC), state estimation (SE), regulation, load following, economic dispatch (ED), contingency reserves and contingency analysis (CA). SE, ED, CA, regulation and load following are implemented as part of the Energy Management System (EMS) in control centers. In most cases, UC and contingency reserve calculation are also integrated with the EMS. Yet, the extent to which wind power forecast has been integrated with these EMS applications varies.

ES.5.6 Advanced Decision Support Tools for Wind Integration

The North American Electric Reliability Corporation (NERC) identified new "advanced decision support tools" that are important to managing grids with large amounts of energy from wind and other VERs. The ranking of respondents' perception of the value of several tools in terms of supporting integration of wind power is shown in Figure 5.

Some of the respondents are currently implementing several tools. However, this snapshot of the perceived value of these applications in the industry is expected to change as grid operators gain more knowledge and experience about these tools.

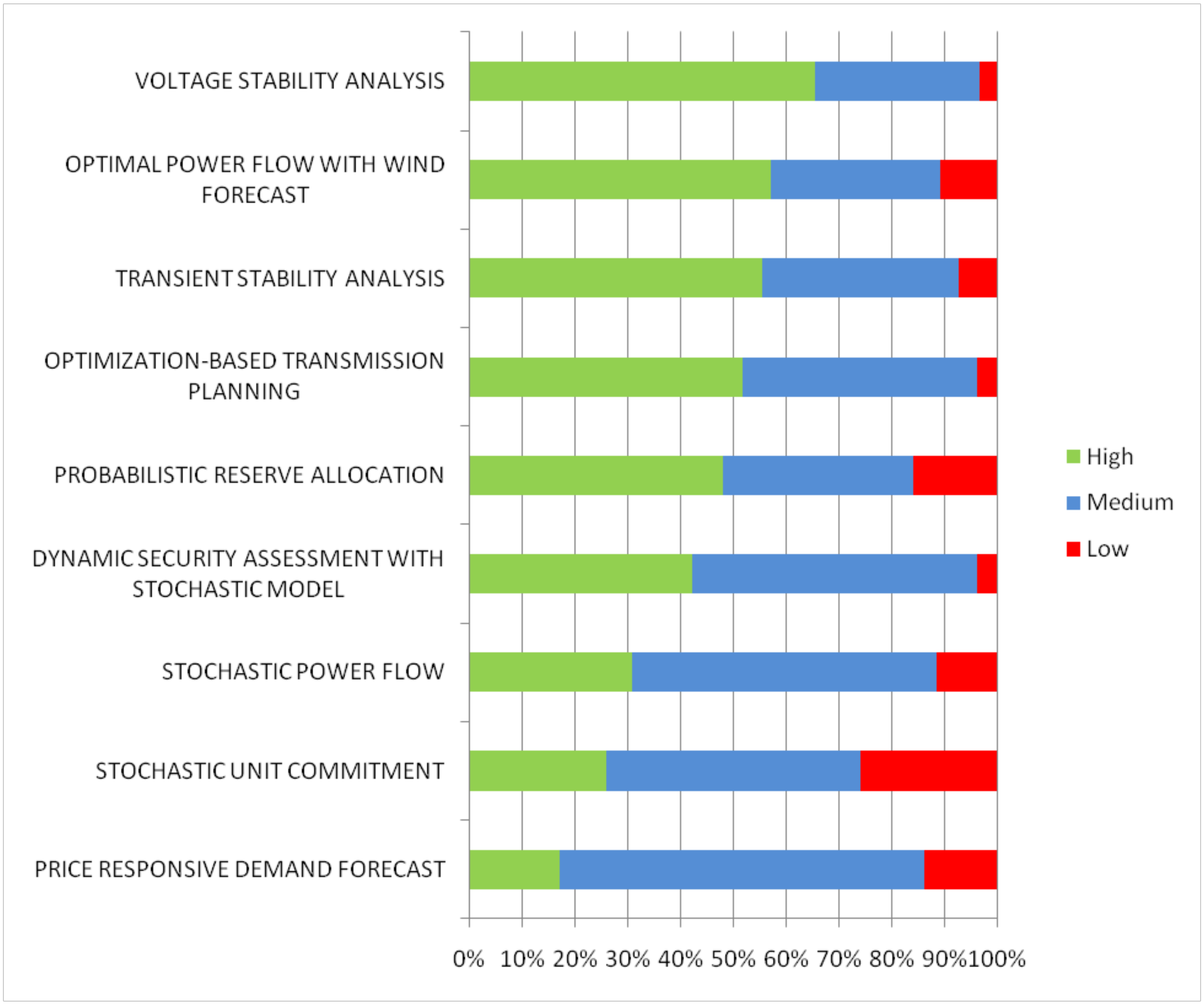

Figure 5. Ranking of Advanced Decision Support Tools to Support Wind Integration

ES.5.7 Changes in Operational Processes and Tools

Integrating wind generation could require changes in the physical grid (e.g., building more transmission), changes in operational business processes, and changes in information technology solutions that support the operators in the control room. The three most highly rated changes that need to be made are: more accurate wind forecasting; more flexible conventional generation; and building more transmission. See Figure 6.

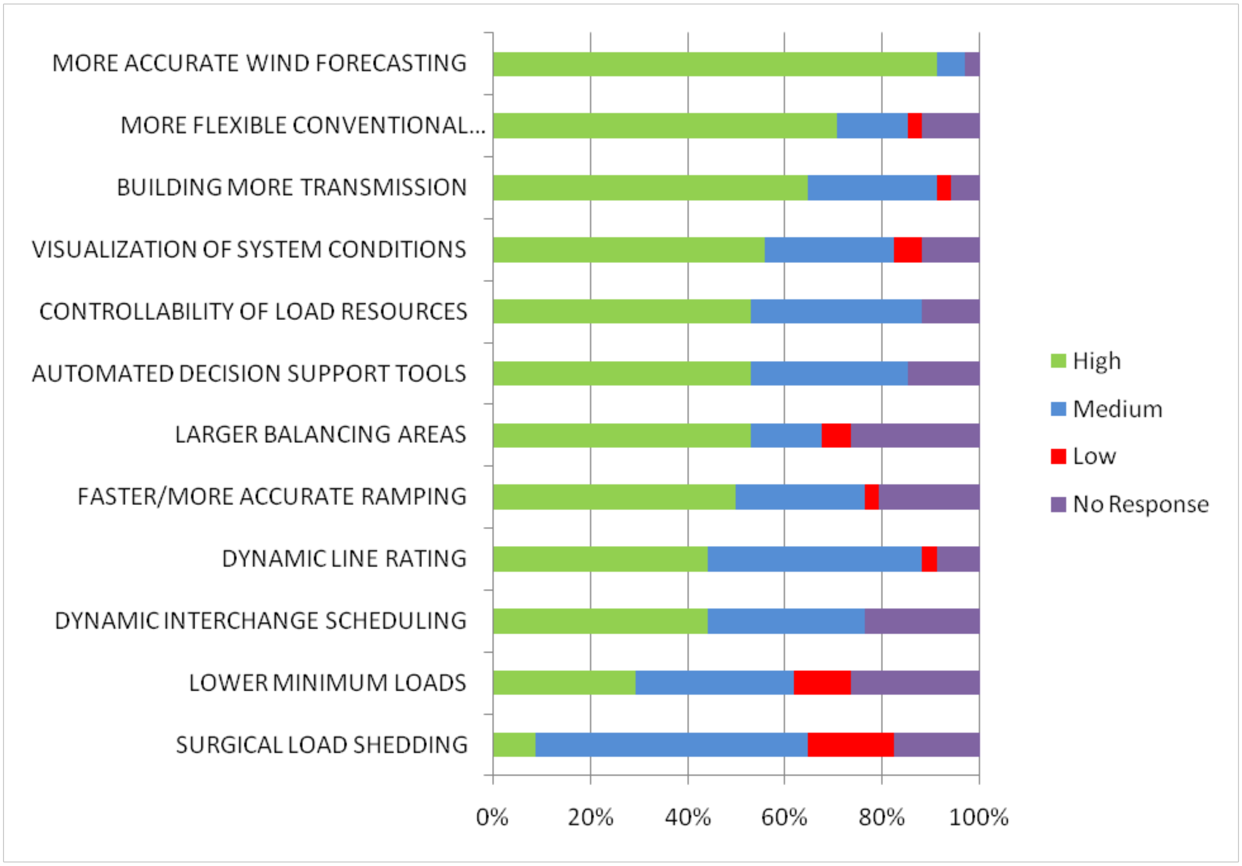

Figure 6. Value Rating of Grid Operational Changes for Large-Scale Integration of Wind Power

Some of these changes require new electricity regulation and market protocols (e.g., more flexible conventional generation, larger balancing areas, dynamic interchange scheduling, controllability of load resources, surgical load shedding). Others may need local or national policy measures (e.g., building new transmission), which might take longer to implement. Yet, grid operators can implement some changes in the short-term (e.g., more accurate wind forecasting, automated decision support tools, visualizations of system conditions).

ES.5.8 Policies and Standards Affect Wind Energy Integration in the Control Room Operations

Grid reliability standards and regulatory policies as well as the laws enacted at the local, state, regional, national and multi-national levels can affect the integration of wind generation in the control room. Seventy-nine percent of respondents agree or strongly agree that integrating a significant amount of wind generation will largely depend on the operating policies deployed to support operators in the control room. See Figure 7. Respondents who are in agreement with various policy statements have high wind penetration levels, while most of those who did not agree have low penetration of installed capacity.

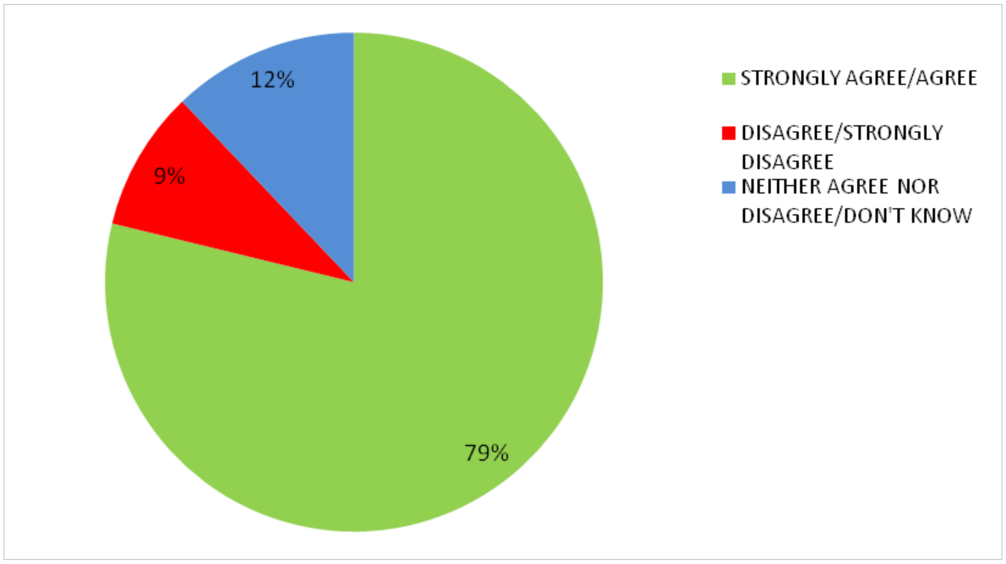

Figure 7. Large-Scale Wind Integration will Depend on the Operating Policies Deployed in Control Rooms

The key policy areas identified for wind integration, which will impact the tools, processes and procedures in the control room include:

- Design effective rules and protocols for electricity markets.
- Greater coupling and harmonization between national and regional electricity markets (e.g., reserve sharing and transmission scheduling).
- Congestion management.
- Standard grid code and interconnection guidelines.
- Standard data requirements for wind plants.
- National initiatives to improve weather service models.

ES.5.9 Impact of Smart Grid Technologies on Wind Integration

Governments, policy makers, regulators, utilities and other stakeholder groups are proposing "smart grids worldwide." Smart grid technologies improve the flexibility of power systems by increasing the accuracy of observation and boosting controllability, and maneuverability of certain loads, generation and storage resources, etc. From the view of the control room environment, Figure 8 shows the percentage of grid operators who have implemented or plan to implement several smart grid applications.

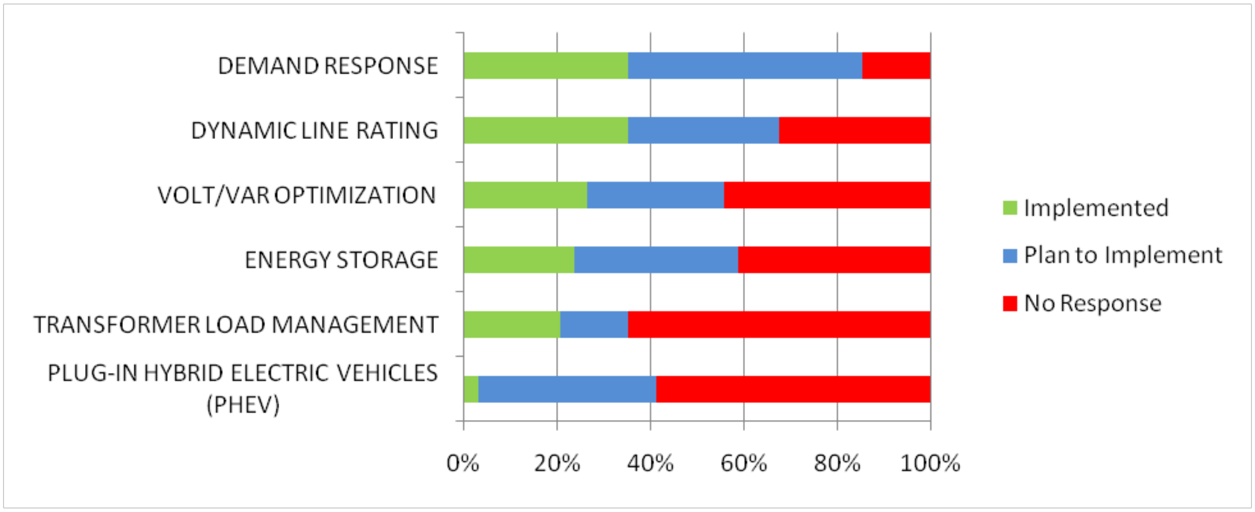

Figure 8. Smart Grid Applications Currently Implemented or Will Be Implemented

ES.5.10 Wind Power and Situation Awareness in Control Centers

A key finding from the questionnaire results and the visits to utilities is the importance of tools that help operators maintain situation awareness (SA) in the control rooms as more wind generation is connected to the grid. Focus is increasing on a new operating paradigm that is more predictive and proactive and less reactive. This is emerging in the control center as a result of greater variability and uncertainty in the power system.

ES.5.11 Look – Ahead and Predictive Solutions in the Control Room will Enhance Situation Awareness

Operational risk management will clearly require applications that allow operators to look ahead and assess the next system conditions before they occur. This ability to project into the future will certainly improve SA. Based on respondents' feedback, more wind power on the system is also expected to hasten the development of a third generation of control center applications, which are needed to support predictive and look-ahead operations.

ES.6 Recommendations

Three categories of recommendations are provided. They are: *Short Term*, *Medium Term*, and *Research*.

- *Short Term:* "Low hanging fruit" actions utilities can implement to successfully integrate wind energy into control rooms. They are not dependent on new regulatory or policy measures, additional research or other catalyst activities.
- *Medium Term:* Recommendations that depend on new regulatory and public policy measures, or that require additional technology development and demonstration before implementation can proceed.
- *Research*: These activities require more basic or advanced research with the support of public-private partnerships, and through collaboration between industry, national laboratories and academia.

ES.6.1 Short Term Recommendations

- **Centralized Forecast –** Implement a centralized wind power forecasting program.
- **Multiple Forecasting Providers –** Use ensemble forecasting which combines wind power forecast from several third-party forecasting providers.
- **Visualization of Wind Power Forecast –** Develop displays that allow operators to compare actual wind generation with wind power forecast data. Also, build displays to monitor net load across the system (i.e., load minus wind) in real-time.
- **Integration of Wind Power Forecast –** Enhance the EMS and other control room decision support tools incorporating wind power forecast data. The nine best practice tools presented in this report is an excellent starting point for defining initial functional requirements.
- **Rapid Update of Wind Power Forecast –** Provide rapid and more frequent updates of wind power information to control room operators and the applications they utilize. This will reduce the degree of uncertainty impacting real-time decision making.
- **Reserve Monitoring –** Implement a tool to monitor operating reserves.
- **Control Room Improvements –** Deploy new visualization tools and other decision support capabilities to enhance situational awareness in control rooms.
- **Look-Ahead and Predictive Operation –** Implement look-ahead and predictive operational capabilities in the control room. This can be accomplished by connecting the real-time production EMS with an ultra-fast dispatcher training simulator (DTS). The DTS includes replica models and algorithms of the real-time EMS. It must have the proper model of wind plants, such as a time series model with actual or simulated wind power forecast.
- **Change Management Process –** It is necessary to develop and follow a detailed change management process when integrating wind forecast in control rooms. For some operators and dispatchers, integrating wind can be a difficult cultural change. Successful integration of wind energy in the control room requires operators to be involved early in the process.
- **Wind Forecast Management –** Assign a dedicated team to manage the wind power forecast. As part of the activities, the team should, at a minimum, generate weekly and monthly performance reports including different forecast errors for the various wind forecasting products used.

- **Operator and Dispatcher Training –** Conduct training on how wind plants function and how wind forecasting can better support operational decision-making. Appropriate training tools for integrating wind power forecast will help operators develop a better understanding of how wind plants operate and how they can interact more effectively with the system. The training simulators should mimic the actual system and include representations of wind generation assets.
- **Industry Wide Training –** Federal and State governments, in partnership with utilities and other private sector parties, should invest in power engineering programs at universities and colleges, in addition to other forms of accelerated specialized training programs that produce the requisite number of engineers and technical workers to replace experienced technicians approaching retirement. More skilled engineers and technicians are needed to ensure a secure and reliable operation of the U.S. power grid infrastructure, which faces major challenges such as increased power generation from wind and other variable energy resources. Modernization of the nation’s electricity delivery (transmission and distribution) system with smart grid technologies also will require new technical workers. Training of the workforce must start now, long before retirements begin draining control room expertise, in order to ensure a smooth transition and business continuity.
- **Information Dissemination –** Grid operators should develop a website portal to provide relevant wind and system information to key stakeholders such as wind plant operators, regulators and researchers. Examples of information that should be delivered via this portal include forecasted versus actual wind power generated on a system and regional level, and other performance metrics. Several utilities featured in this report have deployed web portals dedicated to wind generation.

ES.6.2 Medium Term Recommendations

- **Faster Electricity Markets –** New policies for operating power systems in market and non-market regions should be designed to support the frequent scheduling (e.g., sub-hourly) and dispatching of generation and transmission resources. These policies will facilitate better integration of wind generation.
- **Larger Electricity Markets –** Regulatory policies should be designed and implemented to support the development of multi-regional markets for ancillary services and reserves. This will foster a more flexible use of resources at both the local and global level.
- **More Transmission Capacity –** Inadequate transmission capacity is a key obstacle to integrating more wind energy into existing power grids. Grid operators in this survey cited the need to build transmission as one of the changes needed to increase the share of energy that comes from locationally constrained wind resources. Federal and State regulatory policies should be enacted to accelerate the building of more transmission capacity. Regional transmission planning processes should be modified to accommodate alternative transmission solutions that support harnessing the huge potential of offshore wind resources in the U.S.
- **Dashboards in Control Rooms –** Increased uncertainty and variability in grid operations will require that new decision support systems be designed with Intelligent User Interfaces, in order to improve the communication between the operator and the computerized tools used in control rooms. By 2030, an avalanche of anticipated data, which operators must cope with, will require interfaces that can naturally be personalized and dynamic. Dynamic dashboard technologies will be needed to help operators develop higher levels of SA through the creation of new displays. These displays will be extracted from a geographic overview of a wide area, and will allow operators to zoom in and monitor an area with large wind plants and where extreme ramp events are predicted to occur.

- **Design Systems that Enhance Situational Awareness (SA) –** New control room tools should be designed to enhance SA. The requirements for achieving higher levels of SA must be taken into consideration during the design and not after.
- **Wind Event Warning System –** Develop a high wind event warning system in the control center, which will allow operators to visualize such events and take the steps necessary to protect the system.

ES.6.3 Research Recommendations

- **System Flexibility –** Develop more rigorous methods and tools to accurately quantify, monitor and assess the degree of flexibility in a given power system for a given level of wind power penetration. Collaboration between grid operators and the research community should foster such efforts.
- **Total Value of Wind Forecasting –** Conduct more research into how operational processes and procedures are affected as a result of using accurate wind power forecast. By doing so, operators can demonstrate the total value of the investments that should be made for continuous improvements in the performance of the wind forecasting system. Grid operators and commercial forecast providers should collaborate on these efforts.
- **Develop Tools to Make Better Use of Probabilistic Information –** While the operating conditions under which grid operators make decisions is clouded with varying degrees of uncertainty, the actual decision is deterministic and binary. To address the uncertainty related to wind forecasting, many researchers and power system practitioners suggest that probabilistic information be used. Research must consider how to best integrate probabilistic tools with conventional deterministic tools in the control room. More importantly, research also should examine how probabilistic information should be presented to system operators. Research also should be conducted on the use of stochastic methods for unit commitment, economic dispatch and other processes.
- **Risk-Based Decision Making –** With the onset of increased variability and uncertainty in power systems due to wind and other variable generation, the need to integrate a risk-based approach with decision-making in the control room is critical. Unlike the deterministic approach, a risk-based technique accounts for differing probabilities and grid contingencies. Research is needed on how to quantify relative operational risk and severity of contingencies such as extreme ramp events. Decision-support tools must be designed to incorporate the risks related with varying degrees of uncertainty in wind power forecasts.
- **Extracting Value from the Deluge of Data –** Research should be conducted in the application of advanced techniques such as data mining and pattern recognition in power systems operations. Operators have developed data-driven mental models around the power system. The uncertainty introduced by wind generation and other sources leads to unpredictability in power flow and other unfamiliar operating conditions represented by more data. Operators do not have the proper tools to extract any intrinsic values locked in the large volume of data, and then develop new mental models. Research should be conducted to develop new decision support tools based on data mining and pattern recognition techniques.
- **Improvements in Boundary Layer Forecast –** The U.S. should invest in improving its boundary layer weather forecasts at the national level. A collaboration of the public and private sectors is critical to improving the atmospheric observations, modeling, and numerical weather predictions needed to support a large-scale integration of national wind energy. Improvements of boundary layer weather forecasts will support integration of large-scale wind energy into the nation's electric grid. From the public sector, National Oceanic and Atmospheric Administration (NOAA) should reduce errors in relevant meteorological parameters, such as wind speed and direction in the turbine layer, thereby allowing for

improved, foundational weather forecasts available for public consumption. The private sector parties, such as commercial forecasting service providers, should be responsible for providing value-added products and tailored forecasts of wind power to grid operators. Both the public and private sectors should contribute to the design and deployment of a national observation backbone network to support better boundary layer forecasts. While NOAA should provide an improved foundational weather forecast, the private sector must be the sole provider of wind power production forecasts and the related forecasting products. Investing in an improved foundational, boundary layer forecast will support many industry and national goals, including the addition of more wind and other renewable energies.

- **State-of-the-Art in Centralized Forecasting –** As more grid operators around the world gain experience from centralized wind power forecasting, it is important that lessons learned are captured and disseminated to the broader industry. Because of the benefit to the industry at-large, a new comparative study of centralized wind power forecasting should be conducted. While previous studies focused on grid operators in North America, a new study should consider the programs deployed by grid operators in other countries. Both public and private sectors should provide support for such a study.
- **Knowledge Management to Cope with the Aging Workforce –** The reality of an aging workforce will likely cause many utilities to lose experienced operators, along with vast amounts of undocumented knowledge of how the grid works. Simultaneously, utilities will have to hire new, less experienced operators, who must manage the grid in a hybrid state with both old and new equipment, most notably a mix of conventional and variable energy resources. Grid operators must begin documenting the operational knowledge and experience of existing staff before they retire. Once this information is stored and archived, sophisticated search engines and retrieval tools will be needed in the control rooms to integrate historical data with real-time operations. Being able to incorporate documented knowledge about historical grid operating conditions and critical equipment with other, more current information, will further reduce operators' uncertainty, thus enabling proper diagnosis and timely decision-making. This will lead to the emergence of a Knowledge Management System (KMS) in control rooms. Research into advanced information systems, analytical software and search engines should be conducted to specify requirements and recommendations for the implementation of advanced KMS applications. The research should be supported with investments from the public and private sectors.

ES.7 Summary of Conclusions

- More and more grid operators are interested in applying industry best practices and examples of excellence as the starting point for deploying their own decision support systems built specifically to address wind energy integration at the control center level.
- Realizing a scenario of 20% wind energy by 2030 in the U.S. will be difficult if existing decision support tools in utility control centers do not evolve to meet the new challenges.
- Grid operators worldwide are increasingly positive about integrating wind generation as they share best practices and learn about the successes of their peers.
- Wind power forecasting is indispensible for successful wind integration.
- Efficiently integrating wind energy in power systems requires that forecast and uncertainty information be incorporated into real-time decision support systems and planning tools.
- Higher levels of wind generation have shown to create uncommon system conditions and consequences that operators must learn to manage.
- Efficient integration of wind energy requires grid operators to have access to a proper mix of flexible resources ranging on the supply-side, delivery-side and demand-side.
- Smart grid technologies can aid wind integration by providing additional system flexibility.
- Having skilled operators is necessary for wide-scale deployment and the integration of wind and other variable energy resources.
- Achieving and maintaining the highest levels of situational awareness in control centers is, in general, of pivotal importance to grid operators and will be the case especially for systems characterized by high penetration of wind energy.
- Integrating wind generation could require changes in the physical grid, as well as changes in operational business processes and information technology solutions at work in control centers.
- Grid reliability standards and regulatory policies as well as laws enacted at the local, state, regional, national and multi-national levels affect the integration of wind generation in the control center.
- The industry is on the verge of a new operating paradigm as high levels of wind and other variable generation and increasing operational uncertainty become the norm today and even more so as we move towards 2030.

LIST OF ACRONYMS

AC	Alternating Current
ACE	Area Control Error
AEMO	Australian Energy Market Operator
AESO	Alberta Electric System Operator
AGC	Automatic Generation Control
AWEA	American Wind Energy Association
BPA	Bonneville Power Administration
CanWEA	Canadian Wind Energy Association
CHP	Combined Heat and Power
CIGRE	International Council on Large Electric Systems
CORESO	Coordination of Electricity System Operators
CREZ	Competitive Renewable Energy Zone
CSP	Concentrating Solar Power
CPS	Control Performance Standard
DC	Direct Current
DDST	Dispatch Decision Support Tool
DLR	Dynamic Line Rating
DOE	Department of Energy
DR	Demand Response
DSO	Distribution System Operator
DSS	Decision Support System
DTS	Dispatcher Training Simulator
DWG	Distributed Wind Generation
ED	Economic Dispatch

EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
EU	European Union
EWEA	European Wind Energy Association
FERC	Federal Energy Regulatory Commission
FACTS	Flexible Alternating Current Transmission Systems
GWEC	Global Wind Energy Council
GW	Gigawatt (1 billion watts)
HVDC	High Voltage Direct Current
IAC	Industry Advisory Committee
ICCP	Inter-Control Center Communications Protocol
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator
ISO-NE	Independent System Operator of New England
KMS	Knowledge Management System
MISO	Midwest Independent System Operator
MMS	Market Management System
MW	Megawatt (1 million watts)
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OPF	Optimal Power Flow

PBR	Power Balance Responsible Party
POSOCO	Power System Operating Company
PHEV	Plug-in Hybrid Electric Vehicle
PUCT	Public Utility Commission of Texas
PV	Photovoltaic
RAS	Remedial Action Scheme
RC	Reliability Coordinator
REE	Red Eléctrica de España
REN	Rede Eléctrica Nacional
RMSE	Root Mean Square Error
RPS	Renewable Portfolio Standards
RTO	Regional Transmission Organization
RUC	Reliability Unit Commitment
SA	Situation Awareness
SCADA	Supervisory Control and Data Acquisition
SCED	Security Constrained Economic Dispatch
SGTF	Smart Grid Task Force
STWPF	Short Term Wind Power Forecast
TSO	Transmission System Operator
UC	Unit Commitment
SCUC	Security Constrained Unit Commitment
TSAT	Transient Stability Assessment Tool
UWIG	Utility Wind Integration Group
VER	Variable Energy Resources
VLPGO	Very Large Power Grid Operators

VSAT	Voltage Stability Assessment Tool
WAMS	Wide Area Monitoring Systems
WECC	Western Electricity Coordinating Council
WGPL	Wind Generation Penetration Level
WGR	Wind Generation Resource
WPCPL	Wind Power Capacity Penetration Level
WPF	Wind Power Forecast
WWEA	World Wind Energy Association
WSAT	Wind Security Assessment Tool

1. INTRODUCTION

Electricity generated from variable energy resources, especially wind power, is growing rapidly worldwide. At the end of 2010, approximately 194.4 gigawatts (GW) of installed wind capacity worldwide was in existence, a 22% increase compared to 2009.[7] As shown in Figure 9, the U.S. alone has more than 40 GW of installed capacity. Nine other countries accounting for the top cumulative installed wind power capacity, compared with the rest of the world, are also shown. Figure 10 shows the growth of wind generation in the U.S. and the European Union (EU) from 1997–2010. Similar growth patterns for individual power systems in the U.S. and EU during the same time period are in Appendix A. It is worth noting the correlation between growth curves and the date when various government and regulatory policies were put in place. This connection underscores the importance of coherent and long-term energy policy as an industry driver.

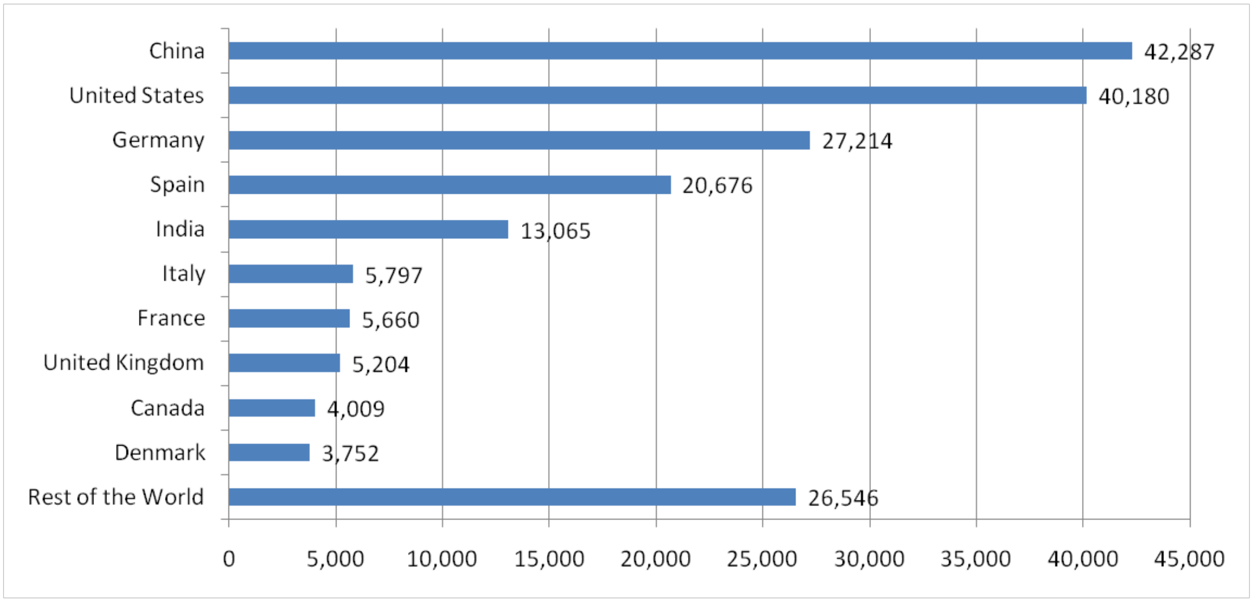

Figure 9. Installed Wind Capacity (MW) Worldwide at the End of 2010

The growth in the U.S. and the rest of the world is expected to continue in the coming decades due to various factors, especially regulatory and policy measures. In the U.S., 27 states have enacted Renewable Portfolio Standards (RPS) requiring that between 10% – 40% of a state's energy, which is supplied to the power grid, must come from renewable sources by 2015 – 2030.[8]

In addition, five other states have non-binding objectives for adopting renewable energy goals instead of an RPS. In its landmark 2008 report, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply* (hereinafter referred to as "20% Wind Energy by 2030"), the U.S. Department of Energy (DOE) examined a scenario and determined that it is technically feasible for wind power to generate 20% of the electricity in the U.S. by 2030.[9]

[7] Global Wind Report, http://www.gwec.net Accessed February 5, 2011.
[8] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm. Accessed on April 2011.
[9] U.S. Department of Energy, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, July 2008, http:/www.20percentwind.org/20p.aspx?page=Report.

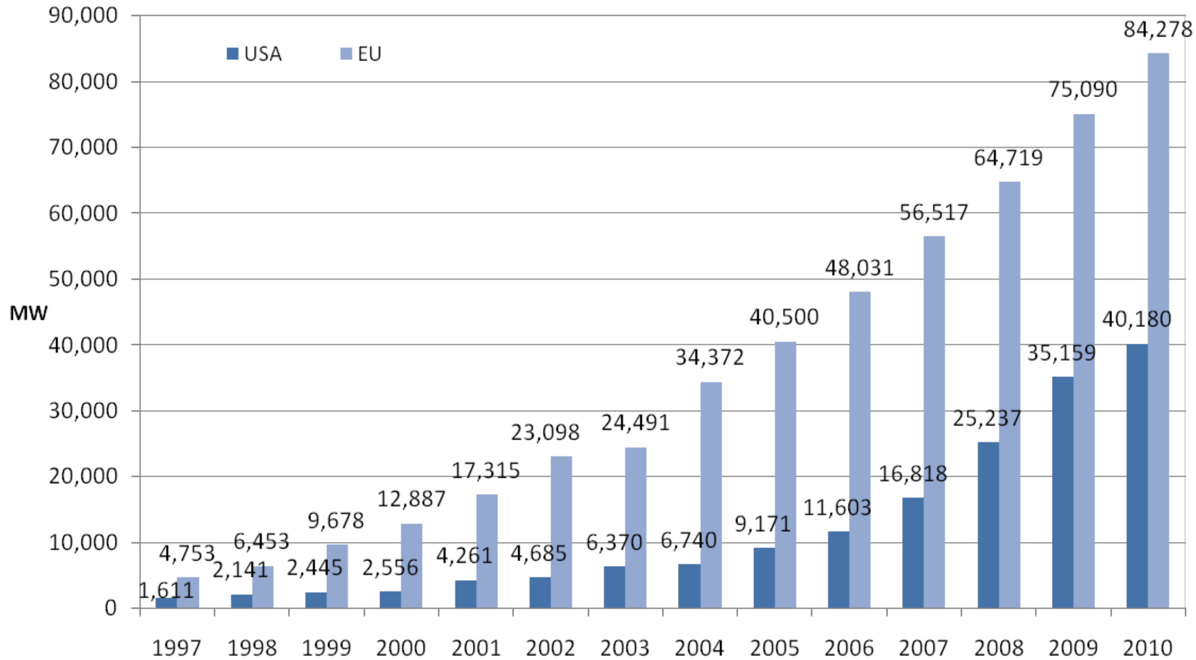

Figure 10. Cumulative Installed Wind Power Capacity in the USA and the EU from 1997 to 2010

In addition to the DOE's 20% Wind Energy by 2030 report, other studies about wind energy in the U.S. and the impacts of wind energy integration on bulk power systems have been conducted. The Eastern Wind Integration and Transmission Study (EWITS)[10] and the Western Wind and Solar Integration Study (WWSIS)[11] were two studies with a regional focus. EWITS was specifically designed to examine the operational impact of up to 20% – 30% of wind energy penetration in the Eastern bulk power system of the U.S., while the WWSIS examined the planning and operational impacts of 35% wind, photovoltaic (PV) and concentrated solar (CSP) in several states (Arizona, Colorado, Nevada, New Mexico and Wyoming). These states are in the Western Electricity Coordinating Council (WECC) system in the U.S. A third study explored the potential trajectories for how the U.S. can get 20% of electricity from wind power (Ryan Wiser, 2010). According to that report, approximately 16 GW of new wind generation must be added annually to achieve 20% Wind Energy 2030. See Figure 11. Studies on wind energy have also been conducted in Europe and other parts of the world (e.g., European Wind Integration Study (EWIS).[12]

It is important to note that the analysis techniques used in these types of wind penetration feasibility studies have progressed and continue to advance. Going forward, it is expected that studies will focus on the integration of wind and other variable generation forecasting in grid operations.

[10] *Eastern Wind Integration and Transmission Study*. Available at www.nrel.gov/wind/systemsintegration/ewits.html.
[11] *Western Wind and Solar Integration Study* Available at http://www.nrel.gov/wwsis.
[12] *European Wind Integration Study: Toward a Successful Integration of Large Scale Wind Power into European Electricity Grids.* Available at http://www.wind-integration.eu/downloads/library/EWIS_Standalone_Executive_Summary.pdf.

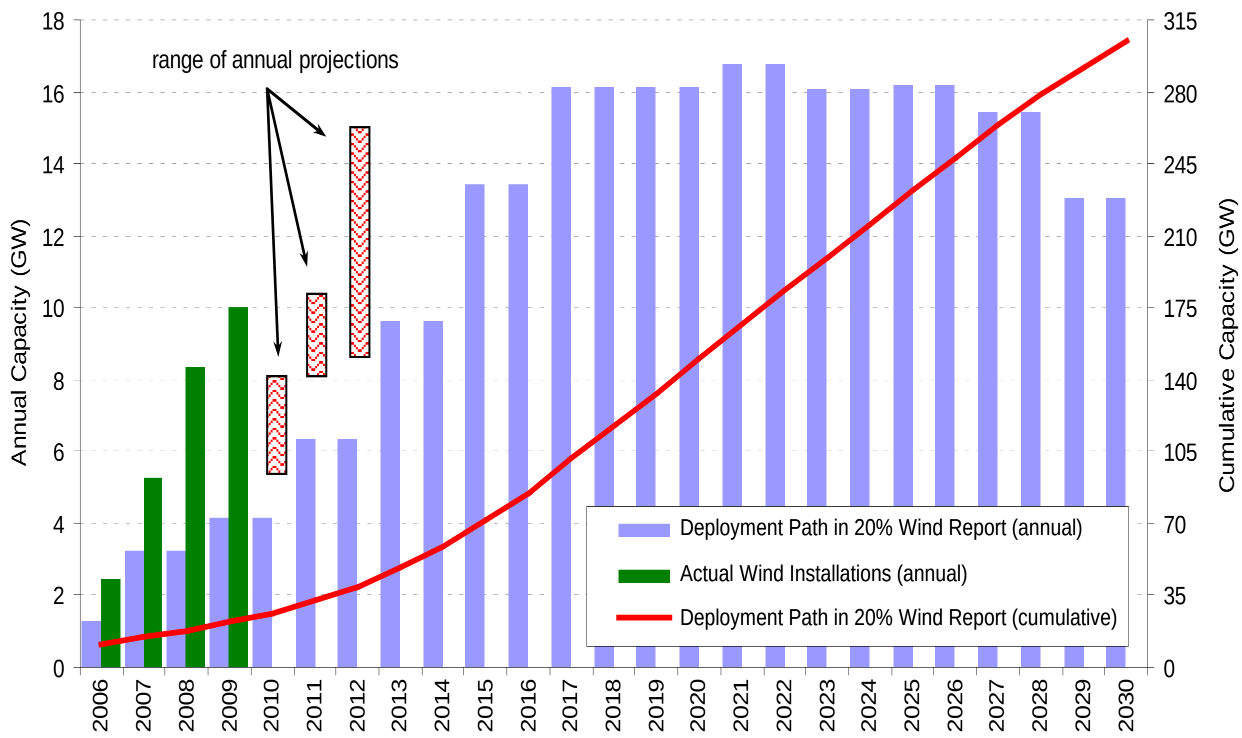

Figure 11. Potential U.S. Trajectory to Achieving 20% of Electricity from Wind Power by 2030 (Source: Provided by Ryan Wiser, Lawrence Berkley National Laboratory)

1.1 Background of the Project

This research project was planned in response to the DOE's solicitation for proposals that addressed challenges and proposed solutions for a scenario of 20% wind energy by 2030 to succeed in the U.S.

Utilities in the U.S. and other parts of the world have developed varying levels of expertise and knowledge of how to operate power grids with increasing amounts of wind power generation. As an example, Figure 12 shows that wind energy consumption in several European countries (e.g., Denmark, Portugal, Spain, Ireland and Germany) was between 9% – 24% in 2009.[13] Grid operators in these countries have experience dealing with many of the operational challenges that dispatchers in control rooms in the U.S. can expect to face, especially as more wind power becomes a part of the generation mix in their systems.

[13] In 2010, 2.3% of the electricity in the U.S. was generated from wind power.

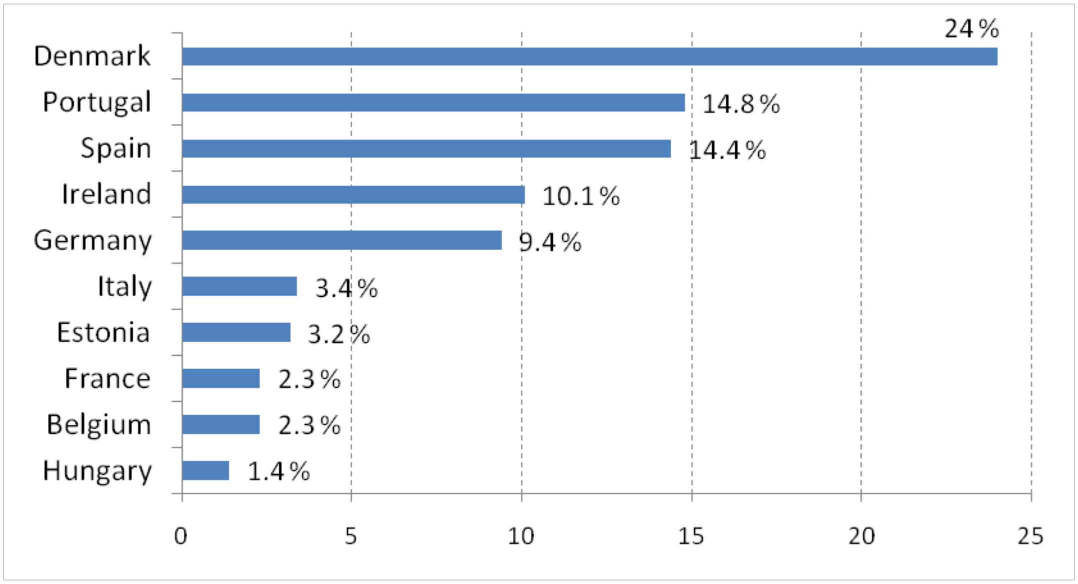

Figure 12. Wind Share of Total Electricity Consumption in EU Countries Represented in the Survey (Source: EWEA)

Fortunately for U.S. balancing authorities and transmission owners who have yet to address wind integration challenges and the use of wind power forecasting, there are significant lessons to be learned from other operators' experiences in parts of the U.S. and other parts of the world. The integration efforts of Transmission System Organizations (TSOs) in Europe with high wind power penetrations levels, island systems such as Eirgrid, Ireland, and in power grids with limited interconnection capacity to other balancing authorities such as the Electric Reliability Council of Texas (ERCOT) in the U.S. and Red Eléctrica de España (REE) in Spain, are of particular interest.

Based on observations and discussions with electric utilities and representatives from organizations, such as the Utility Wind Integration Group (UWIG) and American Wind Energy Association (AWEA), it was found that an important gap regarding wind integration exists. This gap was due to a lack of information regarding how to make the best use of wind power forecasting in utility grid control centers and a narrow understanding of current and emerging best practices for integrating wind power forecast information into the decision support systems used by grid operators.

Effective forecasting of wind power is a prerequisite for successful large-scale wind integration. Several utilities are deploying wind forecasting systems or acquiring wind forecast from commercial providers. However, many of the existing deployments in U.S. utility control centers have not yet provided the value needed for reliable integration of large amounts of wind energy. Specifically, direct integration of wind power forecast into the Energy Management System (EMS) and other tools in control room is not common. There are a few examples of power systems that already experience a significant impact from wind integration and where the benefits of wind power forecasting to the operators in the control room are demonstrated. However, these benefits are not widely known. This study aimed to conduct a survey that would help close the aforementioned gap. Unlike most previous wind integration studies, which have been country or regional specific, this research project took a global approach to identifying best practices, examples of excellence and lessons learned with a central focus on integrating wind power forecast in the control room environment.

1.2 Objective of this Study

The main objective of this study was to identify the best path forward to guiding the development of operational strategies and business processes. It also is designed to determine the necessary tools in control rooms that would support a scenario of 20% energy generated from wind power by 2030. A central premise in meeting this objective is that any framework within which a forward-path is defined must be based on the experiences of power systems operators with wind generation—the best practices, examples of excellence and lessons learned. The future outlook of how power systems develop must also be considered.

1.3 Project Tasks

The research project included five main tasks:

1. Develop a questionnaire about the relevant issues related to integration of wind power with grid operations, including the use of wind power forecast information.
2. Conduct a survey of utilities in the U.S. and other parts of world.
3. Visit grid control centers at selected utilities in the U.S. and Europe.
4. Review and analyze methods and techniques for integrating wind forecast with EMS and other decision support systems in control rooms.
5. Analyze results and write a final report (this report).

2. WIND ENERGY AND UTILITY CONTROL ROOMS IN 2030

An increased demand for electricity in the future is a reality for many consumers. It also is important to consider both the current and anticipated growth of wind power to meet that demand, along with the factors that will affect how to integrate wind energy into the grid and how utility control rooms will evolve. The exploration of future scenarios for the next 20 years was an important subtask of the project. In an attempt to accomplish these goals, several different factors, which will shape the trajectory towards 2030, are considered in this chapter.

2.1 Wind Energy in 2030

The amount of prospective GW generated by wind plants, which are in the planning queue of U.S. system operators, is in excess of the hundreds. While it is unlikely this entire portfolio of wind capacity will be built, the regulatory and policy measures such as the RPS in 27 U.S. states will spur continued growth of American wind power in the next two decades. Similarly, the European Union enacted the so-called 20% by 2020 energy law, which mandates, among other rules, that 20% of the electricity demand in the EU must come from renewable energy sources. Based on the available energy resources in the various countries, wind energy will supply a significant portion of the target. Under the law, each EU country must submit a plan with a binding target as its contribution to meeting the 20% by 2020 goal. Figure 13 shows the 2020 target percentage of electricity demand, which is expected to come from wind energy in various member states of the EU. The installed wind generation in many EU countries could exceed 20% of the total generation capacity within the next 10 years.

Several other factors can affect the pace at which more wind generation is built in the EU. For example, the German government policy announcement on May 30, 2011, that it will shut down all nuclear power plants in the country by 2022, is expected to further increase the share of energy from wind power and other variable renewable generation options in Germany and neighboring countries.

2.2 The Future of Offshore Wind

According to the European Wind Energy Association (EWEA) report *Powering Europe*,[14] the majority of future wind plants in Europe will be offshore, in contrast to the U.S. where most of the proposed wind farms will be built onshore. However, offshore wind plants are now considered feasible in the U.S.[15] According to the National Renewal Energy Laboratory (NREL), it is estimated that there is potentially 54 GW of offshore wind power, which if developed, could supply some of the 20% wind energy in the U.S. by 2030.[16] The Massachusetts Cape Wind project, on track to become the first offshore wind farm in the U.S., received a permit from the U.S. Environmental Protection Agency (EPA) on January 7, 2011.[17] There is growing political and socio-economic momentum to build offshore wind farms along the eastern coast of the U.S. This movement was advanced further in 2009 when the governors from Delaware, Maryland and Virginia signed a

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[14] *Powering Europe* Report Available at http://www.ewea.org.

[15] *U.S. Offshore Wind Energy: A Path Forward was* published in 2009 by the U.S. Offshore Wind Collaborative. Available at www.usowc.org.

[16] See *Large-Scale Offshore Wind Power* published in September 2010 by the National Renewable Energy Laboratory (NREL). Available at http://www.nrel.gov.

[17] Source: http://www.capewind.org/news1174.htm. Accessed February 1, 2011.

tri-state agreement to deploy offshore wind resources in the Mid-Atlantic coastal region.[18] A robust U.S.-based full service supply chain for the offshore wind industry could create several thousand jobs.[19]

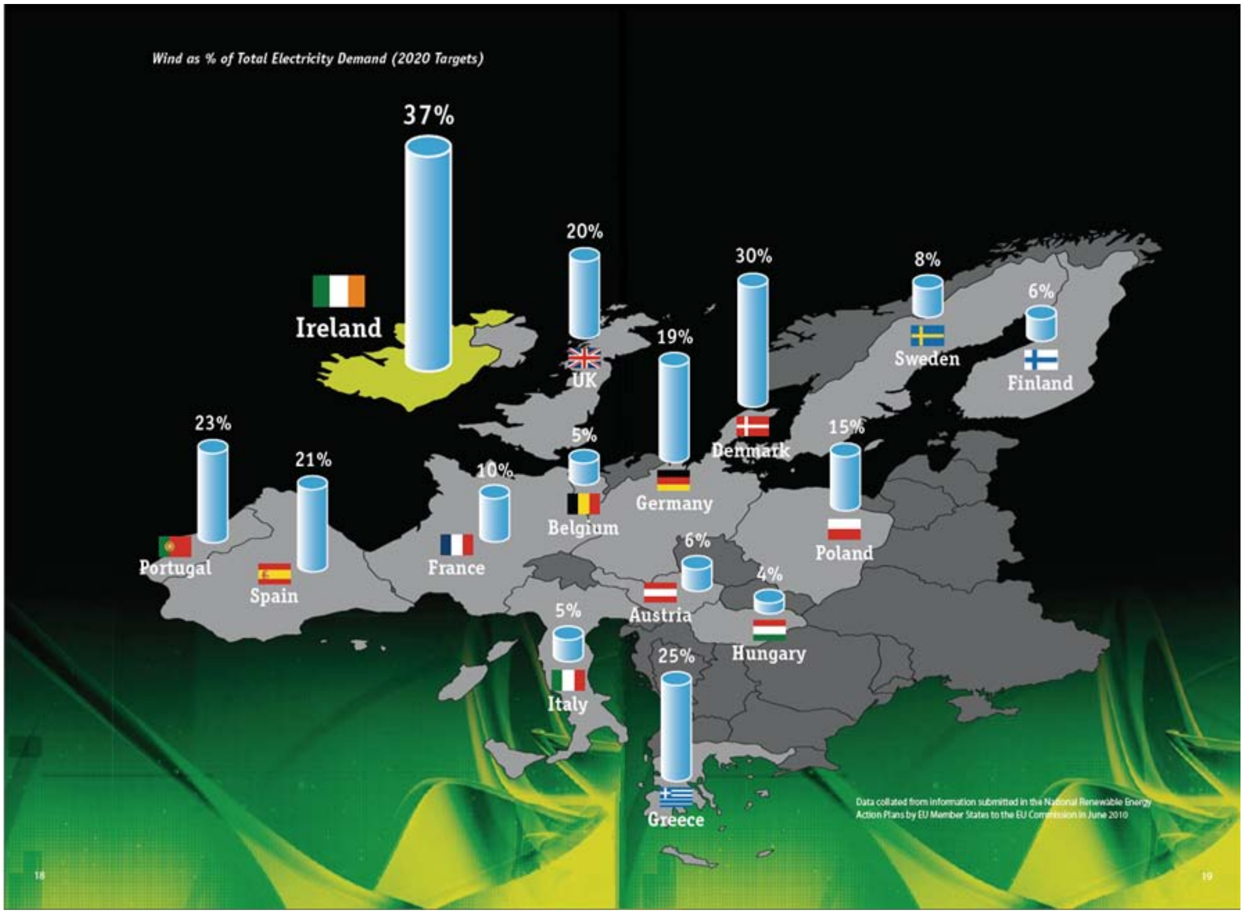

Figure 13. Wind Power in the EU as Percent of Total Electricity Demand by 2020 (Provided by Jon O'Sullivan, Eirgrid, Ireland).

In terms of integrating wind forecast in the tools and systems used by dispatchers, it makes little difference whether the wind plants are onshore or offshore. Many of the issues facing dispatchers who operate power grids with offshore wind plants are similar to those with onshore wind plants. Several of the European TSOs who participated in the survey have experience in integrating wind energy from both offshore and onshore. Therefore, some of the practices and examples of excellence identified in this report can be adapted and implemented in utility control rooms regardless of the wind plant's physical location.

2.3 Utility Control Rooms in 2030

Researchers are devoting a great deal of attention to studying the technical feasibility and different growth trajectories for the 20% wind energy by 2030 scenario in the U.S. As this scenario could be reached within two decades, it is also important to anticipate and analyze the factors and changes that may affect the ability of

[18] Source http://www.governor.maryland.gov/pressreleases/091110.asp. Accessed January 31, 2011.
[19] Email communications with Jim Lanard, Offshore Wind Development Coalition.

dispatchers and operators in control rooms to operate the future power system with large amounts of wind generation. Several factors that will affect the tools and processes in future control rooms include:

- Need for more flexible resources.
- New types of load and demand profile.
- Deployment of new technologies such as energy storage, electric vehicles, demand response (DR), Phasor Measurement Units (PMUs).
- Advances in computer software and hardware performance.
- Improvements in wind generation controls (e.g., regulation, Automatic Generation Control (AGC), synthetic inertia).
- New designs of electricity markets.
- Work force demographics and skills.

Power systems are generally operated with sufficient inherent flexibility such as the ability to cope with variability caused by changes in load, forecast errors and other types of anomalies without jeopardizing the system's stability. However, as more wind energy becomes a greater part of the energy supply mix in the U.S. and other parts of the world, system variability will increase. Ensuring that there are adequate flexible resources in power systems to cope with variability will be a more important issue than is the case today by 2030. Methods and tools to accurately quantify, monitor and analyze system flexibility both during planning and in real-time operation will be critical in the control room.

Looking to 2030 and a world with significantly more utility scale wind and solar power plants, we will have to cope with more system variability and uncertainty. Other sources of increased system variability and operational uncertainty will be the anticipated changes in the amount, characteristics and profiles of the system load. The deployment of DR programs and the potential large-scale adoption of plug-in hybrid electric vehicles (PHEV) may inevitably cause these differences in the system load as well. It is envisioned that by 2030, there will be more embedded distributed generation such as wind and solar generation in the electricity distribution network. A prevalence of smarter electronics (Santen, Khjoe, & Vermeer, 2010) and miniaturized control devices all over the power grid is expected, along with millions of advanced sensors that enable multi-directional flow of power and information through various combinations of electrical alternating current (AC) and direct current (DC) solutions. An illustration of such a future grid is shown in Figure 14. In addition, we anticipate greater interaction between the transmission and distribution systems due to a multitude of feedback loops. Large numbers of dispatchable and non-dispatchable generation resources in the distribution system could affect how the resources are scheduled and used to operate the transmission system reliably. Tools developed for transmission grid control centers will have to accommodate the aggregate response of several hundred or even thousands of generation resources in the distribution system.

Tools used in the transmission and distribution control centers will begin to converge, as the roles and responsibilities of TSO and the Distribution System Operator (DSO) overlap. New grid players also could emerge, such as the aggregators of DR. This future state, which is beginning to take place in some power systems around the world, will require new IT architectures and platforms that facilitate greater interoperability among decision support systems in the control room, such as EMS, Distribution Management System (DMS) and Market Management System (MMS). Advances in analytical software and computational performance will facilitate the design of enhanced visualization tools for better situational awareness. Advanced forecasting will improve real-time operations by using state-of-the-art ultra-fast computers, enabling operators to look-ahead and predict. This capability will ultimately lead to better decision making in control rooms and efficient operations of bulk power systems.

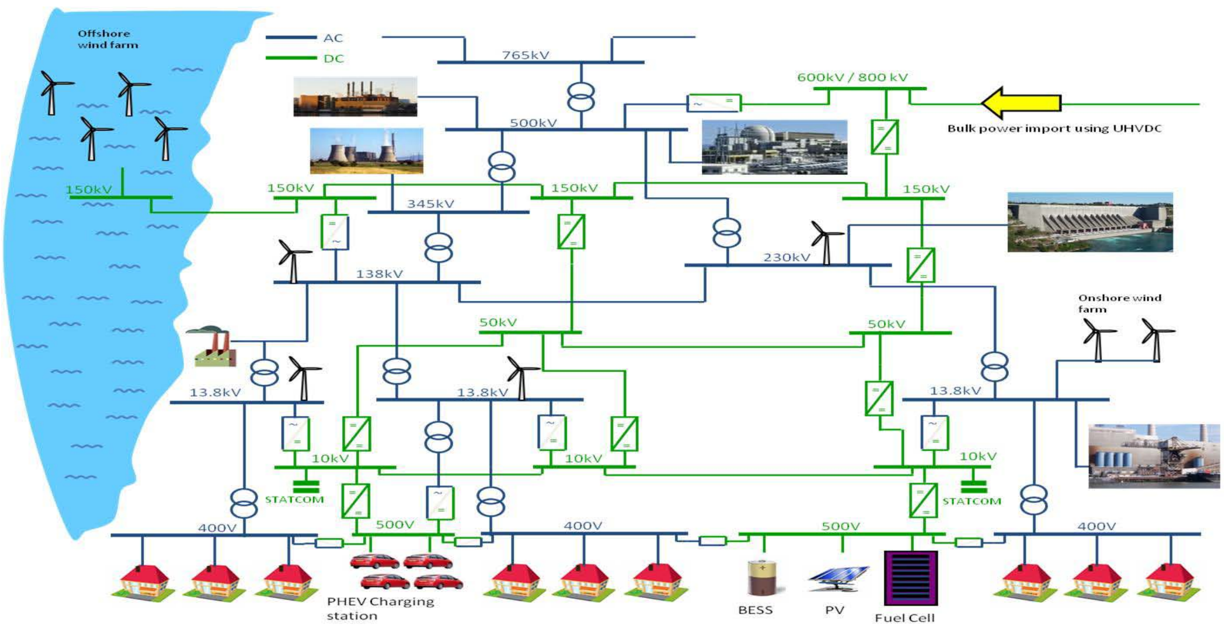

Figure 14. A View of the Future Grid[20]

2.4 To 2030 and Beyond – Era of Look-Ahead and Predictive Grid Operations

Since the 1960s, control center computer applications for analysis and decision support have evolved in response to industry transformations, events and a constant change in how power grids operate. The first generation of computer applications, introduced in the aftermath of the 1965 power blackout in the U.S., focused on the basic tasks of monitoring, control and information gathering. The second generation of tools targeted decision making and taking action. The industry is now on the cusp of another operating paradigm as high levels of wind and other variable generation and increasing operational uncertainty become the new normal (Kuhn, 1996), especially by the year 2030. The emergence of new types of computer applications is expected. Based on the feedback from respondents to the survey, more wind generation on the power system will have already sparked the development of the third generation of control center computer applications. These applications will provide operators with better operational forecasting and predictive capability, which are necessary to efficiently manage uncertainty caused with wind generation or other sources.

2.5 Managing the Impending Data Inferno

Grid operators in utility control rooms today, as well as those in future, face the harsh dilemma of how to extract useful, actionable information from the sea of data in which they swim in daily. More so than today, grid operators in the coming years will have to assemble a huge avalanche of operational data from many disparate sources. They will have to make critical real-time decisions while simultaneously taking the impacts of wind generation and other sources of uncertainty on grid operations into consideration. By 2030, wide-scale

[20] Graphic adapted and enhanced from the original illustration by Neil Kirby of Alstom Grid Inc.

deployment of smart grid technologies such as PMU and other embedded sensors and ubiquitous controls at all levels of the power grid will exacerbate the challenges of this inevitable data explosion.

One study estimates that the amount of power system data utilities will have to manage, communicate and integrate with a host of decision making tools, could increase by 900% within the next decade.[21] Assuming that such a growth rate of data continues for another decade, by 2030, grid operators in control centers will have to cope not only with the resolution of operational challenges related to higher penetration of wind generation, but also how to correlate wind power forecast with other real-time information, originating from a sea of potentially 1,800% more data. Tools and systems to better manage this deluge of data will be essential in order to reduce the impacts of information overload in the control room (Pijpers, 2010), (Yonk, 2011).

The need to exchange data between different entities and systems, such as control centers, is another data-related consequence of this greater proliferation of wind and solar generators as well as an array of other controllable devices and loads in the power system. This exchange of massive amounts of data and information will be required to take place securely (Saito, 2011) and reliably on a daily, hourly, intra-hourly and at even shorter time intervals than what occurs today. All of this will require new IT architectures and high speed communication technologies in order to facilitate predictive mode of the power system operations necessary to ensure real-time situational awareness in the 21st century control center (CIGRE Working Group D2.24, 2011).

2.6 Preparing the 2030 Control Center Workforce

The reality of an aging workforce is one change among many that the electric power industry will face within the next 20 years. The potential workforce crisis will be rooted in its lack of a skilled workforce (Canton, 2007). According to the U.S. Power and Energy Engineering Workforce Collaborative of the International Electrical & Electronics Engineering (IEEE) Power Engineering Society, it is estimated that 45% of utility industry engineers will be eligible for retirement by 2014.[22] As this is happening simultaneously with other major changes, utilities and national and local governments will have to make significant investments in advanced engineering education as well as other kinds of accelerated training programs. By doing so, this will produce more qualified power system and computer science engineers, as well as other technical professionals to manage the power grid infrastructure. Training of new engineers and grid operators must start today, far in advance of when the more experienced engineers and operators retire, to ensure a smooth transition and business continuity. Grid operators inherently have vast experience with existing and older equipment in the power systems. As such, many will undoubtedly be focused on fixing yesterday's problems, while concurrently learning to cope with new problems created in a foreign operating environment with new types of devices like wind and solar generation, as well as other smart grid technologies.

Control room operators and dispatchers in 2030 will have to master a mixed set of skills and technologies in order to harness system flexibility that will be needed to maintain the demand-supply balance. Therefore, as utility transitions to the grid scenario of 2030, training for operators and dispatchers will require the use of advanced simulation tools that accurately consider the increasing variability and uncertainties in the grid, as well as the temporal interdependencies between various business processes. Use of these advanced simulators will also be an integral part of the real-time and look-ahead operations in control rooms.

[21] Press release from Lux Research about the report "The Data Revolution: How Intelligent Hardware Will Drive the $34 Billion Smart Grid," http://www.luxresearchinc.com. Accessed on February 1, 2011.

[22] Source: "Preparing Personnel" in Intelligent Utility. Vol. 2, Issue 5. September/October 2010, pp. 28 – 30.

As discussed in the previous section, the quantity of data that grid operators must cope with will increase exponentially by 2030. Ubiquitous high-speed computing and advances in mobile technologies (Unhelkar, 2010) will provide more power system experts secured remote access to real-time grid information such as the wind power forecast, and to the same dashboards and visual displays that are in the control room. This will lead to improvement in the ability to offer technical support to the dispatchers who are on-site. Analytical tools for dealing with uncertainty will create new data and information, thus requiring skills in statistics and data mining techniques to extract the relevant information. Combined, these developments will lead to a new information era in power systems operations and usher in a new breed of grid operators that can be physically or virtually in the control room, the so-called, “Terabyters equipped with über-geek data-capturing tools.”[23]

The findings presented and discussed in this report offer some clues about what utilities are doing or should be doing, in preparing a new workforce; a workforce able to operate power grids with significantly higher penetration of wind generation and other variable energy resources.

[23] See Thomas Frey, “Coming of the Terabyters: Lifelogging for a Living”, in *The Futurist*, January – February 2011, pp. 35-36. Terabyter is one of the emerging future jobs listed in the Special Report: 70 Jobs for 2030. See also Cynthia G. Wagner, “Emerging Careers and How to Keep Them”, Ibid. pp. 30 – 33.

3. SURVEY METHODOLOGY

Researchers set out to conduct a survey to explore issues related to increased wind integration from the viewpoint of utility grid operations' personnel in the control room. Factors that contributed to successfully meeting the project's objectives were: 1) the extent to which the utilities from around the world participated in the survey; and 2) the quality of the data and information respondents provided.

Three complementary methods were used in this research project: 1) A questionnaire to collect both qualitative and quantitative data; 2) On-site visits to utilities in order to interview control center staff and other personnel; and 3) Survey of existing literature. Each method is discussed in the following sections.

3.1 The Survey Questionnaire

The questionnaire was developed to identify the "best" practices, examples of excellence and lessons learned from integrating wind power in utility control room operational strategies, business processes and decision support tools.

Questionnaires are commonly used to for conducting surveys. When developing a questionnaire, it is important to carefully consider how the questions are formulated, the number of questions, the relevance of the survey question for the respondents and the psychology of the respondents at the time when the survey is conducted (Iarossi, 2006). The questionnaire for this survey required that particular attention be given to the different environments (geographical, regulatory, operational culture) in which the utilities operate. These differences also contributed to the other challenge of persuading utilities from around the world to complete the survey.

As the first step in developing this survey's questionnaire found in Appendix C, the project team developed a list of nearly 100 questions, topics and issues related to the survey's objective. The questions were then grouped under one of the following seven categories:

- *Organization*: Investigate the roles and responsibilities of the utility as it relates to wind integration.
- *Wind Forecasting*: Different kinds of wind forecasting products and how forecast errors impact grid operations.
- *Integration of Wind Forecast*: How wind power forecast information is integrated into decision support systems and tools in control centers.
- *Decision Support Systems and Tools*: Seeks to identify analytical software and other information systems deployed in control centers to support wind integration.
- *Processes and Procedures*: Explore grid operational processes and procedures, including key regulatory policies.
- *Wind Energy Information*: Identify operational data required for managing wind power variability and uncertainty, the source of wind integration information, and how information is disseminated to various stakeholders.
- *Training*: Address pertinent aspects of training dispatchers and engineers in the control room as it relates to wind integration including wind forecasting.

These categories of questions vex the subjects related to managing wind energy in power grid control centers and the integration of wind forecast information. Each category then formed the basis for grouping the various practices identified.

There were three kinds of questions: 1) multiple choice; 2) explanatory/descriptive; and 3) subjective and objective. The questions covered the collection of both qualitative and quantitative data. In order to cross validate and ascertain the global importance of certain topics, the categories were considered in more than one question but from different perspectives.

Forty questions made up the final questionnaire, and the Industry Advisory Committee (IAC) also reviewed each question before sending it to utilities. Five industry experts comprised the voluntary IAC established at the start of the project. The committee also provided diverse perspectives and unbiased assessment of the final questionnaire to ensure each question was relevant to the categories outlined above. They also shared their knowledge and insight about various aspects of wind integration with the investigators during the course of the project. In several cases, the IAC members introduced the investigator to the correct contact person at the utilities. Lastly, but very important, the IAC members reviewed initial versions of this final report.

3.1.1 Survey Key Metrics

Different metrics are used to evaluate and describe the quality and success of surveys. One of the most common metric is the number of respondents to the survey questionnaire or the number of respondents interviewed. In this report, the ratio of the total installed wind capacity in the power grids represented by the utilities in the survey to the total installed wind capacity in world defines the metric used to measure success. This metric is called the Survey Wind Penetration Index (SWPI). The reason for defining this metric is that, in general, utilities with more wind generation in their system should have gained substantial experience in managing the uncertainty and variability of wind power in their control centers, and in the use of wind power forecast. In other words, the higher the SWPI, the greater the chances are to identify practices that have been used to support wind integration. A high SWPI should increase the confidence of grid operators to evaluate and consider implementing the findings in this report. On the contrary, a high number of respondents but a low SWPI could affect the applicability of the study results. Therefore, a crucial task in this project was to develop a questionnaire with relevant questions that would persuade utilities around the world with high penetration levels of wind power capacity to devote time and resources to participate in the project.

3.1.2 Survey Sample

Between July 2010 and January 2011, the questionnaire was emailed to more than 60 utilities in Argentina, Australia, Brazil, Canada, Chile, China, Canada, India, Korea, Mexico, New Zealand, South Africa, the U.S., and in 20 countries in the European Union. The initial sampling represented transmission companies with wind plants connected to their power grids. To increase the chances that many utilities would respond, researchers also made initial introductory telephone calls to the targeted utilities. The questionnaire was sent to the utilities with a cover letter that highlighted the objectives of the project. See Appendix D. The project team conducted subsequent follow-up telephone interviews when it was deemed necessary.

3.2 Visit to Utility Control Centers

The second method used to collect information on how utilities are integrating wind power forecast in the control room was to conduct on-site visits at several utilities. The objectives of the visits were: to dive deeper into some of the survey questions through interviews with control center personnel and dispatchers; to see first-hand integration of wind power forecast in the EMS and other decision support tools and processes; and identify areas in which the utility has demonstrated excellence.

Three grid operators in the U.S. and three in Europe were selected based on criteria defined by the project objectives and approved by DOE.

More details about the visits, the criteria for selecting which utilities to visit and a summary and discussion of key findings are provided in this report. With the permission of the utilities, figures, sample computer graphics and other visuals from decision support systems in control rooms have been included herein.

3.3 Literature Survey

The third method used to identify best practices was to conduct a survey of existing literature about tools, processes and procedures that utilities around the world have deployed in support of wind integration. Based on the literature review, it is evident that not much is published about the successful practices of the effective incorporation of wind forecast with real-time power system operations. Most of the known results in the literature are from wind integration studies that focused on system planning, reserve calculations (Milligan, et al., October 2010), and economics of wind integration (Ahlstrom, Jones, Zavadil, & Grant, 2005). However, there are many published results on various aspects of wind forecasting techniques, e.g., improving forecast accuracy (Marquis, et al., 2011 accepted), (Ernst, et al., 2007), methods for computing different kinds of forecasting products such as ramp forecasting (Ferreira, Garma, Matias, Botterud, & and Wang, 2010) and short-term forecast (Giebel & Kariniotakis, 2007).

Researchers found no previous works that address the topics in this report and the objectives of this research project. Likewise, no previous work that provides the scope of both qualitative and quantitative results based on a global sampling of power grid operators was found. Several respondents provided internal documents describing some of the processes and tools for managing wind energy in their control rooms. Others provided evidence of effectively integrating wind forecast. Where permission has been granted, some of those materials are included in this report.

4. DEFINING BEST PRACTICES AND EXAMPLES OF EXCELLENCE

A “best practice,” as used throughout this report, refers to those practices that have demonstrably helped utilities successfully manage the integration of high penetration levels of wind power. Such practices include the effective use of wind forecast information in the decision support tools and systems, as well as in the processes and procedures used in control centers. In general, all the identified practices must also have one or several of the attributes described below that characterize a “best practice.”

4.1 Best Practices

The terms “best practices,” “lessons learned” and “promising practices” are used frequently in different industries. However, there is no universally accepted definition for what is a ”best practice.” These terms are typically used to describe specific techniques, methodologies or processes that have helped organizations achieve specific results and performance goals under specific circumstances. There are a few generally accepted attributes that characterize a “best practice.” The practices must:

- Be innovative and take advantage of technology.
- Have the potential to be replicated.
- Place the organization in a top ranking in the particular industry.
- Have been implemented.
- Be recognized by peers.

The notion of “best practices” is commonly based on the premise that lessons learned by one group can be transferred and replicated by other groups. In addition to lessons learned, another phrase that is related to best practice is the so-called “promising practices” or “emerging best practices.” These practices have only recently been implemented but have already shown some immediate benefits. In some cases, however, practitioners in management and business process reengineering have used what is referred to as an “example of excellence” to represent best practice.

4.2 Examples of Excellence

Examples of excellence in different aspects of wind integration are identified as those cases where the practices and tools deployed in the control room allowed the utility to achieve demonstrable and considerable success in managing operational challenges related with wind integration. Also, practices considered to be examples of excellence have received significant interest, attention and recognition from other utilities and throughout the industry.

4.3 The Case for Applying Best Practices and Examples of Excellence in Control Rooms

As stated above, it is not easy to formulate a generally accepted definition of “best practices” on a specific topic, even for a given industry. For example, the April 5, 2004 report, which the U.S.-Canada Power Outage Task Force issued following the August 14, 2003 blackout, suggested that the power industry establish best practices in certain areas. NERC was charged with identifying these best practices and established the Operating Committee Best Practices Task Force (OCBTF) and the Real-Time Tools Best Practice Task Force

(RTBPTF).[24] The OCBTF was tasked with defining the term "best practice" and identifying where or how these practices applied to the industry at large. No previous definition of this scope was ever provided. Instead of attempting to define best practice, the decision was made to focus on "examples of excellence." Subsequently, after the 2003 blackout, NERC identified and classified several practices and tools deployed by utilities across North America as being examples of excellence.[25] However, in another report on operating practices, procedures and tools related to wind integration (NERC IVGTF Task 2.4, 2011), NERC discusses best practices in tools for situational awareness and visualization that are deployed in the control rooms at several grid operators in the U.S. and Canada.

Power systems operational practices may vary due to different factors (e.g., network topology, generation mix, regulatory framework, etc.). However, the basic functional goal of all grid operators is the same: to ensure a safe and secure delivery of electricity to meet the demand at every moment in time. While many grid operators take pride in preserving their unique set of approaches and tools used to achieve this common goal, it is often the case, and yet also unknown, that grid operators will seek to learn from the successes and "examples of excellence," and from the mistakes of their counterpart utilities. Over time, they adapt processes and solutions that are known to have yielded positive results elsewhere.

4.4 Integrating Wind Generation by Sharing Best Practices and Examples of Excellence

Grid operators in the control room are generally risk adverse. This is understandable, given the nature of their job and the consequences of bad decisions. Grid operators often take conservative approaches in operating the power system. As wind generation is considered by many to be an energy source of unmanageable variability, uncertainty and unfamiliar operating patterns, grid operators' reactions about connecting wind farms to their system has been one of apprehension, caution, and in some cases, even institutional resistance for many years. This discretion is rooted in what psychoanalyst Robert Winer refers to as "the human intolerance for uncertainty" (Winer, 1994). Now, after decades of operating power systems with the certainty of generation availability to meet the variable load, grid operators and dispatchers find that they must cope with the uncertainty of wind and other variable energy resources.

The findings in this report indicate this attitude is changing, and grid operators around the world are successfully addressing many of the earlier concerns. Put plainly, wind power forecast integrated in the control room brings some degree of certainty.

To continue changing the cautious approach and misinformation about the impact of wind generation on the power grid, operators should share best practices, lessons learned and examples of excellence. In addition, operators should also share the promising practices of their peers who operate power grids that have higher penetration of wind generation in their system and have developed expertise in coping with operational challenges due to wind.

When utilities are faced with the decision of whether to change existing systems used in the control room, it is important for them to visit other utilities that have implemented similar solutions or made the same kinds of changes in operational procedures. The visits will help inform their decisions about the choice of technology and the implementation approach. However, it is not always possible to visit peer utilities. Similarly, lessons learned and best practices are not well documented in many cases.

[24] North American Electric Reliability Corporation. (March 2008). *Real-Time Tools Survey Analysis and Recommendations.* Princeton.
[25] See http://www.nerc.com.

The sampling of respondents to the questionnaire in this report is an indication that more utilities are interested in and open to applying industry best practices and examples of excellence.

5. ANALYSIS OF SURVEY QUESTIONNAIRE RESULTS

In this study, the questionnaire in Appendix C was used to collect data about how utilities in the U.S. and around the world are managing wind energy in control rooms, as well as how the utilities are integrating wind forecast information into existing tools, new tools and operational strategies. The survey results are important for understanding wind integration issues from the perspective of the control room; in particular, how the results relate to decision-making technologies, operational policies, procedures, processes, training and workforce. This chapter provides a detailed analysis of the results.

The results quantified and validated some of the generalized assumptions and assertions made about connecting large wind plants to the power grid, and about the use of wind forecast in power system operations. For example, because grid operators in the same region of a country can have different operating guidelines, it was useful to quantify what portion of the sample population who encountered similar challenges applied the same or different solutions. This kind of quantitative data is helpful in determining what the areas of focus regarding best practices and examples of excellence should be.

While the responses to some questions are very specific to a given system, others seem to be more applicable to any power system. Each response was analyzed carefully to determine if it could be generalized for most utilities. The responses are in the tables found in Appendix E. For cases where several similar responses were given for a particular question, only one response is included in the corresponding table.

5.1 Description of Respondents

More than 60 utilities received the survey questionnaire, and 34 completed and submitted their response. This resulted in a Survey Wind Penetration Index (SWPI) of 72%.[26] As previously mentioned, the combined total installed wind power capacity covered in the study was more than 140 GW. The list of respondents and data about each power system can be found in Appendix B.[27]

Each respondent was self-identified as being one or several of the following types of organizations based on their operational and functional responsibilities defined by NERC and/or FERC in the U.S., or similar regulatory entities in Canada, Europe and other countries. The types included: Balancing Authority (BA), Regional Coordinator (RC) without BA responsibility, TSOs mainly in Europe, Independent System Operator (ISO) / Regional Transmission Organization (RTO), Wind Plant Owner, Wind Plant Operator, Generation Owner, and Generation Operator. The utilities in the survey operate in jurisdictions with either regulated or deregulated electricity markets.

Several utilities with wind plants connected to their transmission network received the survey, but did not respond because they are part of an RTO/ISO and therefore, perform no dispatching nor balancing functions.

5.1.1 U.S. RTOs/ISOs and Balancing Authorities

By the end of 2010, the majority of installed wind capacity in the U.S. was in regions with organized wholesale electricity markets administered by RTOs and ISOs. Six out of the seven RTOs/ISOs in the U.S., who account for nearly 60% of the total installed wind capacity in the country, responded to the questionnaire.

[26] SWPI is defined in Chapter 3.1.1.
[27] Data shown was collected from the respondents for period ending December 31, 2010.

Figure 15 shows the list of grid operators in the U.S. who responded to the survey. They account for nearly 80% of the total in installed capacity in the country.

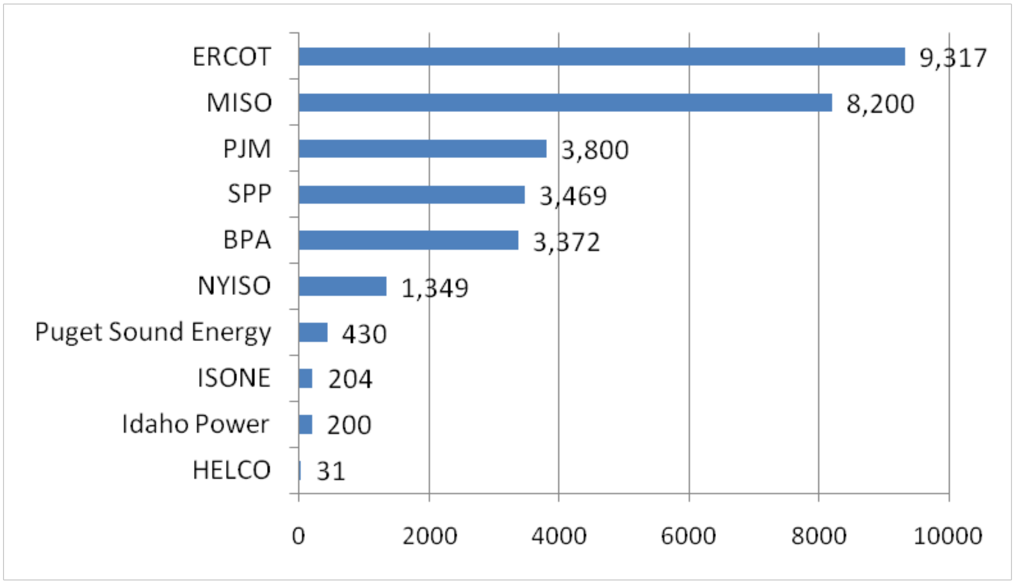

Figure 15. Installed Wind Capacity (MW) in Power Systems of U.S. Respondents to the Survey

5.1.2 European TSOs

Twelve European TSOs, who participated in the survey and are listed in Figure 16, are all part of the European Network of Transmission System Operators for Electricity (ENTSOE).[28]

Another respondent to the survey was the organization responsible for the Coordination of Electricity System Operators (CORESO),[29] which monitors the transmission grids of the four TSOs in Germany. Three are directly represented in the survey and one is represented indirectly via CORESO. This adds an additional 10,978 MW to the net total German installed wind power capacity that is covered in the survey, which makes the total European wind installed capacity accounted for in the survey 66,859 MW.

[28] See www.entsoe.eu.

[29] CORESO launched its operations in February 2009. Its shareholders are the following TSOs: 50Hertz (Germany), ELIA (Belgium), National Grid (England), and RTE (France). CORESO does not own nor operate any transmission system. Instead it performs 24/7 current day and day-ahead coordination services such as system monitoring and grid security coordination studies for five European TSOs. It also provides additional wide-area situation awareness and makes recommendations about corrective actions to mitigate potential reliability problems. Specifically for wind, CORESO has developed and implemented tools and procedures which have enabled a better understanding of the operational impacts of the wind power on the grids they monitor. More information is available at www.coreso.eu.

5.1.3 ISOs/TSOs in Other Countries

According to Figure 9 in Chapter 1, China and India were ranked 1st and 5th in the world respectively in terms of the total installed wind power capacity by the end of 2010. Utilities in both countries participated in the survey. The State Grid Corporation of China (SGCC), who, based on its survey response, had 28,260 MW of installed capacity, represented China. The Power System Operating Company (POSOCO) with 13,065 MW represented India.

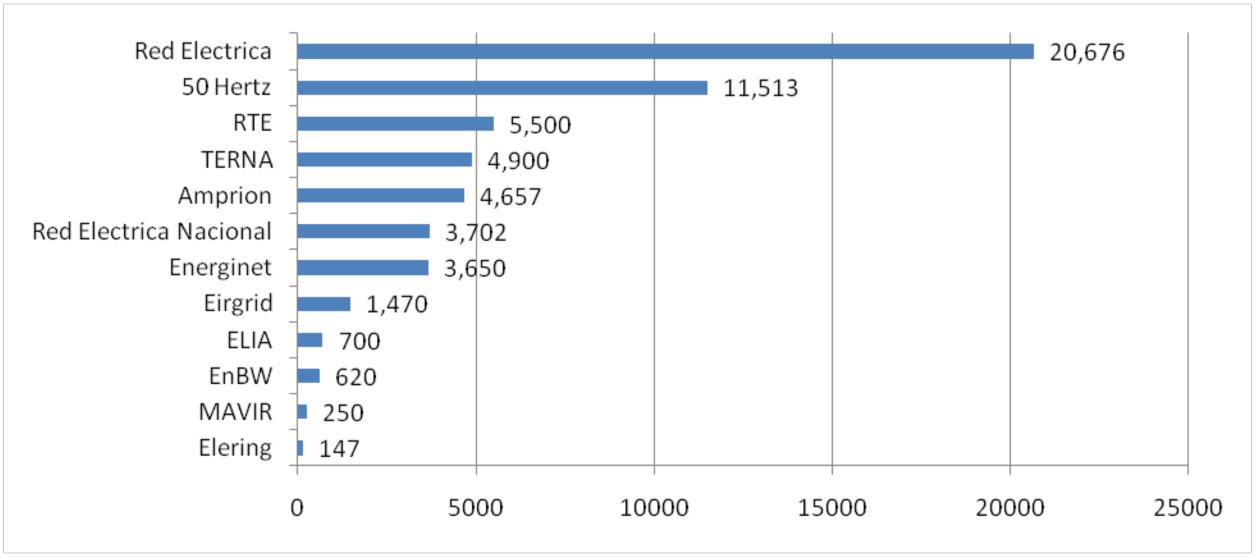

Figure 16. Installed Wind Capacity (MW) in Power Systems of European TSO Respondents to Survey

Nine power grid operators from five other countries (Australia, Canada, Korea, New Zealand and South Africa) participated in the survey. Because the installed capacity for each operator is small in comparison to SGCC and POSOCO, the data is plotted separately. The ISO/TSO from these five countries and their corresponding installed wind power capacity are shown in Figure 17. Four operators (AESO, Hydro Quebec, Manitoba Hydro and NBSO) are based in Canada and two others (AEMO and Transend Networks) are in Australia.

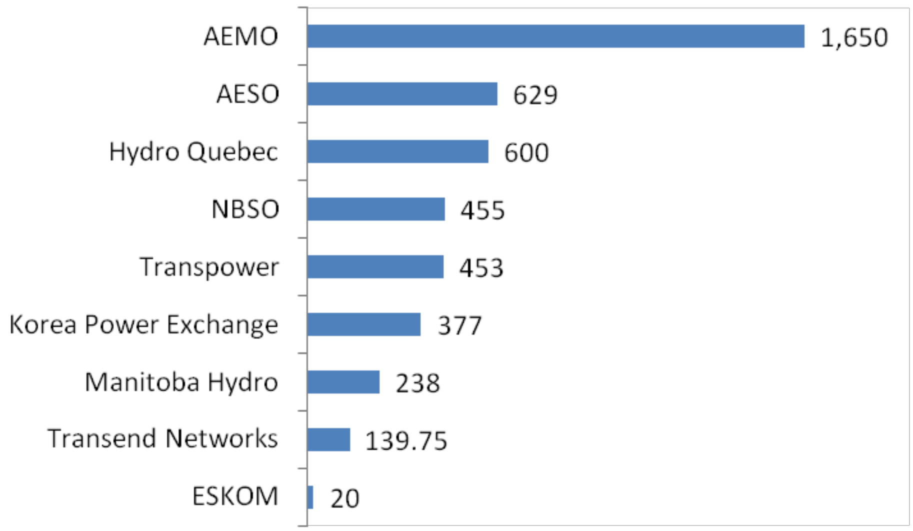

Figure 17. Installed Wind Capacity (MW) in Power Systems of Respondents in Australia, Canada, Korea, New Zealand and South Africa

5.2 Wind Penetration Level

The challenges and issues associated with integrating wind generation are closely related to the wind power penetration level in a given system. Penetration levels are often used to identify potential relationships or general rules of thumb for making approximate assessments about different aspects of wind integration. One example is the attempt to find a rudimentary way to estimate levels of additional reserves needed in a given system for a certain penetration level. However, application of such generalizations must be done carefully, given that there are myriad factors which determine system reserves. Notwithstanding, in analysis of the survey results, any common patterns between penetration levels and other wind integration topics identified will be noted. For example, it would be instructive to see if operators of systems with high wind penetration use wind forecast in more advanced ways, compared to those with lower levels.

Wind energy penetration level can be defined in several different ways. In this report, two definitions of penetration level are used. The first penetration level commonly used is referred to as Wind Power Capacity Level (WPCPL).[30] It is defined as the ratio of the total installed wind power capacity to the peak demand over a given period. The WPCPL for the systems in the study are shown below in Figure 18.[31] By using the WPCPL, one U.S. power system is in the top five. Among the next five, two are from the U.S. and Europe respectively, and one in Canada.

In Figure 19, the Wind Generation Penetration Level (WGPL) is shown as another measure of wind penetration for each system. WGPL is defined as the ratio in percent of the total installed wind power capacity to the total generation installed in the system. With this penetration level, the top five systems are based in Europe. Among the next five, three are from the U.S., one is from India and one is from Canada.

[30] Wind Energy Facts available at http://www.wind-energy-the-facts.org/en/part-2-grid-integration/chapter-1-setting-the-scene/. Accessed on May 31, 2011.
[31] The data used to compute the penetration levels shown in Figure 18 and Figure 19 can be found in Appendix B.

Figure 18 and Figure 19 also show that the survey respondents represent systems ranging from the highest wind penetration levels in the world to those with the lowest. This diverse sampling of system operators in this study offered a unique opportunity to capture and explore a broad set of perspectives and experiences, as well as some common themes on wind integration.

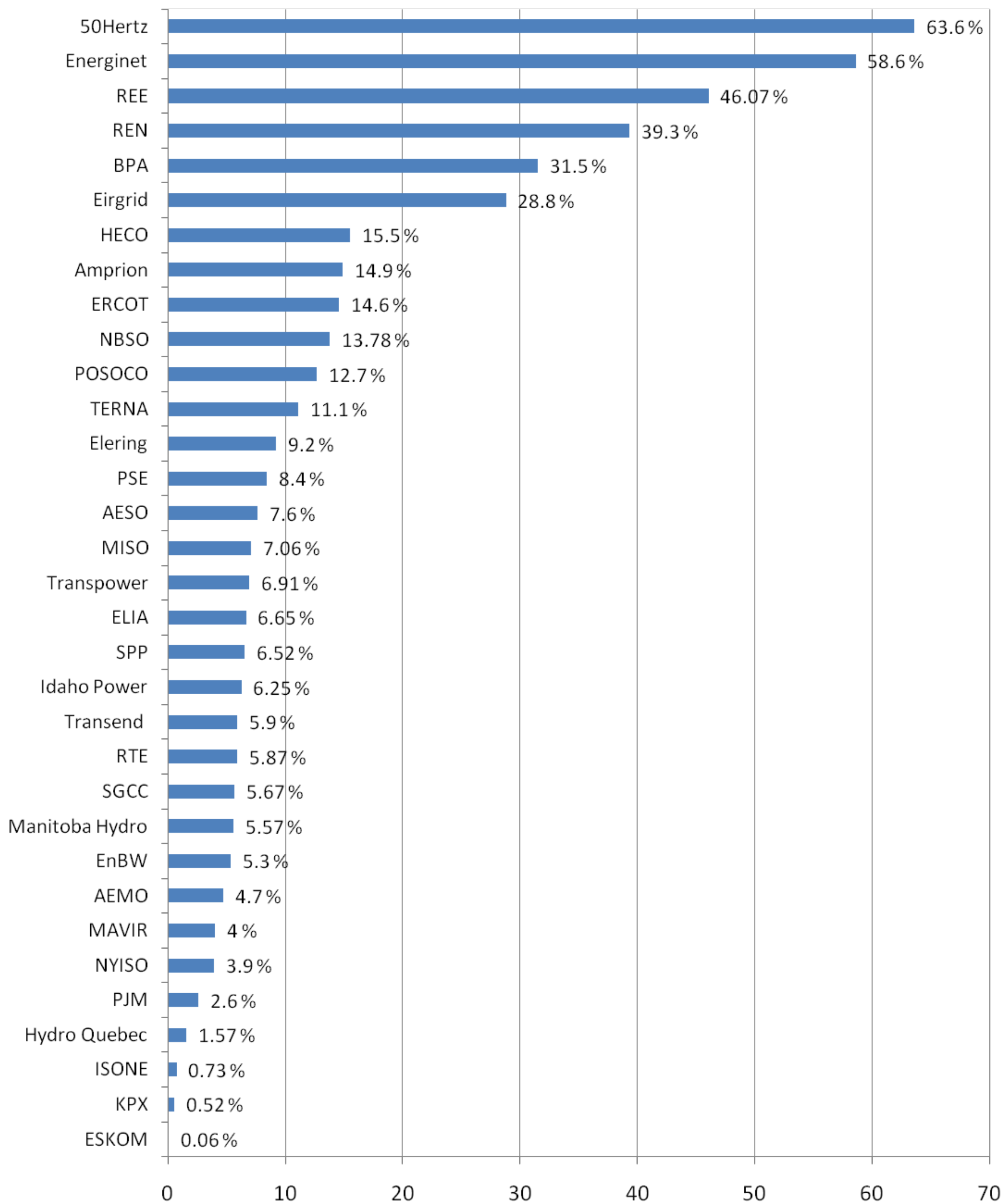

Figure 18. Wind Power Capacity Penetration Level (%)

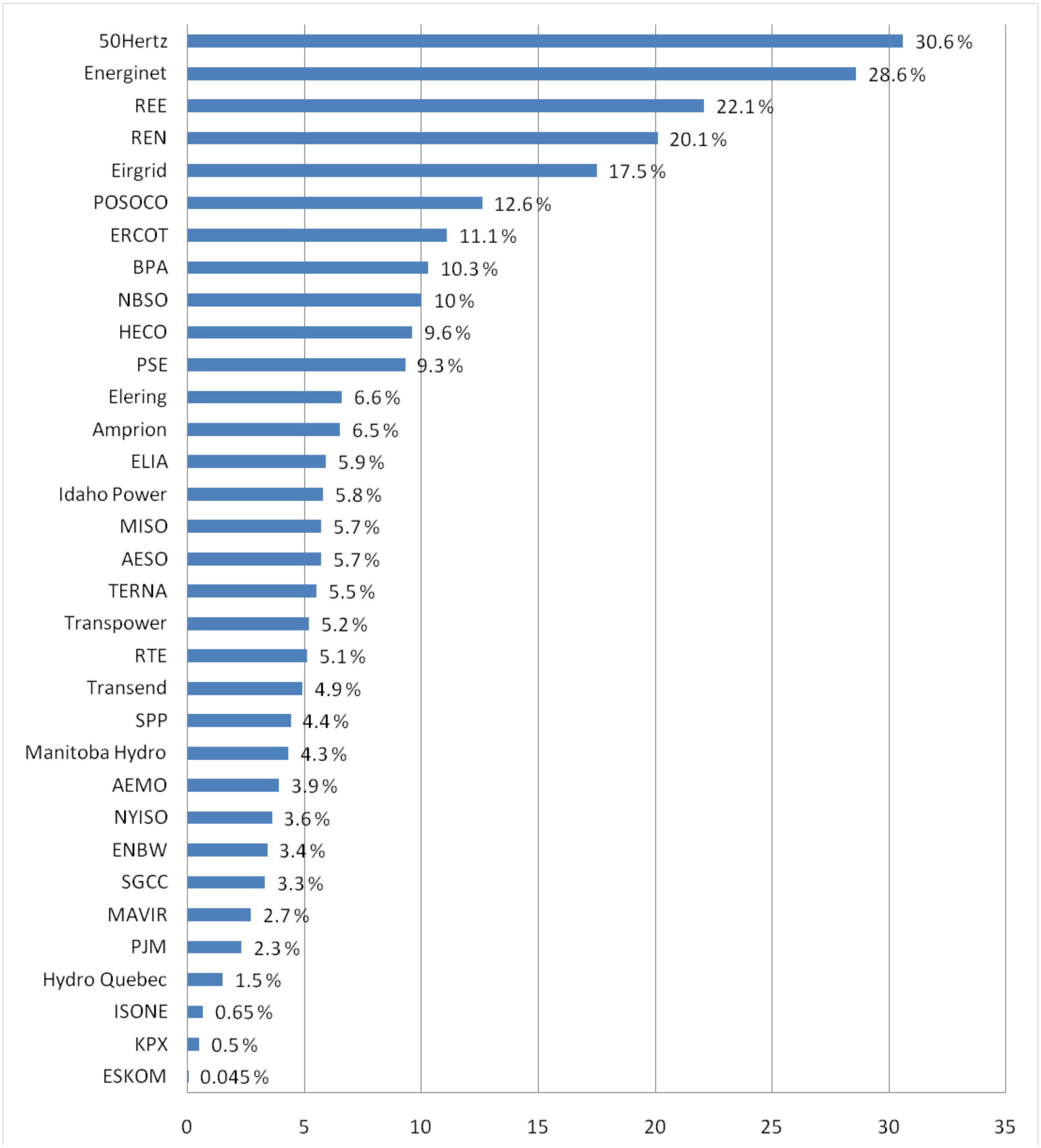

Figure 19. Wind Generation Penetration Level (%)

5.3 Operational Time Scales and Wind Variability

Power system operation is characterized by different phenomena that occur within varying time frames, determined by the physics of the grid and the recursive interaction of myriad interconnected equipment, components and devices. The phenomena are controlled and managed using different automated processes that can be time-, event- or human-triggered. The time frames of the phenomena range from seconds to minutes, hours and days.

In power systems, both supply and demand are constantly changing. The system behavior also varies due to equipment outages and errors in scheduling, commitment, dispatching and other processes. As shown in Figure 20, power grid operations depend on the availability and response time of generation resources deployed to meet changing systems conditions.[32] Operators' decisions are subject to uncertainties, which are considered to exist within an "operational cone" of possible scenarios that can have different impacts on the system. The shape and size of the uncertainty cone is constantly changing depending on the types of resources and the operating conditions. Operators are always working to develop a good understanding of the cone of uncertainty with the tools they have at their disposal. Higher penetration of wind energy affects the nature of the uncertainty cone around which the grid must be operated, therefore introducing new operational challenges for operators and dispatchers along the time spectrum.

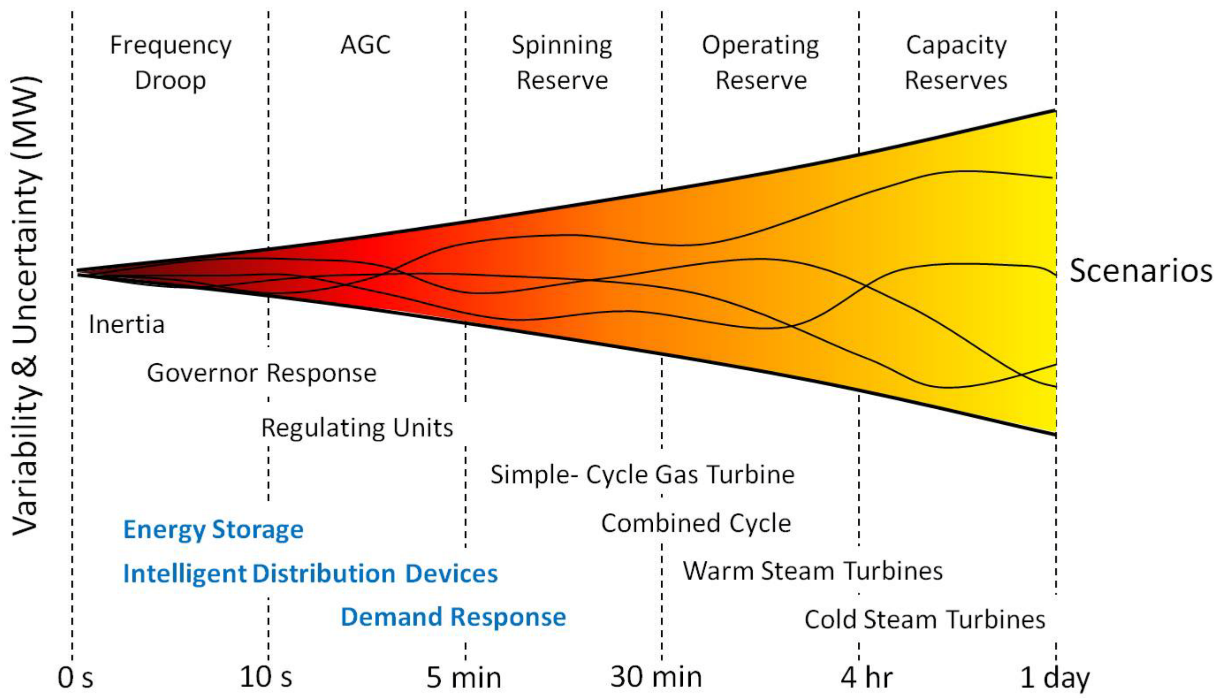

Figure 20. Response Times of Generation Resources (Source: Russ Philbrick)

Variability of wind power occurs within time frames that are typical for certain power grid operational phenomena, automated processes, and for some conventional generation. Therefore, the first step in identifying best practices is to understand what the respondents say about critical time frames. Within these critical time frames, wind variability and uncertainty have the most significant impact on operation grids and on the decision support tools and processes in the control room. Examples of processes and tools that time frames affect include: scheduling of generation and transmission capacity; allocation of different types and levels of generation for reserves; unit commitment and load following; and the real-time dispatch of resources that keep the system balanced.

According to Figure 21, 30% of respondents indicated that wind variability has the most impact on their current system operations in the 10 minutes to 1 hour time frame, compared to 33% who indicated the 1 day time frame as the most affected. These findings support information reported in previous studies. While the

[32] "Wind Integration and the Need for Advanced Decision Support Tools," C. R. Philbrick, accepted paper, IEEE 2011 PES General Meeting, Detroit, MI, July 2011.

results here are based on the opinion of operators, the previously mentioned studies such as EWITS and WWSIS provide excellent quantitative analysis of the impact of wind variability in different time frames.

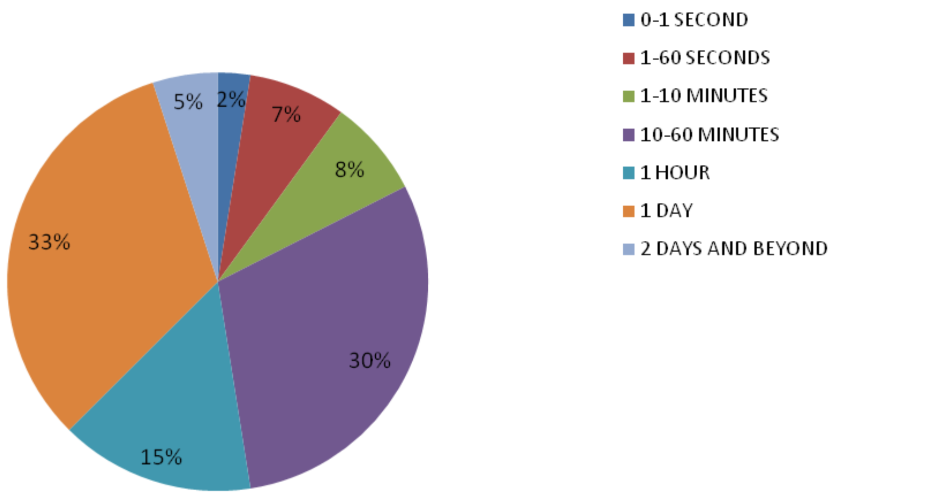

Figure 21. Time Frames that Wind Power has Most Significant Impact on Current Operations

All the respondents expect the amount of wind generation on their system to increase in the coming years. Figure 22 shows the results for the same question but in terms of the expected future impact. While the percentages have changed slightly, the respondents still expect the most significant time frames in terms of wind variability and uncertainty to remain 10 minutes to 1 hour, 1 hour and 1 day (day-ahead forecast). More respondents expect the intra-hourly time frame to be most significant in the future with higher wind penetration levels.

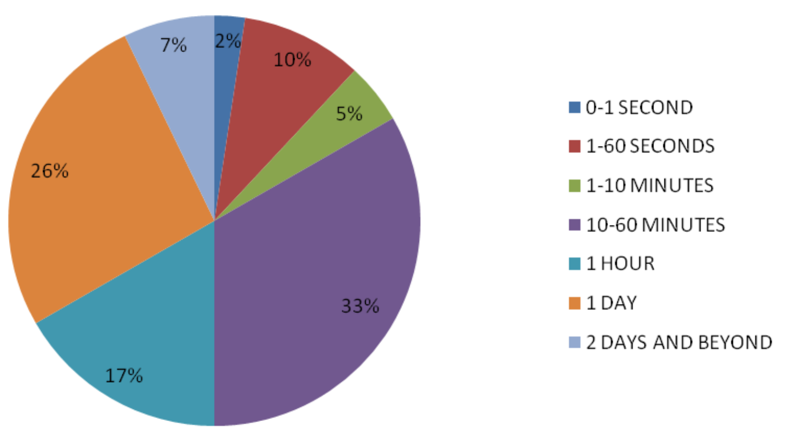

Figure 22. Time Frames that Wind Power has Most Significant Impact on Future Operations

Several respondents who have already implemented various processes such as the 5-minute dispatch of resources in systems where electricity markets are in operations, also ranked the aforementioned time frames with the highest percentages as shown in Figure 21 and Figure 22. Those time frames ranked the same as the time frames where wind variability has the most significant impacts for current and future grid and market operations. However, as discussed later in this report, the impact of intra-hourly variability of wind is expected to become less of an issue when more frequent dispatching (5-minute intervals) is allowed.

5.4 Impacts of Wind Generation on Grid Operations

Maintaining power system reliability in the presence of load and other conventional sources of uncertainty is a fundamental task of grid operators and dispatchers. More precisely, the task involves making real-time decisions under uncertain conditions so that the power generated matches electricity demand instantaneously. Generally, this can become more challenging with increased uncertainty due to wind power. For example, in many systems, the net load (i.e., load minus wind) is shown to experience increased variability and uncertainty.

Higher levels of wind generation have shown to create uncommon system conditions and consequences that operators must learn to manage. A central undertaking in this study was identifying the best practices related to those aspects of maintaining reliability, which will become most difficult as wind power is connected to the grid. Table 3 in Appendix E lists several aspects according to the respondents. Here is a summary of the main ones:

- Procuring the flexible resources necessary to cope with increased system variability.
- Managing congestion.
- Forecasting to cope with ramp events.
- Efficient electricity markets.
- Determining adequate operating reserves and transmission capacity.
- Unit commitment and economic dispatch that takes into account the transmission network.
- Managing new operational constraints, e.g., inertia, fault currents, unusual power flow limit.
- Controlling system voltages.
- Maintaining dynamic performance – Transient and Small signal stability (voltage, frequency and rotor angle).

The ability of the grid operators to deal with problems surrounding each aspect is a function of experience with wind integration and the kinds of tools and processes that have been implemented in control rooms.

5.5 System Flexibility and Wind Integration

Flexibility is an intrinsic characteristic of power systems. It refers to the availability of fast responding resources that can be called upon in a timely manner to help maintain the balance of supply and demand. Over decades, grid operators have acquired tremendous experience in controlling flexible resources in response to variation in demand. Increasing penetration of wind generation leads to more variability in the net load and thus, the need for solutions that provide additional flexibility as the grid grows.

Sources of flexibility typically include:

- Adequate transmission capacity, both internally and externally with neighboring systems.
- Dispatchable loads.
- Existing flexible generation (e.g., gas turbines).

- Flexible AC Transmission Systems (FACTS).
- Energy storage (e.g., pumped hydro storage).

Examples of operational measures, which can also be used to gain more flexibility in the system, include:

- Better forecasting.
- Larger balancing areas.
- Efficient ancillary services markets.
- Faster electricity market operations.
- Wind curtailment.

Efficient integration of wind energy requires that the grid operator has access to the proper mix of flexible resources ranging from the supply-side, delivery-side and the demand-side. According to Figure 38, several of the changes in operational processes, which respondents rank as having high value for wind integration, are related to measures that are known to provide flexibility to power systems. Answers to several survey questions in the tables in Appendix E either mention the issue of flexibility explicitly or the stated sources of flexibility. Grid operators interviewed also stressed the need for more flexible resources to cope with wind-induced variability on the system.

While many respondents emphasized the need for more flexible resources, the more difficult task is how to accurately determine system flexibility. The amount and type of flexible resources that are needed will depend on the different behavior of wind generation and the system as a whole. An excellent and detailed overview of the flexibility needed to balance power systems with wind and other variable generation can be found in (IEA, 2011). That report also proposes a methodology known as Flexibility Assessment (FAST) to determine system flexibility.[33]

5.5.1 Net Load and System Flexibility

Understanding the system net load (load/demand minus wind), is crucial to managing successful wind integration. The net load affects the degree of flexibility needed. Based on discussions with respondents who operate systems located within different natural geographies and weather regimes, wind-load relationship can either be correlated or inversely correlated, depending on the time of the day. Inverse correlation is when the demand rises in the morning while the wind tends to drop sharply. In the evening, the load falls while the wind is picking up. An example of wind-load relationship is shown in Figure 23. This graph illustrates that the wind-load relationship can be correlated during certain periods for a given day, and inversely correlated during other times.

[33] FAST was developed as part of the project, Grid Integration of Variable Renewables (GIVAR), conducted by the IEA to examine how to balance power systems with high penetration levels of renewable energy.

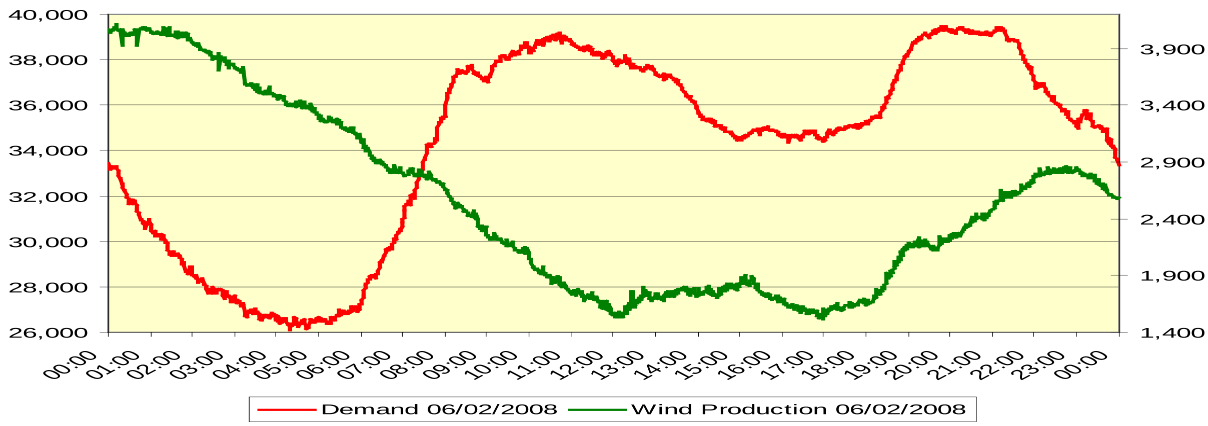

Figure 23. Example of Wind-Load Relationship in the Spanish System (Source: REE)

Several grid operators expressed the need for real-time monitoring of the system net load in the control room. It is important that dispatchers, power system engineers and market operators begin to use net load as an important variable when making decisions. The variability in net load is a key factor, which will determine flexibility requirements, when performing an operational impacts assessment.

5.6 Reserve Requirements

A subject of key concern for grid operators is the need for additional operating reserves required for integrating wind. Reserves are typically characterized based on: 1) the direction of the response provided by the resource; 2) the event which initiated the response; and 3) the timescale. Literature is replete with studies that provide results about the impact of increased wind penetration on the reserve requirements for a given power system. Numerous research projects have been conducted on the impact of wind on grid operations.[34] Figure 24 shows how respondents to the survey say increased penetration of wind power has affected the reserve requirements on their system.

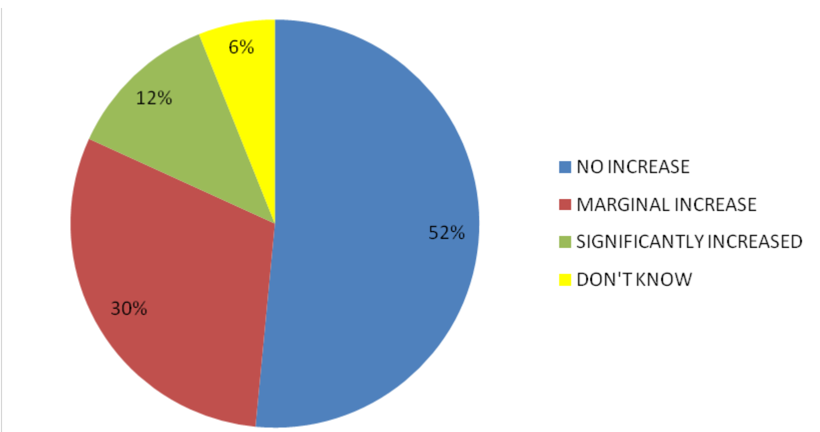

Figure 24. Impact of Wind Penetration on Reserve Requirements

[34] The IEA Wind Task Report "Reserve Requirements for Wind" by H. Holttinen et al. provides an excellent treatise of the subject of wind power impacts on system reserves.

Only 12% of respondents reported a significant increase in their reserve requirements due to wind and 30% said it increased marginally. The majority of the 42% of utilities that saw an increase had relatively high wind penetration levels in comparison to the 52% who saw no increase in the need for additional reserves. Several respondents indicated that the flexibility of their system was another reason why their reserve requirements had not changed markedly.

A closer analysis of the findings also shows that grids that are more tightly interconnected, part of RTOs or in a large BA experienced less of an impact on their reserve requirements, compared to grids on island systems. Grids with limited connection to other grids therefore lacked the ability to participate in reserve sharing with neighboring systems and were also impacted more.

Question 3 in the survey asked respondents, “What are the reserve requirements on your system with and without wind for each of the following reserve categories?” The categories of reserves most affected were reserves for load following, regulation, contingency, frequency and ramping reserve. While it is important to understand the operators’ perspective on the reserve requirements, quantifying the needs for different types of reserve must be conducted as part of detailed wind integration studies. There have been many studies and approaches for calculating operating reserves of power systems with wind (Milligan, et al., October 2010). However, there is no current, generalized framework or rule of thumb for quantifying the amount of reserves that are required for a given level of wind generation capacity. Most of the common approaches are based on deterministic analytical solutions, although interest in using probabilistic techniques is growing.

Many respondents expect that the need to calculate and monitor operating reserves will be exacerbated with higher penetration of wind generation in the system, as the net load variability increases in different time frames. In Appendix A, examples of tools for monitoring system reserves at several of the utilities visited are presented.

5.7 Wind Power Forecasting

In the context of power system operations, the term “wind forecast” generally refers to the predicted wind power output from the wind plant at that location. Some people prefer the term “wind power forecast,” rather than “wind forecast,” since it really is the forecasted power schedule that matters. In this report, we use the terms interchangeably.

An overwhelming majority of respondents identified wind power forecast as an important prerequisite for integrating wind energy. Predictability of wind plant output is the key to managing uncertainty. This section discusses some of the key findings related to wind forecasting and how the forecast information is being integrated and used in several utility control rooms around the world.

Wind forecasting has improved significantly over the past two decades. There are now many providers of wind forecasting systems and services. As wind energy becomes a greater part of the supply mix in power systems worldwide, many commercial forecasting vendors are taking competitive positions. In the past, the activities of most wind forecast vendors were focused within a given geography. Today, as a result of improvements in meteorological tools, information, monitoring and communications technologies, there are wind forecasting companies operating in multiple countries and on several continents.

A paramount concern for a grid operator, which is also the challenge for forecast providers, is the accuracy of the wind forecast. An error affects the level of confidence the operators place in the data and whether it may be integrated and used in the control room. Generally, operators are more confident about the data when the forecasting error is small. According to Figure 25, 94% of the respondents indicated that integration of a significant amount of wind power will ultimately depend on the accuracy of the wind forecast.

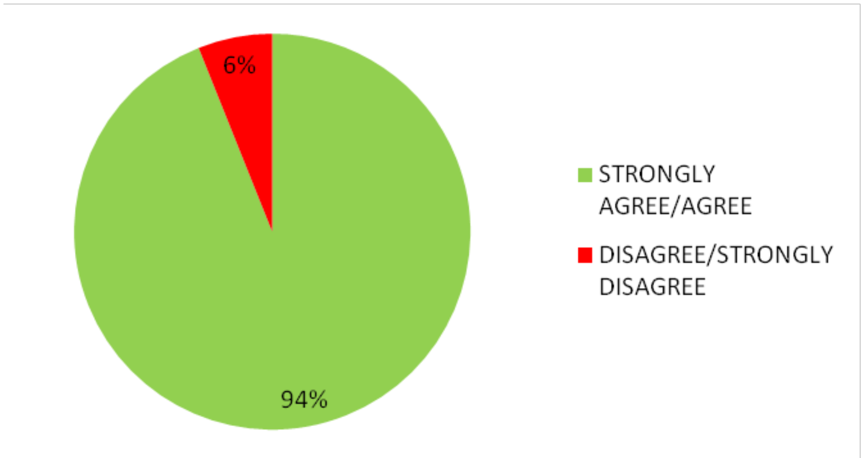

Figure 25. Integrating Significant Amount of Wind will largely depend on the Accuracy of Wind Power Forecast

Improving the accuracy of wind forecast remains a key area of research and development for the wind forecasting community, and for the grid operators who use the data.

5.7.1 Centralized Wind Power Forecasting

Centralized wind forecasting refers to the situation in which a single system provides the wind power forecast for all the wind generators connected to a power system. The centralized forecasting system, which can be maintained by the grid operator or outsourced, typically receives its input data from one or several commercial forecast providers. In the case that it comes from multiple providers, the single system combines the different forecasts and forms a single ensemble forecast. In contrast, for a decentralized forecasting approach, all wind plants connected to the grid must independently submit the wind power forecast to the grid operators.

Today, there is broad agreement across the industry that, in order to effectively integrate wind energy in power system operations, centralized forecasting is the best approach. More and more, grid operators around the world are acquiring centralized wind forecasting system and services. Ninety percent of respondents in this study have implemented some type of centralized wind forecasting system or are in the process of putting one in place. A few grid operators still rely on decentralized wind power forecasting, but even in those cases, a transition to the centralized approach seems inevitable.

A comparison of centralized wind power forecasting programs in North America by RTOs and electric utilities is provided in (Porter & Rogers, April 2010). Several of the grid operators listed in that comparative study are also respondents in this report. For each organization, that report presents information such as when the wind power forecast went into operation; the forecast vendor; wind forecast tools and techniques; applications that use the wind forecast; data that is required from the wind turbine and wind project; if a ramp forecast is provided; forecast performance metrics; and how wind power forecast is performed. Since that publication, more utilities have deployed or are investigating a central forecasting system. Therefore, in order to capture the state-of-art and most updated centralized forecasting programs in North America, it is recommended that a new comparison study be conducted.

In Europe, many TSOs incorporate the wind power forecast from several commercial forecast vendors into their centralized forecast system. A few utilities have also developed their own wind power forecasting system. Two examples of systems developed by TSOs are SIPREOLICA, developed by Red Eléctrica de España in Spain, and PREOLE, developed by RTE in France. Using a forecast from multiple providers is a good way of ensuring that the centralized forecasting system's performance is constantly improving through the selection of a forecast with the best accuracy at any given point in time.

Using multiple providers promotes competition and compels forecast providers to continue investing in R&D to improve the quality of the forecast they supply to the grid operator. In spite of this advantage of getting forecast from several providers, all the North American grid operators in this study used only one forecast vendor. A Canadian grid operator who chose three different vendors as part of its wind forecasting pilot project was one exception. Several U.S. utilities interviewed in this project stated that, based on the experience of their European counterparts, they are evaluating the need to use multiple vendors as part of their wind power forecasting program.

5.7.2 Data for Centralized Forecasting

A key element for central forecasting is the data used by the forecasting system. The type, quantity and periodicity of data required of wind plants for forecasting is a pivotal issue to consider. Generally, the wind turbine data and the wind project data are the two sets of required data. However, no standardized set of data that must be provided exists today. Each grid has specific data requirements, either as part of its grid codes or in separate data guidelines. While some grid operators require large amounts of wind speed and direction data, it is not clear if such data requirements are absolutely necessary or the most cost effective. Germany, Denmark and Spain all have very good centralized forecasts without a requirement for massive amounts of data. However, there are conflicting views about data requirements. In any case, it is good practice for grid operators, owners of wind generators and other stakeholders to work together to resolve data issues. The requirements should be re-examined at least once a year to determine the most critical data necessary to maintain a high performance and good forecast. The issue of data requirements is also a concern for regulators and policymakers in several countries around the world.[35]

5.8 Wind Power Forecast and Grid Operations

Wind power forecasting systems apply various analytical methods to data taken from weather forecast models. It then combines this information with knowledge of how the wind plant behaves under similar weather situations. Once complete, the system creates a power forecast for the wind plant for various time frames and/or under particular operating conditions. According to an Integration of Variable Generation Task Force report by NERC, several kinds of wind power forecasting products are important for integrating wind

[35] In November 2010, the US Federal Energy Regulatory Commission issued a Notice of Proposed Rulemaking (NOPR), Docket No. RM10-11-000 on Integration of Variable Energy Resources. In that NOPR, FERC, among other topics, asked for comments regarding requirements for the meteorological and operational data that should provided by the operators of Variable Energy Resources (VERs), i.e. wind generators, "…to public utility transmission providers to facilitate public utility providers' development and deployment of VERs power production forecasting tools."

generation.[36] Varying kinds of forecasting products have also been proposed (European Wind Energy Association, November 2010). Grid operators use the following list of forecasting products:

- Day-ahead (DA) forecast.
- Wind-plant high-resolution forecast.
- Weather situational awareness forecast.
- Short-term forecast (e.g., 10 min.).
- Ramp risk forecast.
- 6 hour forecast.
- Nodal injection forecast.
- Ramp forecasting.
- Next-hour forecast.
- Probabilistic forecast.
- Ensemble forecast (use of multiple wind forecasts).

It should be noted that some of these "products" are not always clearly defined and there may be an overlap in the interpretation in their exact meaning. For example, some vendors may provide a unified forecast product that serves multiple needs, while others may argue that they require separate products.

For many years, DA forecast was the focus of much attention. Significant improvements have been made to reduce DA forecasting errors. However, as grid operators and researchers learn more about wind variability and the operational impacts of wind in different timescales, there are efforts underway to continuously improve the accuracy and use of other forecasting products.

In Figure 26, how respondents rank different forecasting products in control room real-time operations is shown. A brief explanation of each forecast product can be found in Appendix F. The three most-ranked products are next-hour forecast, ramp forecasting and ensemble forecasting.

The majority of respondents ranked the importance of next-hour forecast as HIGH due to the fact that many grid operators use processes in the control room that require 1-hour prediction. Therefore, they have a natural affinity to look ahead one hour. The need for short-term forecast (5-10 minutes) will gain more importance as a result of increased penetration of wind generation.

An ensemble forecast, which combines multiple wind power forecasts from several third party forecasting providers, has shown to offer better operational forecast compared with what a single forecasting provider supplies. More European TSOs currently use ensemble forecasting, compared to their counterparts in the U.S. who use a single forecast provider. Proponents of incorporating multiple providers argue that, in addition to improving forecast, it also encourages competition among forecasting vendors, which drives innovation. As discussed in Section 5.7.1, several U.S. grid operators are considering the use of multiple forecasting services.

[36] NERC Variable Generation Power Forecasting for Operation Report can be found at www.nerc.com/filez/ivgtf_Operation.html.

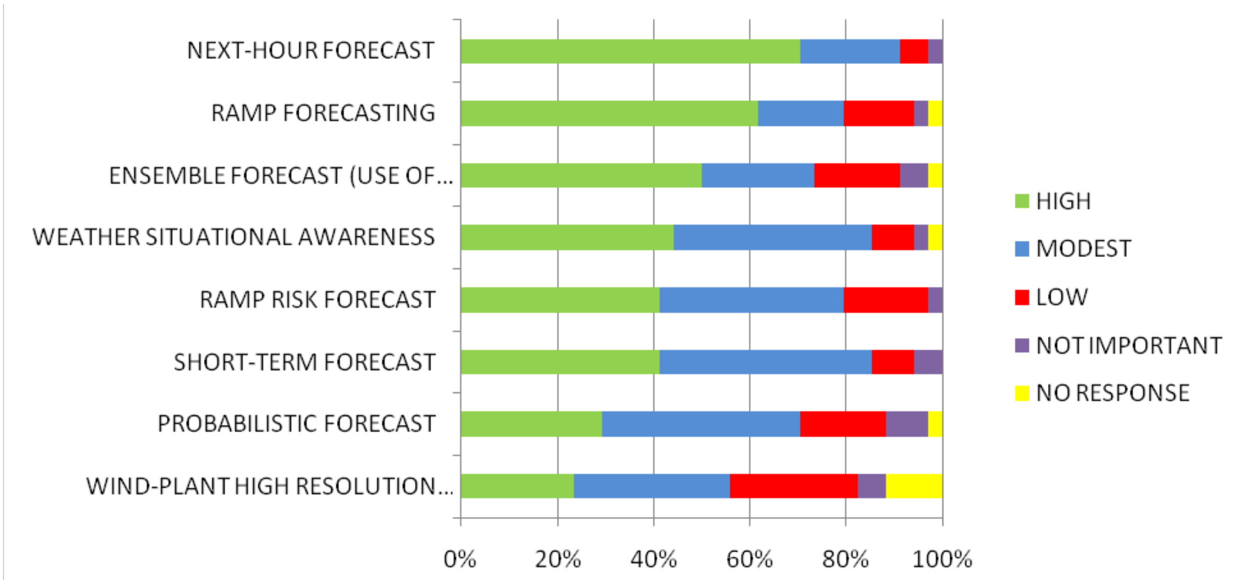

Figure 26. Importance of Wind Forecasting Products in Control Room Operations

5.8.1 Wind Ramp Events Forecasting

Sudden and large increases or decreases in wind power output typically characterize wind ramp events. Large up and down wind ramps are rare. These extreme events often have characteristics akin to events referred to as “black swans.”[37] However, unlike “black swans,” which are highly improbable and unpredictable events, wind ramps can be predicted with varying degrees of accuracy. This is also the case for other kinds of extreme events if the data that was available were analyzed using appropriate tools (Posner, 2010). The more accurately “black swans” such as extreme wind ramp events can be predicted, the more efficient grid operators will be in integrating large-scale wind energy in power systems. Figure 27 depicts an illustration of an actual ramp event that took place in Germany on January 27, 2010. Other examples of actual ramp events are illustrated in Appendix A.

[37] Nassim Nicholas Taleb, in his book *Black Swans: The Impact of the Highly Improbable* (Taleb, 2010), defined a Black Swan as an event with three characteristics: 1) it has never occurred before; 2) it would have an extreme impact if it did occur; and 3) it is easy to predict only after the fact.

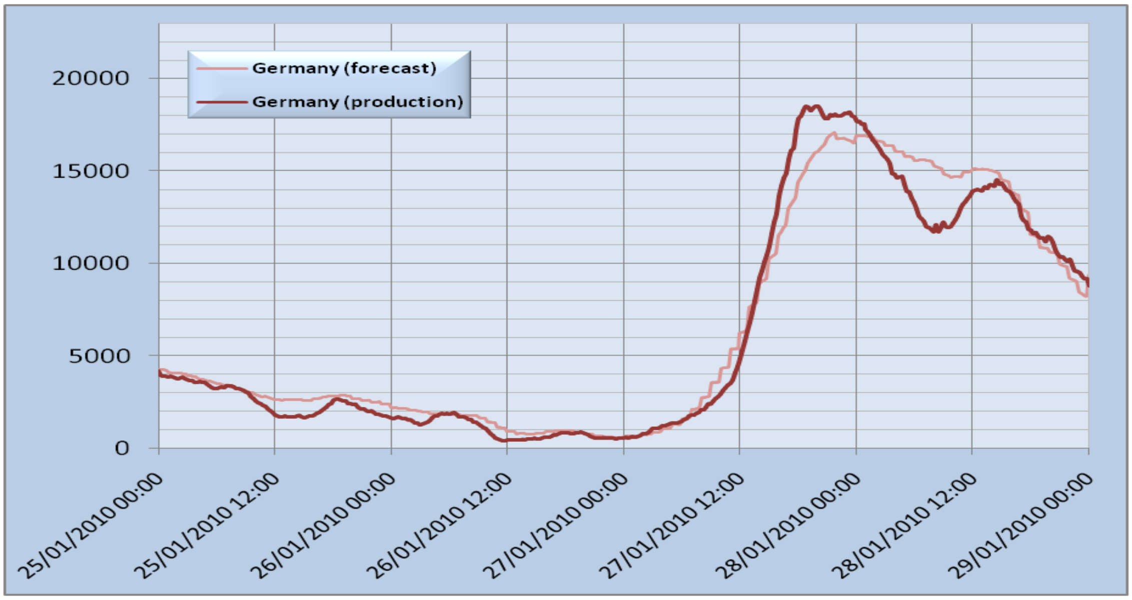

Figure 27. Example of a Wind Ramp in Germany on January 27, 2010 (Source: CORESO)[38]

The findings in the study reiterate and provide additional broad evidence of the concern among electricity grid and market operators regarding the rapid change in power production from wind plants. While ramp forecast is ranked as highly important for control room operations, not all forecasting systems provide a separate ramp forecast or ramp risk forecast. However, systems do provide information about the likelihood and characteristics of ramp events for a given forecast period. It is not clear on how this information should be presented to the grid operator and dispatchers though.

Unlike common forecasting problems in power system operations, predicting ramp events is not trivial. These forecasts only recently started to gain grid operators' attention as large quantities of wind power were added to the generation mix. Wind ramps are the result of different weather events. The ability to forecast ramp events depends on the meteorological phenomena causing the ramp (Grant, et al., 2009). Some of these phenomena are easier to predict, while others are more complex. Another ramp forecasting challenge is the lack of a commonly accepted definition of a ramp event. In (Ferreira, Garma, Matias, Botterud, & and Wang, 2010), at least four definitions of ramp events are surveyed, along with different forecasting models for ramp events, error metrics and other issues on the subject.

The relatively high ranking of ramp forecast in Figure 26 could suggest that operators simply want a better forecast within the day. They also want a forecast that shows good details about the power changes from wind power plants. Whether this is best accomplished by improving core wind forecast products or by augmenting them with a separate ramp risk forecast is currently a topic of much debate in the wind forecasting community.

Some grid operators currently use the ramp event forecast already provided. Figure 28 shows the percentage of respondents who take the forecast of wind ramps into consideration when determining reserves and unit commitment.

[38] This data for the German TSOs can be found at www.transparency.eex.com.

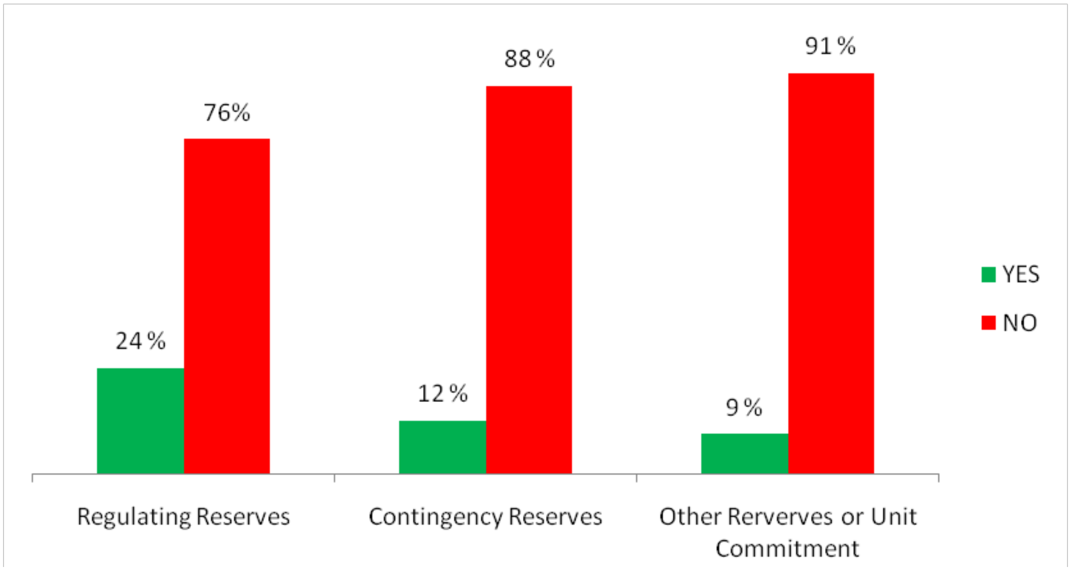

Figure 28. Percentage of Respondents who take Ramping Events into Consideration when Determining Different Reserves or Unit Commitment

5.8.2 Probabilistic Forecast

Power system and electricity market operations are beset by increasing levels of uncertainty, forcing many RTOs/ISOs/TSOs to request wind power forecast uncertainty information. Many experts in industry hold the opinion that this information could be very valuable for system operations. Like all humans, grid operators naturally think in probabilities, although they may not be aware. According to Figure 26, only 25% of the respondents ranked the importance of probabilistic forecast as HIGH, the lowest percentage of all the forecasting products. One reason for this low ranking could be because many grid operators currently have no experience in dealing with probabilistic information. However, this fact is expected to change over time as more research is conducted into how to integrate this kind information in control room applications and what tools are necessary to improve how they think in probabilities (Posner, 2010). A few respondents currently use or are exploring the use of probabilistic information. In Appendix A.6, ERCOT's use of probabilistic information is discussed. Other examples of how some respondents are investigating and prototyping the visualization of uncertainty also are described in Appendix A.

In general, the terms "uncertainty" and "risk" are often used interchangeably, although some researchers and risk practitioners have argued that they should not. Uncertainty involves doubt, while risk suggests the possibility of losing something or some kind of injury. While risk is associated with uncertainty, it is subjective: "Risk is in the eye of the beholder" (Savage, 2009). How will two dispatchers in same or different control rooms view the risk related with a given wind ramp event? In this context, during interviews, several respondents raised the question, "How will grid operators today and in the future, working under increasing uncertainty due to wind power and other sources, assess the operational risks when making real-time decisions in the control room?" Probabilistic methods are used for power system planning (CIGRE, 2010), but more research is needed to develop probabilistic risk-based assessment tools for real-time operations.

5.8.3 Limitations of Existing Wind Power Forecast

The respondents indicated limitations with the current wind power forecast. Table 5 provides a list of several of these limitations of forecasting systems that some respondents use. These include: a lack of accurate ramp event forecasting and that the forecasting system is not tuned to predict wind ramp events; only persistence forecast is used in the short term; a lack of intra-hourly forecast; limited resolution of the National Oceanic and Atmospheric Administration (NOAA) weather prediction models;[39] a range of uncertainty is not delivered with the forecast; and infrequent or limited updates of the forecast. In discussions, several respondents stated that removing these limitations would improve wind integration in the control center.

5.8.4 Dual Approach to Operational Forecasting

In the real-time environment of the control room, operational forecasting will typically be determined using a mixture of analytical forecasting tools and what is often referred to as "Human Forecasting Techniques." It is well known that over time, operators become good human forecasters as they learn to recognize and correlate the emergence pattern of different weather events. In some cases, they may even outperform advanced forecasting tools as they are better skilled in piecing different weather warning signs and alerts patterns together and then making a very good prediction (Grant, et al., 2009). Given the difficulties in forecasting wind ramp events and its dependency on complex weather phenomena, a dual approach to operational forecasting, which combines the knowledge of human forecasters with the results from forecasting software, should be supported. Weather situational awareness forecast (see Figure 26), which provides alerts and warnings when correlated with human forecasting, can also be very valuable in detecting precursors to extreme weather events. Human forecasters and other users of wind power forecast develop a good understanding of the physics-based and statistical models that produce wind power forecast. More research is needed into how to best combine human forecast with the computed forecast in a useful way for grid operators.

5.9 Integrating Wind Power Forecasting with Control Room Applications

To efficiently integrate wind power in power systems requires that wind power forecasting tools be deployed in control rooms, but more importantly, that forecast and uncertainty information be incorporated in the real-time decision support systems as well as planning tools and models. Figure 29 shows the extent to which respondents have integrated wind forecast in different processes and tools that are used in real-time operations and planning.

Congestion management is one of the most important functions of the grid operator. Congestion in the grid occurs when the amount of transmission capacity required for electric power to flow at a given point in time is greater than the capability of the transmission network. Higher penetration of wind power in the grid can introduce new patterns in the flow of power in the transmission and distribution networks. These unexpected flows could overload some transmission lines, causing new operational limits and congestion in the system.

[39] In recognition of the need for improved meteorological observations and predictions across a range of time scales, the Department of Energy/Energy Efficiency and Renewable Energy and the Department of Commerce/National Oceanic and Atmospheric Administration signed a Memorandum of Understanding in January, 2011. The memorandum formalized cooperation between the two agencies to develop improved science and services that will support growth of wind energy and other sources of renewable energy. One activity that falls under the DOE-NOAA MOU is the upcoming Wind Forecast Improvement Project (WFIP), a DOE-funded research project in which DOE, NOAA, and private sector companies will aim to improve the accuracy of NOAA's weather forecast models as well as the private sector's wind power predictions, and to determine the economic savings accrued from such efforts. Published studies on the economic value of weather forecasts to the wind energy industry are important (Marquis, et al., 2011 accepted). The WFIP is a 12-month field study that will run from July 2011 to July 2012.

The uncertainty and variability of wind power pose additional challenges to operating the system. About 55% of the respondents have integrated wind forecast in their software tools or processes to manage congestion. Large RTOs/ISOs and TSOs that are interconnected to neighboring utilities were included in this percentage. Most of these respondents expressed concern about the operational risk of not fully understanding the potential impacts that wind variability and forecast error could have on identifying bottlenecks and critical contingencies in their systems.

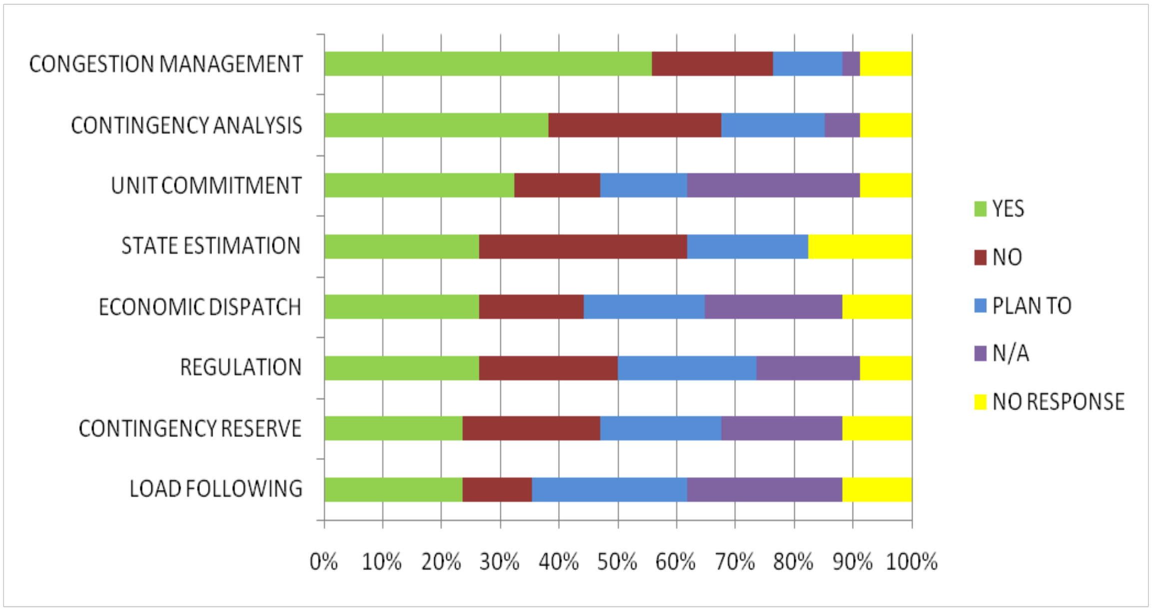

Figure 29. Integration of Wind Forecasts in Real-Time Applications and Processes

Congestion can be managed in different ways and there is still no consensus on the best approach (CIGRE Working Group C6.08, 2011). However, methods used in various electricity markets in the U.S. and parts of Europe continue to evolve as operators gain more experience. More research is highly recommended to capture the lessons learned and best practices of methods to transparently and cost effectively deal with congestion, while simultaneously accommodating integration of more wind generation. Respondents overwhelmingly agree that better congestion management will make the job of grid operators and dispatchers less burdensome.

Twenty-five percent or more of all the respondents have incorporated wind forecast in real-time applications and processes for managing voltage stability, unit commitment (UC), state estimation (SE), regulation, load following, economic dispatch (ED), contingency reserves and contingency analysis (CA). SE, ED, CA, regulation and load following are implemented as part of the EMS in control centers. In most cases, UC and contingency reserve calculation are also integrated with the EMS. Yet, the extent to which wind power forecast has been integrated with these EMS applications varies.

According to Figure 30, in terms of the resource planning, nearly 50% of respondents take wind forecast into consideration when determining new transmission, compared to about 22% who do so when planning for new generation. Less than 20% account for wind forecast when planning for FACTS.

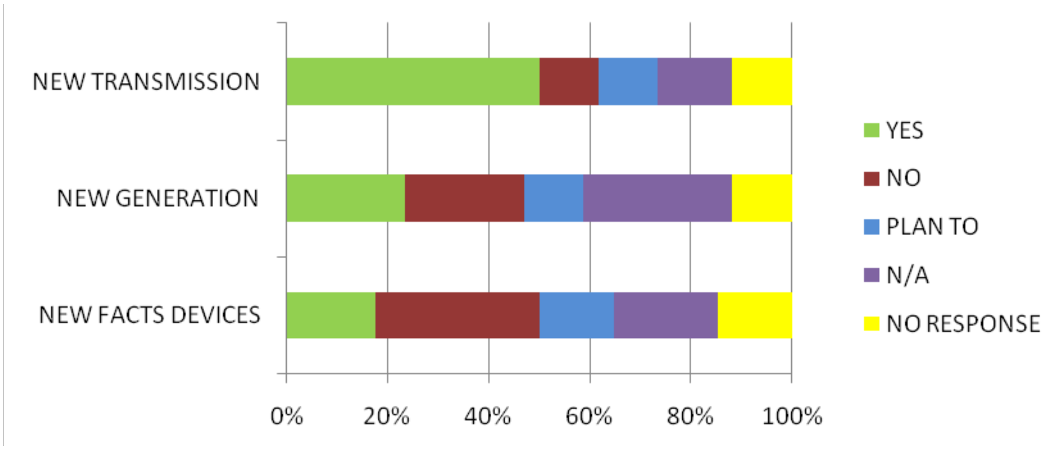

Figure 30. Integration of Wind Power Forecast in Resource Planning

The stability of the power system can be assessed using real-time and planning tools for voltage stability and transient stability analysis. Reconfiguring the network by switching (connecting/disconnecting) transmission equipment following system faults, for maintenance or as part of a preventive or remedial action, is another important and regular task that grid operators conduct.

Figure 31 shows the percentage of respondents who have integrated wind forecast in stability assessment tools and transmission switching process or tools. Most of the respondents who operate systems which currently experience or are susceptible to stability problems, have integrated wind forecast with these tools. According to the result, this is independent of the wind penetration level. On the other hand, most of the respondents who have not integrated forecast in these tools typically have low penetration levels, in addition to having a strong transmission network.

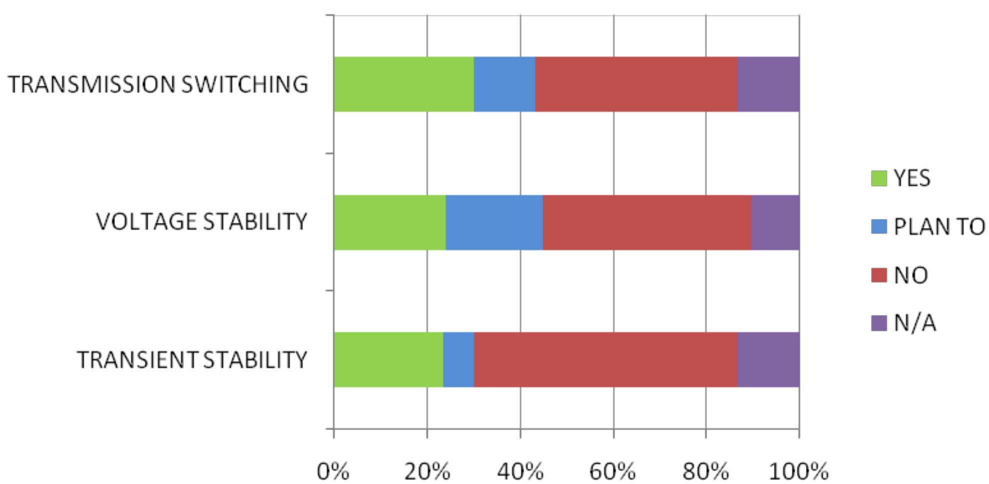

Figure 31. Use of Wind Forecast in Stability Assessment and Network Configuration

5.10 Decision Support Systems and Tools

The control room is the nerve center for operating power systems. It is equipped with different decision support systems and tools, the core of which is the EMS. In grids where wholesale electricity markets are operated, there is also a MMS. According to Figure 32, 94% of the respondents agree or strongly agree that the ability to integrate a significant amount of wind will also largely depend on the decision support tools deployed to support control room operators.

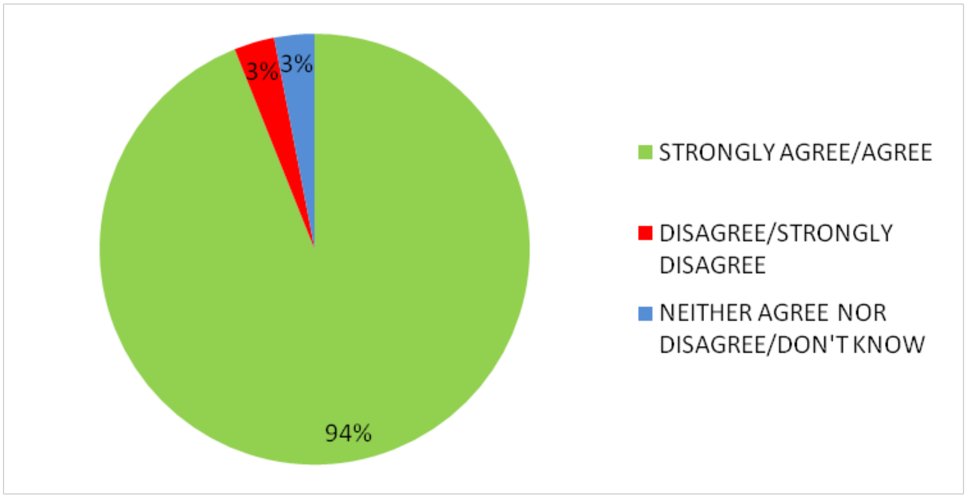

Figure 32. Integrating Wind Depends on Decision Support Tools in Control Room

Several organizations have also acknowledged the need for advanced tools. For example, the North American Electric Reliability Corporation (NERC) has noted that new "advanced decision support tools" are important to managing grids with large amounts of wind energy. To quantify utilities' perception of the value of these tools, the respondents were asked to rank each tool in terms of supporting integration of wind power. The results of the ranking are shown below in Figure 33.

The ranking of voltage stability correlates well with the fact that wind plants are known to cause voltage stability problems in power systems with insufficient reactive power support. Having the proper tools to assess system voltage stability in real-time becomes even more critical with higher wind penetration levels, coupled with a weak transmission network.

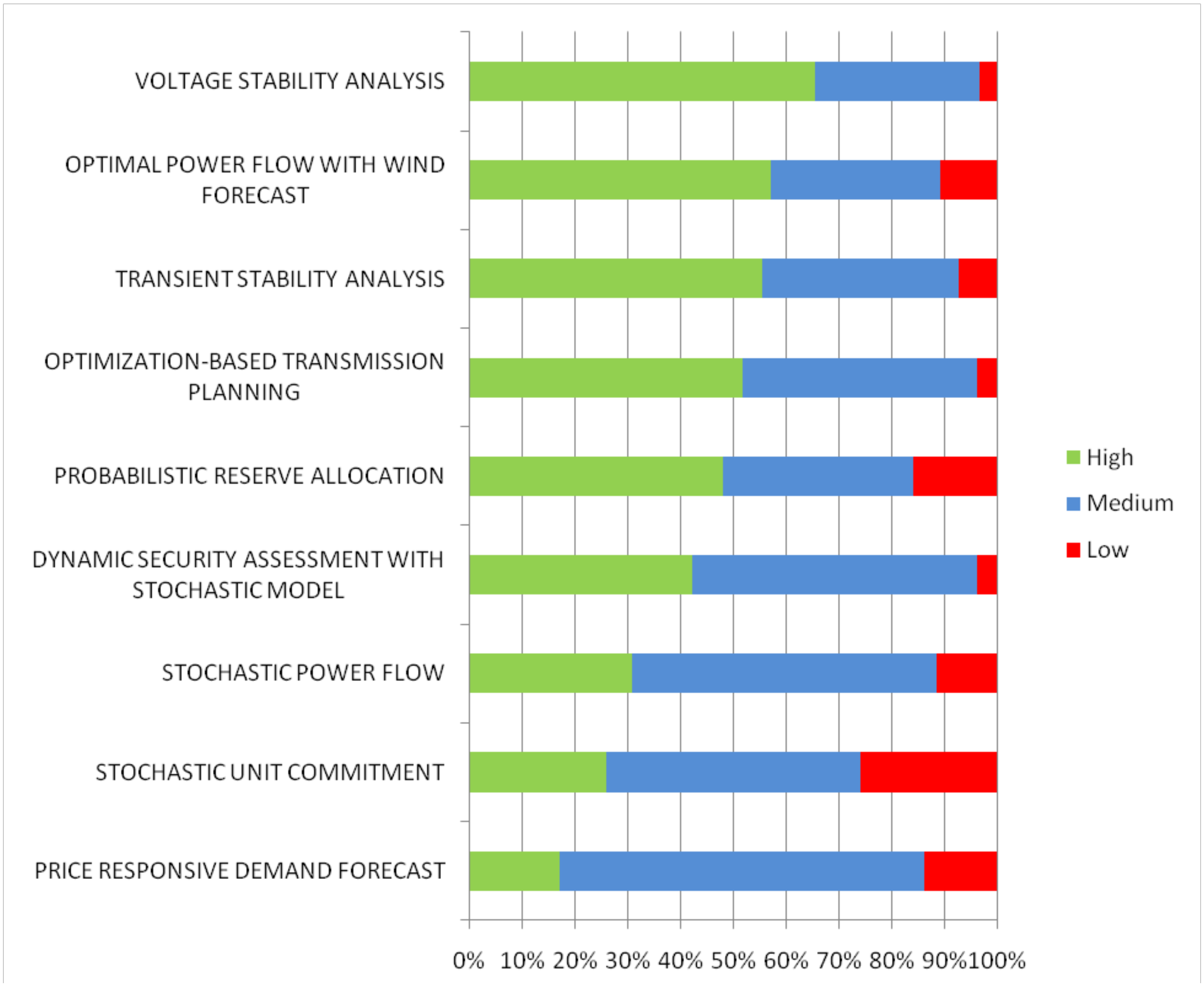

Figure 33. Ranking of Advanced Decision Support Tools to Support Wind Integration

Optimal power flow (OPF) is a well-established power system application. Grid operators use OPF to determine the power flow in the network, subject to generation and transmission limitations. As more wind energy becomes part of a system's generation portfolio, additional uncertainty and variability are introduced. These factors can affect the amount and type of resources as well as control actions required to maintain system balance. Incorporating wind power forecast and uncertainty in OPF solutions is just one approach that accounts for the impact of wind generation.

According to Figure 34, of the nine advanced decision support tools, seven have already been implemented or there are plans to have them implemented by some of the respondents. Voltage and transient stability analysis are the two advanced decision support tools implemented the most. This ranking is to be expected since these are important for grid operations with or without wind generation. Stochastic power flow and stochastic unit commitment are tools which none of the respondents has implemented. However, roughly 13% of respondents have plans to implement these tools, compared to 77% who did not know if they will or will not implement either or both.

This current snapshot of the status of implementation of these applications in the industry is expected to change as grid operators gain more knowledge and experience about these tools. Utilities and the industry at-large must work to educate operators more about these tools and demonstrate the benefits of using them as utility-scales wind plants are connected to the grid.

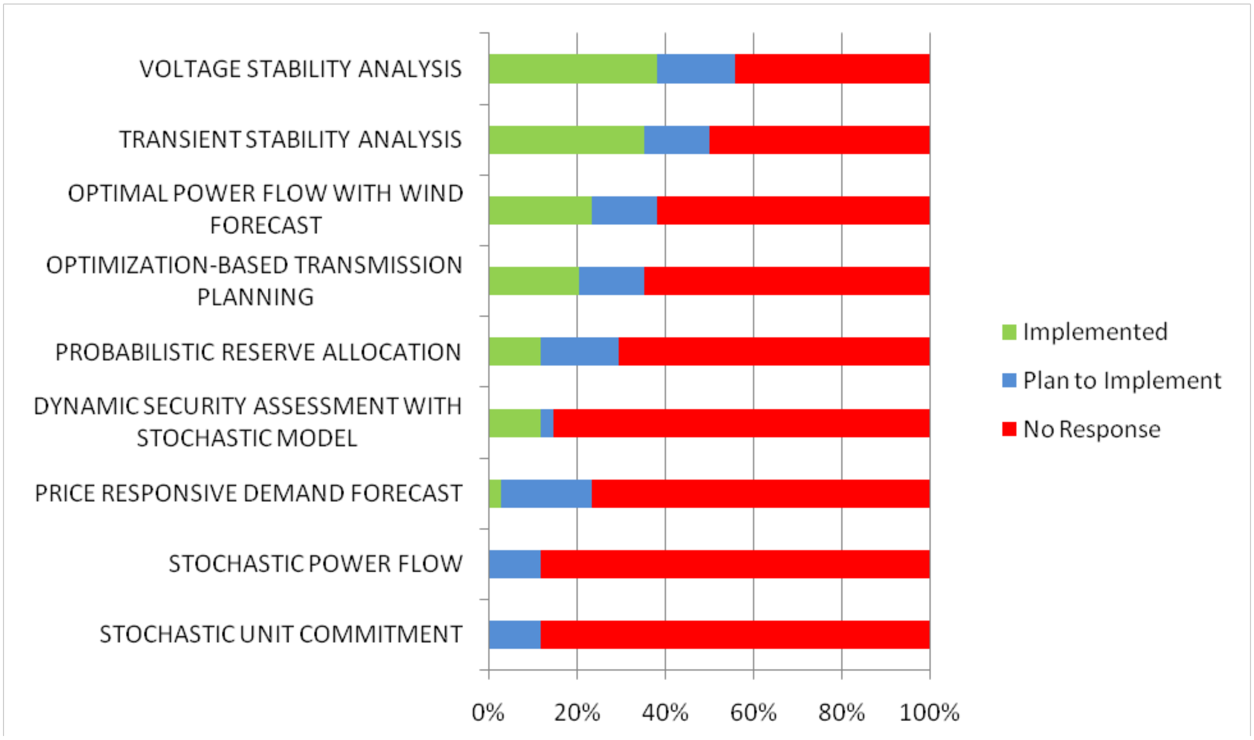

Figure 34. Implementation of Advanced Decision Support Tools in Control Rooms

5.11 Operating Processes and Procedures

Power systems are operated using different business processes and procedures ensuring that proper and adequate amounts of resources are allocated to maintain system reliability, subject to operating guidelines and regulatory requirements. Examples of processes and procedures include: scheduling, commitment, dispatching and curtailment of resources. Large-scale wind generation introduces other challenges for grid operators, which may require that established processes and procedures be augmented or new ones implemented. Table 10 and Table 11 summarize several internal operating procedures and business processes that respondents have established in their control rooms to manage wind integration. This section discusses survey results regarding the integration of wind power forecast with three processes: scheduling, dispatch and curtailment.

5.11.1 Scheduling and Dispatching

Power system operation basically focuses on how resources (e.g., generation, transmission and load) are effectively and economically scheduled and dispatched to achieve the quintessential goal of balancing supply and demand. These processes are also exposed to different levels of variability and uncertainty.

It is more advantageous to manage wind power variability if generators in electricity markets are able to make frequent changes in the schedules they submit to the system operator. Several of the respondents who operate electricity markets indicate that scheduling generation resources on an intra-hourly basis can help integrate wind generation, compared with hour-ahead or even 30-minute scheduling. In addition, intra-hourly dispatch of generation can improve wind integration. Survey results in Appendix E and from follow-up discussions with respondents operating both in regions with and without wholesale competitive electricity markets, substantiated the general view that clearing electricity markets frequently is a very efficient way to control the response of conventional generation to wind power variation.

The majority of European TSOs in the survey agree that one of the ways to reduce day-ahead forecast errors is to reduce the gate closure times, therefore making electricity markets faster. Similarly, most U.S. and Canadian respondents support the case for faster markets. Thus, a faster market based on shorter dispatch time, frequent scheduling of resources and short gate closure time is an important best practice for integrating more wind generation in power systems.

Figure 35 shows the percentage of respondents who have had wind generation affect their processes for scheduling conventional generation and transmission.

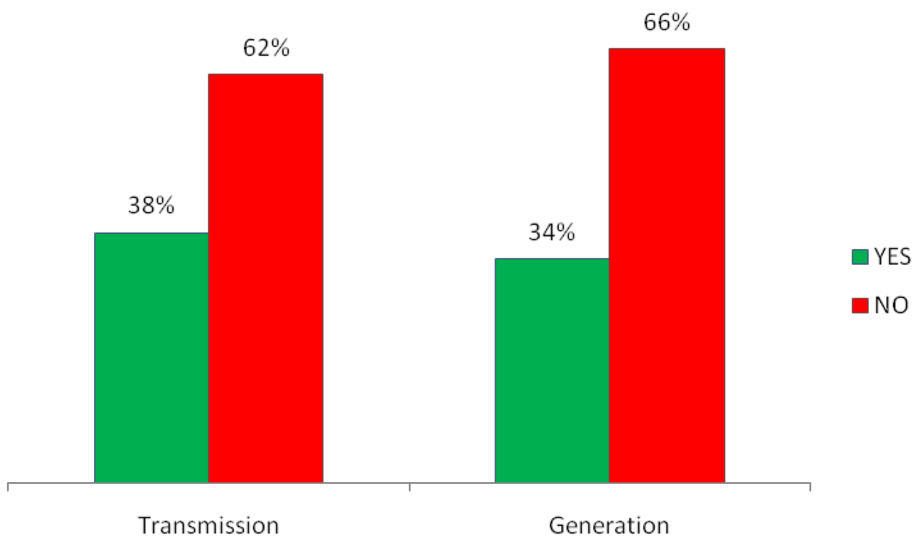

Figure 35. Wind Generation has Affected How Conventional Generation and Transmission are Scheduled.

Table 8 in Appendix E provides descriptions of some of the resource scheduling and coordination processes implemented between TSOs in Europe, RTOs and BAs in North America and in countries where multiple grid operators reside. Some of the processes include:

- Outage scheduling coordination on annual, monthly, weekly and daily basis, as well as weekly multi-TSO conference calls.
- Hourly inter-BA scheduling with ongoing work to increase the scheduling frequency to every 5, 15 or 60 minutes.
- Analysis of the impact of wind power in one system on the transmission constraints and on the interconnections between and within other systems.

5.11.2 Wind Dispatch

Wind plants cannot be dispatched in the way conventional generations can, although the notion of dispatching wind plants is commonly used in the industry. Operators can schedule and control (increase or decrease) the fuel input to conventional power plants. The output of the wind generators fundamentally depends on the wind speed.

"Wind dispatch" generally refers to a condition when the wind plant is online and producing energy, while the plant output is reduced for reliability reasons. This output reduction can result from manual intervention or via automatic control, based on set point signals that are communicated to the wind plant controller, which then apportions the signals to the individual turbines in the wind park. It is also possible, although less common today, for grid operators to ask wind plants to increase its output above what was previously scheduled.

In terms of dispatch, two important distinctions can be made. In the first case, dispatch is based on regulatory policies, which obligate grid operators to accommodate the wind energy once wind plants are connected to the system. The only exception occurs when conditions that affect grid reliability and the wind plant is ordered to reduce its power output, or be disconnected from the grid until the problem is addressed. The EU Priority Dispatch (Andrea, 2010) is an example of this policy. The other form of wind dispatch requires the wind plant to submit a bid and follow signals from the dispatch software, much like any other generator. The practice of treating wind like a conventional generator or as part of the system dispatch software is relatively new and has been deployed in some systems that operate competitive electricity markets in the U.S. As more operational data is gathered from this approach to "dispatching" wind, it will be important to evaluate the performance and make the necessary enhancements to both the software and market protocols. Examples of both forms of wind dispatch implemented by grid operators are discussed in Appendix A.

5.11.3 Curtailment

Wind plants are traditionally curtailed mostly for conditions of congestion in the transmission network, other reliability problems not necessarily due to wind generation and during conditions of excess wind generation which affects reliability. Wind curtailment techniques and solutions are more developed in some power grids than in others. An overview of several wind curtailment initiatives can be found in (Rogers, Fink, & Porter, July 2010). According to Figure 36, 41% of respondents use automated tools and solutions to curtail wind.

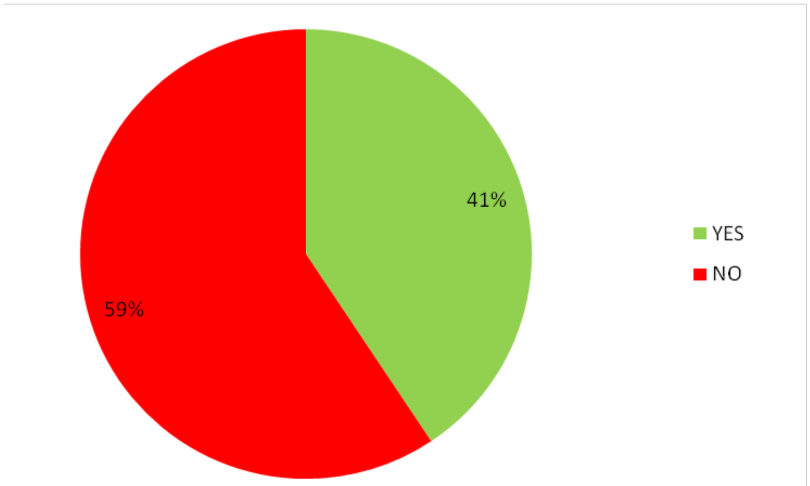

Figure 36. Use of Automated Tools and Solutions for Wind Plant Curtailment

In Table 6 of Appendix E, descriptions of various automated tools and solutions that some respondents use are provided. Some of the more common approaches include:

- Use of deterministic rules for curtailment conditions and curtailment allocation which are executed in the generation dispatch tool.
- Curtailment is achieved as part of the Security Constrained Economic Dispatch algorithms.
- The state estimator determines binding congestion and the Out of Merit Energy instructions to curtail wind.
- Automated dispatch tools treat wind plants like other resources and curtail them based on economic dispatch.
- Contingency analysis tools determine the need for wind curtailment and sends orders to the wind plants.

The results in this report reconfirms that accurate wind power forecast in the control room is vital for successful integration of wind generation in real-time grid operations through the improvement of different processes such as scheduling of resources and determining the operating reserves. Other benefits of wind power forecast do exist but they have not received as much research attention to date. The survey finding that accurate forecast affects wind curtailment is just one example. Figure 37 shows that 24% of respondents said the frequency of curtailment and the amount of wind power curtailed are reduced with better integration of wind power forecast. However, 18% report that neither the frequency nor the quantity decreased.

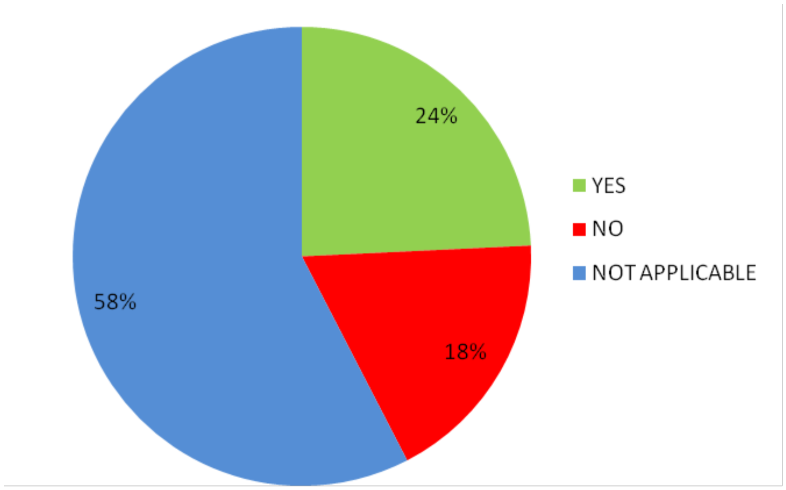

Figure 37. Integrating Wind Power Forecast has reduced the Frequency in Curtailment Orders and the Quantity of Wind Power Curtailed

More research into how operational processes and procedures are affected as a result of using accurate wind power forecast will demonstrate the total value of investments that grid operators should make for continuous improvements in the performance of the wind forecasting system.

5.12 Changes in Operational Processes and Tools

Integrating wind generation involves three areas: physical, operational and informational (Jones L. E., April 2009). For the grid operator, this integration could require changes in the physical grid (e.g., building more transmission), and changes in operational business processes, and information technology solutions in the control room. While some of the changes will be immediately necessary, others will require research and careful planning before they are implemented. In Table 4, respondents list some of the most substantial and/or most changes needed to support more wind energy integration. The most common changes include:

- Improvement of operational forecasting.
- Tools to enhance situational awareness.
- Efficient ancillary services markets.
- More transmission capacity.
- Better forecast of wind ramp events.
- More flexible resources.

To quantify the perceived value of various operational changes, respondents were asked to rank a list of changes that system operators around the world have identified. Figure 38 shows how respondents rated these different changes. Note that the three most highly rated changes, more accurate wind forecasting, more flexible conventional generation, and building more transmission respectively are also cited as critically important for wind integration, based on other results in this report.

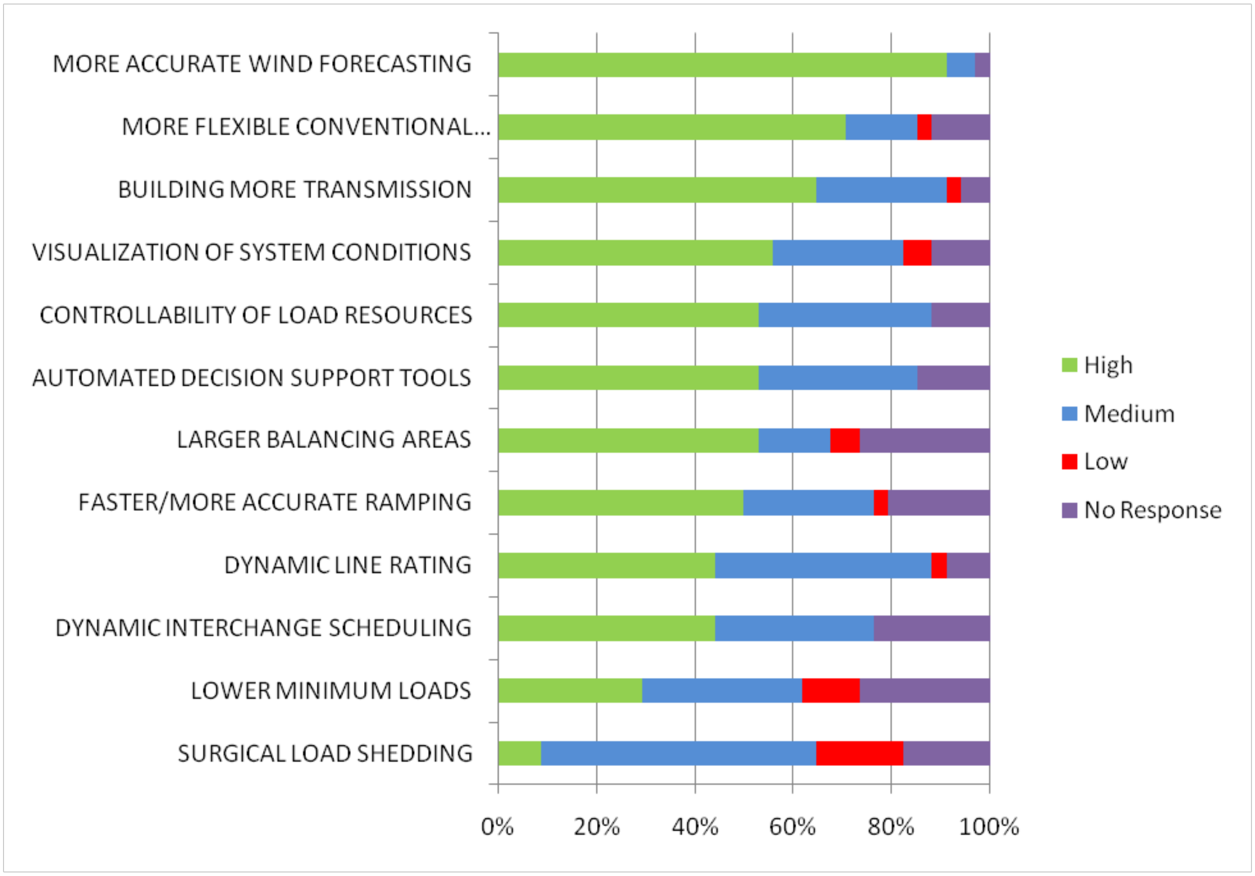

Figure 38. Value Rating of Grid Operational Changes for Large-Scale Integration of Wind Power

Some of these changes require new electricity regulation and market protocols (e.g., more flexible conventional generation, larger balancing areas, dynamic interchange scheduling, controllability of load resources and surgical load shedding). Others may need different kinds of local or national policy measures (e.g., building new transmission), which might take longer to be implemented. However, grid operators can also directly implement some of these changes (e.g., more accurate wind forecasting, automated decision support tools, visualizations of system conditions).

5.13 Policy

Reliability standards and regulatory policies as well as the laws that are enacted at the local, state, regional, national and multi-national levels affect the integration of wind generation in the control room. In addition, operating policies and guidelines established to facilitate communications and cooperation and coordination between two or more grid operators, also are established to facilitate the reliable integration of wind power.

According to Figure 39, 79% of respondents agree or strongly agree that integrating a significant amount of wind generation will largely depend on the operating policies implemented in the control room. Table 9 lists operating policies that the respondents have established with other entities to manage wind power integration.

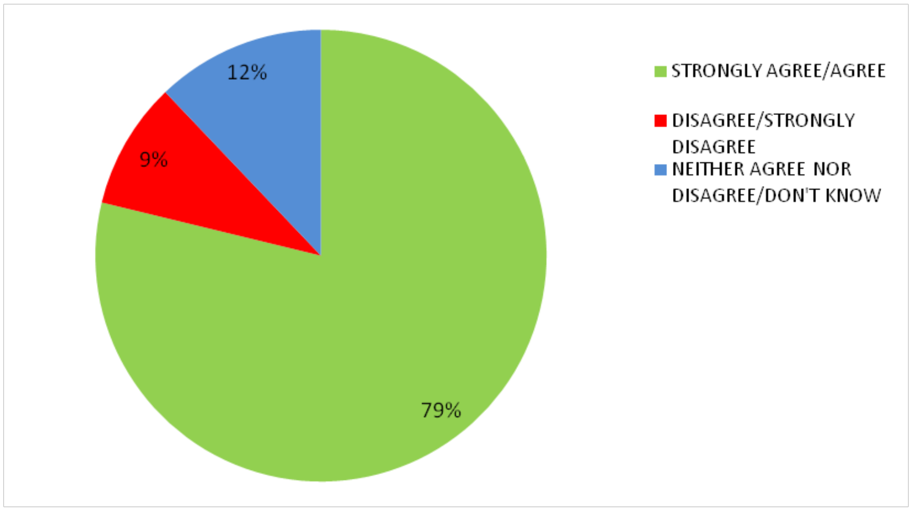

Figure 39. Large-Scale Wind Integration Will Depend on the Operating Policies Deployed in the Control Room

Table 12 includes respondents' views on policies and grid code changes needed to support large-scale wind integration. The key policy areas identified, which will impact the tools, processes and procedures in the control room include:

- Rules and protocols for:
  - Ancillary services markets (e.g., efficient procurement of more flexible resources).
  - Faster electricity markets (e.g., shorter gate-closure closer to real time, frequent intra-hourly schedule).
  - Greater coupling and harmonization between national and regional electricity markets (e.g., reserve sharing and transmission scheduling).
  - Congestion management.
- Standard grid code and interconnection guidelines.
- Standard data requirements for wind plants.
- National initiatives to improve weather service models.
- Reliability standards for the bulk power system.

Based on feedback from respondents and results from the literature survey, a broad industry consensus affirms that the design of efficient electricity markets is one of the most important policy areas for wind integration. See also (Borggrefe & Neuhoff, 2011). The other critical area, of which there is little disagreement, is the call for national initiatives to improve weather service models. Many commercial wind forecast providers and grid operators use weather service models. Policy changes in both of these areas are ongoing in several countries. As an example, FERC released its Variable Generation Notice of Proposed Rulemaking in 2010, which could impact the market rules and information that wind generators will have to provide to grid operations. NOPR could also affect the tools and procedures (e.g., scheduling and dispatch) in the control room.

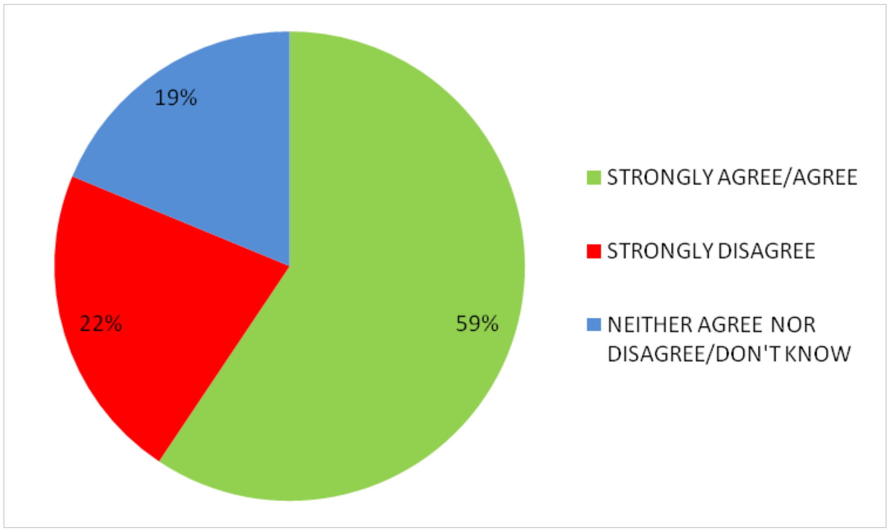

Figure 40. Grid Codes and Reliability Standards must be substantially changed to Support Wind Integration

Notwithstanding, respondents differ in opinion regarding the need for, and significance of policy areas that suggest certain changes on wind integration management. For example, Figure 40 and Figure 41 show the level of agreement among respondents in a few areas. In the first case, 59% of respondents say they agree or strongly agree that grid codes and reliability must be substantially changed to support wind integration. Twenty-two percent did not agree, while 19% had no comment.

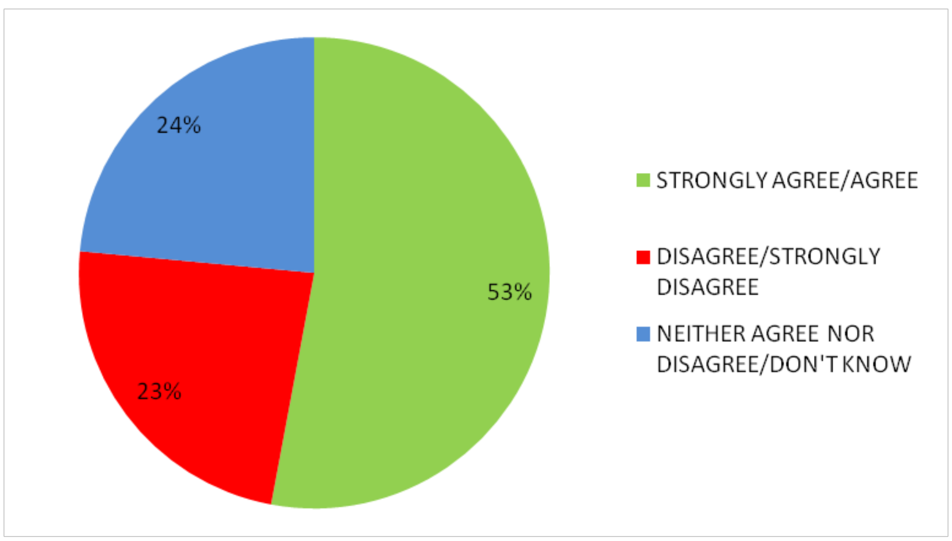

Figure 41. Standard Data Communication Protocols and System Interoperability are not sufficiently developed to Support Wind Integration

For the second case shown in Figure 41, a smaller majority of respondents (53%) say they agree or strongly agree that standards for data communications protocols and system interoperability are not sufficiently developed to support integration of high penetration levels of wind power. Twenty-three percent did not agree, while 24% had no comment. A central issue in the evolution of smart grids around the world is the need for standards that will ensure interoperability of smart grid devices, equipment and systems.[40] Given that wind generation is projected to be a larger part of the electricity supply by the year 2030, it is imperative that issues related to wind integration in future smart grids be considered as the standards are being developed.

Respondents in agreement with the various policy statements also have high wind penetration levels, while most of those who did not agree nor had any comment have low penetration of installed capacity.

Another way of viewing the impact of policy on wind integration is to consider how different policy measures have affected wind penetration. Figure 42 shows the cumulative wind capacity for seven of the grid operators featured in this report. It is interesting to note that the fastest rate of increase for all of them occurred in the same time period of 2004 – 2010. The fact that these utilities are in different countries indicated several things: 1) Some policies around the world were converging; 2) The global market drivers were at play; 3) Utilities were looking and learning from each other.

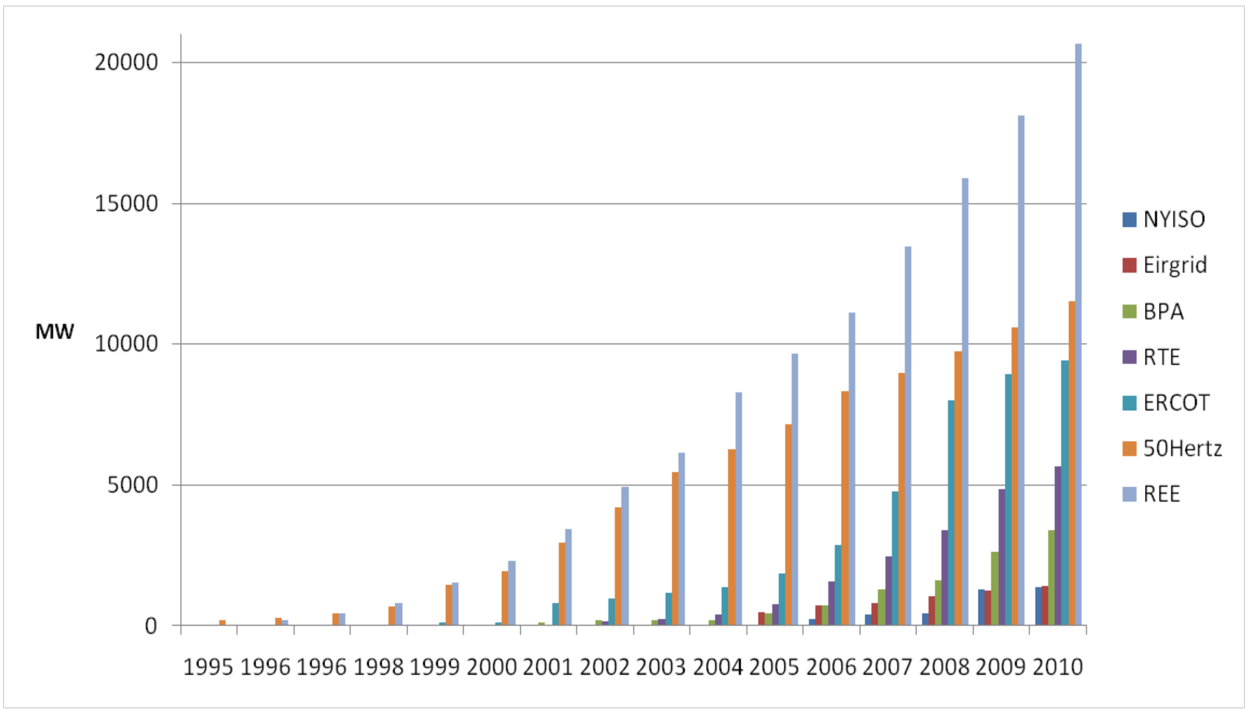

Figure 42. Cumulative Wind Power Capacity for Grid Operators

[40] In the U.S., development of a framework and an architecture for smart grid interoperability is strongly coordinated by the National Institute for Standards and Technology (NIST). Other organizations around the world, e.g. CIGRE, IEA, IEEE are also involved in different activities to develop standards for operating a modernized power grid with smart technologies in the generation, transmission, distribution, and consumption parts of the grid.

5.14 Wind Energy Information

Accurate information about wind energy is critical to the successful integration of wind generation in grid operations. As more grid operators are expected to cope with a higher penetration of wind generation in coming years, experts look to provide recommendations about where they can find helpful information on wind integration and learn about emerging issues addressed using different strategies and tools.

Figure 43 shows the various sources from which grid operators obtain wind integration information. The total number of respondents who gather information from the different sources is also given. Respondents most referenced sources such as the IEEE, NERC, and UWIG. Although these three organizations are based in the U.S., many respondents who obtain information from these sources are from other countries.

Another aspect related to wind information addresses systems that operators use to gather and/or develop information that supports wind power integration. Table 13 provides the kinds of systems and tools respondents use to acquire data. Most of these deal with meteorological data from towers located near wind farms, as well as other operational data sent to the grid operators from the wind turbine SCADA system. The requirements that some grid operators have instituted are important elements of data gathering. As discussed previously in this report, no universal agreement on the complete set of data required by the grid operators for centralized forecasting or other operational tools for that matter exists.

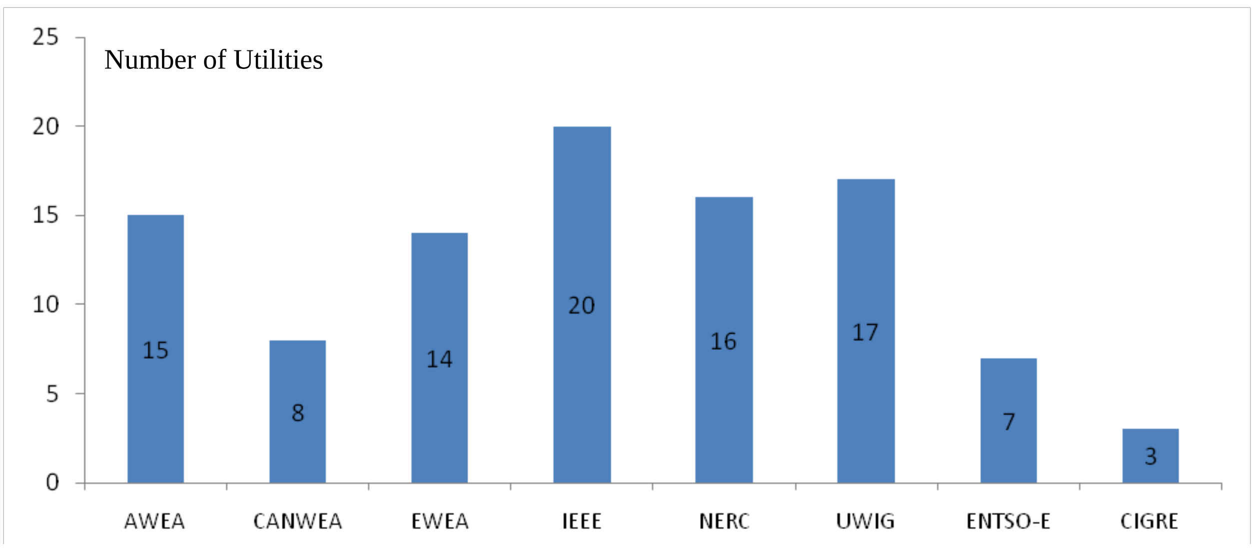

Figure 43. Source of Information about Wind Integration Issues, Tools and Methodologies

5.15 Impact of Smart Grid Technologies on Wind Integration

Governments, policy makers, regulators, utilities and other stakeholder groups are proposing "smart grids" worldwide. The importance of smart grid technologies in modernizing the U.S. electric grid infrastructure and facilitating a clean energy economy through increased integration of wind and other variable renewable energy sources is highlighted in the report *The Policy Framework for the 21st Century Grid – Enabling Our Energy*

Future.[41] Section 1302 of Title XIII of the Energy Independence and Security Act (EISA) passed by the U.S. Congress in 2007 identifies characteristics of a smart grid.[42] The European Commission adopted the Communication *Smart Grids: from Innovation to Deployment*,[43] which sets out the policy framework for driving the development and future of European electricity networks with the focus on smart grids. The IEA discusses smart grids from a global perspective and explores definitions and potential technology and policy issues in its Smart Grid road map.[44] The DOE National Energy Technology Laboratory (NETL) Modern Grid Initiative in its *Characteristics of the Modern Grid* lists several characteristics of smart grids.[45]

Researchers have a global expectation that smarter grids will increase customer participation and reduction in peak demand; improve the reliability, efficiency and security of electricity delivery systems; and accommodate the integration of more renewable sources of energy. This last of these, renewable integration, falls within the scope of this project. Consequently, a salient question to ask is: "How can smart grid technologies help operators in the control room integrate and manage wind power?"

There is no common definition of a smart grid. However, the Smart Grid Task Force (SGTF) of the NERC Planning Committee has agreed upon the following industry definition:

Smart Grid – "The integration and application of real-time monitoring, advanced sensing, communications, analytics and control, enabling the dynamic flow of both energy and information to accommodate existing and new forms of supply, delivery, and use in a secure, reliable, and efficient electric power system from generation source to end-user." (North American Electric Reliability Corporation, December 2010)

One challenge with operating power systems with increased levels of wind penetration is the need to increase the levels of flexibility in the system. Based on the aforementioned definition, it can be said that smart grid technologies may improve the flexibility of power systems by increasing the observability, controllability, and maneuverability of certain loads, generation and energy storage resources. The use of more controllable power electronics based devices in transmission and distribution networks also makes the system more flexible to cope with wind generation.

Several studies and reports list existing smart grid applications, as well as those applications under development, that can impact the reliability of transmission and distribution systems. Specifically, in terms of integrating wind energy from the view of the control room environment, the following six smart grid applications can be considered:

- Demand Respond (DR)
- Dynamic Line Rating (DLR)
- Energy Storage
- Plug-in Hybrid Electric Vehicles (PHEV)
- Transformer Load Management

[41] This report was prepared by the Subcommittee on Smart Grid of the National Science and Technology Council, Committee on Technology in the Executive Office of the President of the United States. It is available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/nstc-smart-grid-june2011.pdf. Accessed on June 13, 2011.
[42] Full text of the EISA is available at http://energy.senate.gov/public/index.cfm.
[43] The Communication is available at http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/20110412_act_en.pdf.
[44] The IEA Smart Grid Roadmap is Available at http://www.iea.org/papers/2011/smartgrids_roadmap.pdf.
[45] Report available at http://www.netl.doe.gov/smartgrid/.

- Volt/VAr Optimization

Demand response, energy storage and electric transportation including PHEV were identified as Priority Applications in the Smart Grid Policy[46] of the U.S. FERC.

Figure 44 depicts how respondents rank the impact that each application, when integrated with wind forecast, will have on integrating wind power in real-time grid operations. It is important to note that, these rankings, similar to others in the survey, reflect the respondents' present understanding of the various tools and concepts. As respondents become more knowledgeable and gain experience, these rankings will change.

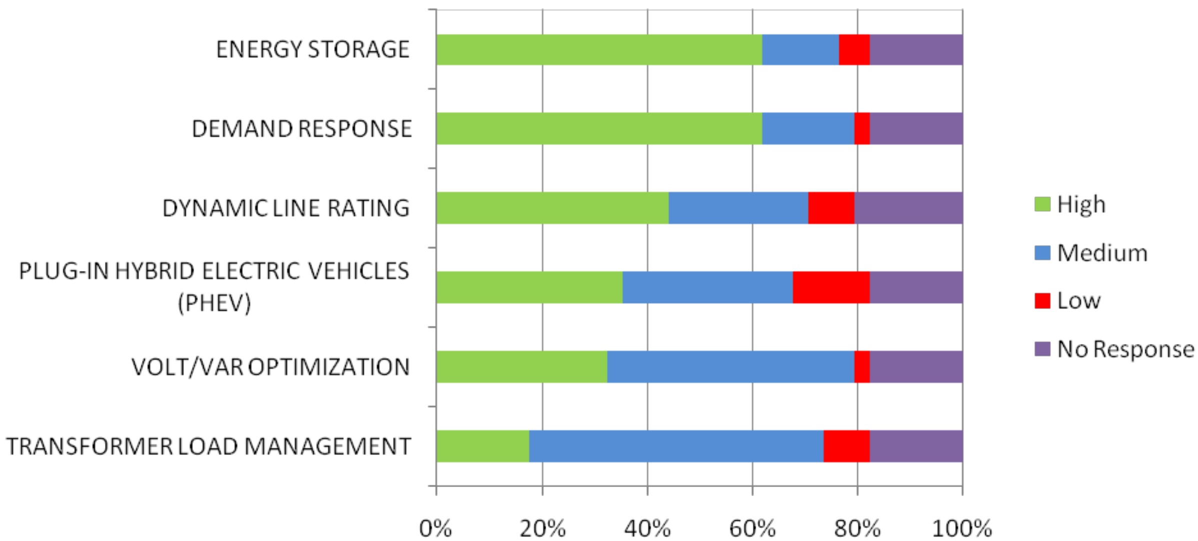

Figure 44. Impact of Smart Grid Applications Integrated with Wind Power Forecast on Real-Time Operations

DR, PHEV and energy storage (e.g., pumped-hydro and compressed air energy storage (CAES)) may help operators balance ramps associated with wind generation. These applications can provide relatively quick responses to system changes from wind, thus contributing to the flexibility. To be effective in changing wind integration, these applications will have to be modeled and implemented in, and then controlled from within the EMS or another real-time decision support system in the control room.

More than 60% of respondents ranked the impact of energy storage on wind integration as HIGH. This ranking occurs despite the fact that there are no known study results that suggest energy storage is absolutely needed to integrate wind large amounts of wind generation in existing power systems. In fact, according to the DOE *20% Wind by 2030* report, storage is not a prerequisite to reach the 20% level. The high ranking could be interpreted as a result of respondents' perceptions and expectations about how storage technology may advance and become cost effective in the next 20 years. However, once storage technologies are well developed, they could have a very positive impact as a flexible resource in the long run. For example, further discussions with respondents and findings in the literature indicate that the potential benefits of storage for wind integration will mainly be in providing ancillary services (EPRI, 2010).

[46] Issued in July 2009, the FERC Smart Grid Policy Statement provides guidance regarding the development of a smart grid for U.S. bulk power transmission focusing on the development of standards to achieve interoperability and the functionality of smart grid systems and devices. Available at www.ferc.gov/whats-new/comm-meet/2009/071609/E-3.pdf.

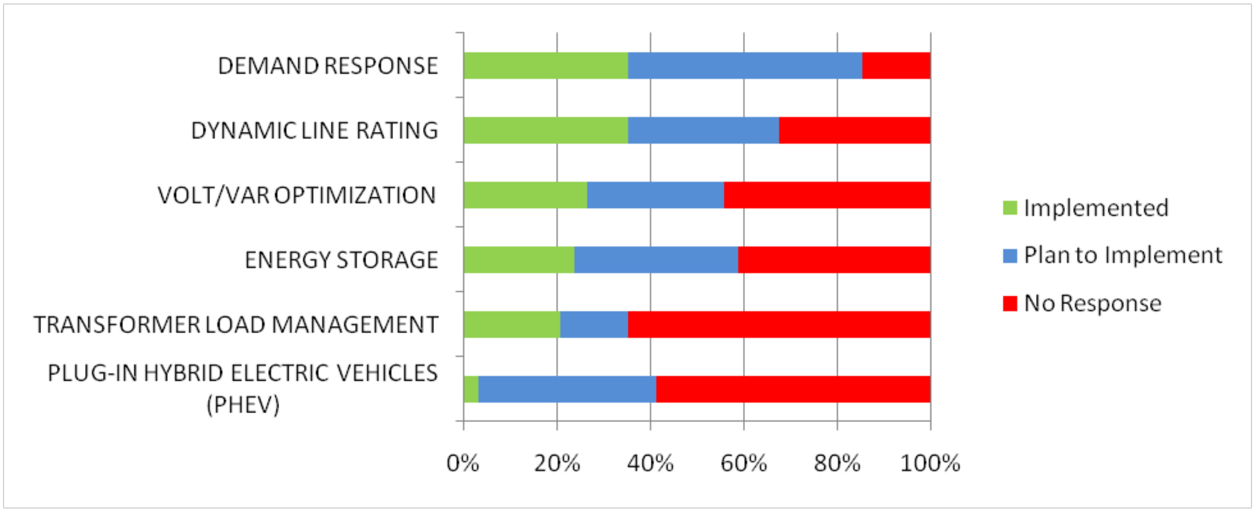

Figure 45. Smart Grid Applications Currently Implemented or Will be Implemented

Figure 45 shows the percentage of respondents who have implemented or have plans to implement the different applications.

Nearly 38% of respondents who have implemented DR programs are in systems with competitive electricity markets. DR can serve as an energy or capacity resource, can provide reserves (spinning, non-spinning, or regulating) and can support wind integration. About 45% of the respondents have plans to implement DR programs in the future.

DLR has been around for more than a decade and is perhaps the most developed of the six smart grid applications considered here. Use of the DLR can increase available transfer capacity (ATC), alleviate potential transmission constraints, and allow more efficient integration of wind generation. More than 35% of respondents have implemented DLR, and nearly 30% plan to implement it in the future. Wind is the most critical factor that affects the DLR of an overhead line (CIGRE, 2006). As a result, measuring or forecasting the wind including ambient conditions like air temperature and using this data to calculate the DLR of a line is one of the most common approaches. Other approaches propose relying on more real-time measurements and predictions about the current carrying capability of overhead lines (Schell, Nguyen, & Lillien, 2011). Regardless of the efforts to improve the accuracy of DLR, the benefits to wind integration will be realized only when the real-time ratings are in the EMS and included in visualization tools that correlate wind power forecast with the ATC and other system information.

In spite of the high ranking about the perceived value of storage to wind integration, just over 20% of respondents say they have implemented storage and many have only pumped-hydro storage. About 20% have plans to implement storage in the future.

Thirty-five percent of respondents believe that the PHEV could have a high impact on wind integration, but less than 5% have PHEVs in their system. However, close to 35% have plans to implement PHEVs in the future. Just as is the case for energy storage, it is anticipated that, PHEVs will become more advanced and cost will reduce by the year 2030. Cost reduction is crucial when one considers the number of PHEVs that must be connected to a system for the aggregate to have any real impact on large-scale wind integration as a source of energy and operating reserves.

5.15.1 Phasor Measurement Unit

PMU is one technology that is considered a critical component for smarter solutions for operating transmission networks. PMU devices can perform fast measurements of the phase and frequency of AC voltages and current. Operators also use PMU data to identify the impacts of wind energy on grid operations. With synchrophasors, operators can calculate the ratings of the devices connected to the grid more accurately. These PMU-based ratings could be integrated with EMS applications such as state estimation, and tools for congestion management and security constrained economic dispatch, to support better wind integration. Several of the respondents are currently deploying PMUs in their system. More research into how PMU data can be used to develop advanced applications is needed.

In general, more research and development is needed into how operators can maximize the contributions of smart grid technologies and applications to integrate a large amount of wind energy.

5.16 Training

Having skilled operators is critical for wide-scale deployment and the integration of wind and other variable energy resources. A need to develop training that is focused on preparing control center personnel to better utilize wind forecasting information also is required. Unless operators gain more confidence and experience in managing increased uncertainty and variability, they could end up with overly conservative and suboptimal system operations.

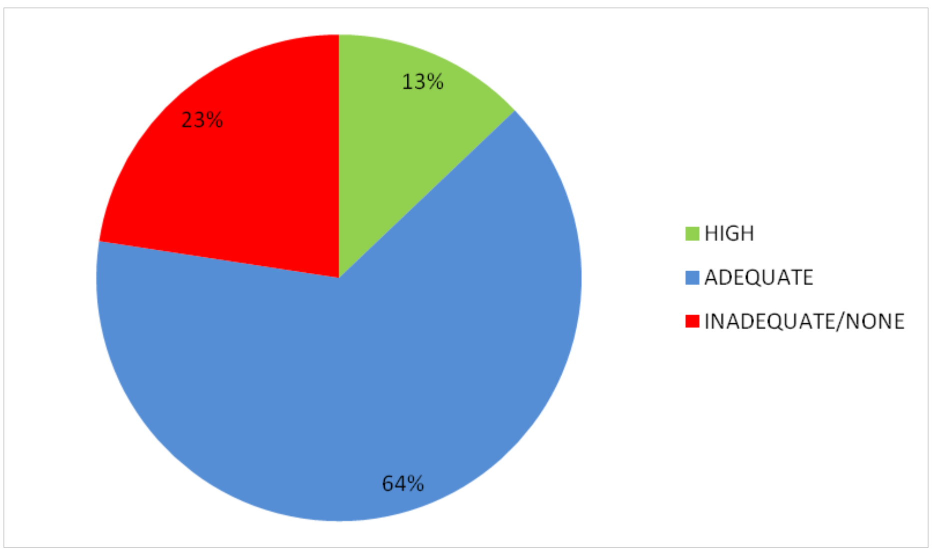

Figure 46. Current Level of Training in Control Centers to Manage Higher Levels of Wind Power

Figure 46 shows how respondents rank the level of training in their respective control centers necessary to manage higher levels of wind generation. Sixty-four percent of respondents say that the level is ADEQUATE, and 13% report that it is HIGH. The results in here also indicate a strong correlation between the levels of penetration in the system and the level of training. More than half of the 64% of respondents who indicated that they have adequate training also have wind capacity penetration level below 3%. Most of the 23% of the respondents reported they have inadequate or no training, also had limited or no experience of integrating and using wind forecast information in their daily operations. The 13% of respondents with high levels of training have deployed wind forecasting tools in their control room and have also integrated the wind forecast information with their decision support tools such as the EMS. These respondents also have greater than 10% wind capacity penetration.

Table 15 in Appendix E lists respondents' perspectives on the various skills that operators will need in order to cope with wind generation. Key skill sets include meteorology (e.g., how weather pattern affects wind resource), wind forecasting, probability and statistics.

Education of operators as more wind generation is connected to the grid is critical for successful wind integration. The goals of this education should at a minimum be twofold: 1) to give operators an understanding of the new tools for operating power systems with higher wind penetration; and 2) to help operators overcome misinformation about wind generation and the potential impacts on grid operation. Table 15 summarizes areas that should be emphasized in education and the training program for grid operators. In follow-up interviews, respondents stated that the learning curve for grid operators to become proficient in running their systems with a large amount of wind must be shortened. This shortening will enable operators to cope with the rate at which wind power plants are being, or expect to be connected to the grid. Implementing intensive simulator-based operator training programs is one approach to accelerate learning and build experience. A straightforward method for this type of training involves integrating the wind forecast into the Dispatcher Training Simulator (DTS). A DTS in effect models and mimics the EMS in the control room. Appropriate representation of utility-scale wind plants can be modeled in the DTS to facilitate operator training with wind power forecast.

For most operators, being trained to carry out numerous manual processes such as curtailment that are triggered by different policies in grid code can be very taxing and ineffective. One way to reduce the need for training in such administrative tasks in the control room is to automate the processes and integrate them with the EMS and/or other relevant decision support tools as much as possible. In addition, several respondents emphasized the need to support efforts to capture and provide operators with knowledge of the best practices and lessons learned from the integration of wind in utility operations from other systems. This education will be another way to help operators build confidence by learning from their peers.

As other results in this study have substantiated, providing operators with the appropriate decision support tools that incorporate wind power forecast will enhance their situational awareness and increase their confidence in dealing with uncertainty and increased variability. Educating operators on the functionality of the new tools will also help shorten the adoption period. The more operators are educated about wind generation and how to manage the impacts, the more likely operators will run the grid less conservatively. This will ultimately allow a greater percentage of the installed wind capacity to actually be dispatched.

6. VISITS TO CONTROL CENTERS

On-site visits were conducted at control centers of grid operators in the U.S. and Europe. These visits were designed to enable the researchers to identify examples of excellence and correlate them with the best practices found in the questionnaire results. The visits also allowed the investigators to further explore some of the survey questions through in-depth interviews of dispatchers and other control center personnel, as well as see first-hand successful implementation of decision support tools and processes that demonstrate examples of excellence.

A main focus of these visits was to learn about existing wind forecasting tools, how wind power forecast is integrated in the EMS, and other decision support tools and operational processes that have been deployed in the control rooms for managing wind generation.

Six utilities, three in the U.S. and three in Europe, respectively, were selected based on the criteria defined by the project investigators and approved by DOE. In addition to the visits, three other grid operators were not visited but are featured in the report due to the recognition and attention each has received in the industry for excellence in their work to advance wind integration in control rooms and/or for exceptional operational strategies they developed to manage wind energy.

In this chapter, criteria for selecting the grid operators are described and a list of the areas in which excellence has been demonstrated is provided. For each of the nine grid operators, each area of example of excellence is discussed in Appendix A.

6.1 Criteria for Selecting Grid Operators Visited

The criteria used in selecting the control centers to visit were:

- The utility is known to have experienced and successfully managed operational challenges due to high wind penetration.
- The current percentage of wind generation is at least 5% of the total installed generation.
- The current percentage of wind generation relative to peak load is at least 5%.
- The system must currently have at least 1,000 MW of installed wind generation.
- The future penetration of wind generation will be greater than 5%.

The fast rate of penetration of installed wind capacity over a relatively short period was common to the selected utilities. Finding the key factors related to the successful integration of significant amounts of wind in these power systems, both physically and operationally, was a key part of the investigation. Identifying, if possible, what went wrong and what could have been done different was equally important.

While there are many grid operators in the U.S. and EU that met one or several of the criteria above, it was important that the chosen group of operators were diverse. They were each chosen in terms of regional geography, regulatory and policy framework, electricity markets, system topology, generation portfolio and other operational differences. This diversity ensured that many utilities in different parts of the U.S. would find the results useful.

During the visits, researchers explored the following questions:

1. How wind energy and wind power forecast are integrated into their real-time operational system in the control center?
2. What tools have been implemented or are being developed to facilitate wind integration?
3. What operational challenges have control centers encountered and what specific solutions did they use to resolve them?
4. What are operators' future plans about the growth of wind generation in the system and for developing new tools and policies?

Several grid operators also provided the investigators with relevant system data, computer graphics and displays from the tools in their control rooms. Some of these materials have, with permission are included in Appendix A.

6.2 Grid Operators Selected

The six grid operators visited between August and October 2010 are: ERCOT (August 16), NYISO (August 17), Bonneville Power Administration (September 30), EirGrid (October 5-6), Red Eléctrica de España (October 7) and Energinet (October 13).

The three operators not visited, but featured here for their exemplary efforts to support wind integration, are 50Hertz (Germany), AESO (Canada) and RTE (France). The information about these operators was collected via the survey, and in some cases through several telephone interviews and email communications.

Each of the grid operators also featured in this report has shown excellence based not solely on the observation of the investigators, but also on feedback from discussions with other respondents and industry experts about each utility's activities in wind integration.

The remainder of this chapter summarizes the areas of examples of excellence identified for each of the nine grid operators.

6.3 Summary of Areas of Excellence

The results of the survey show that grid operators around the world are at different stages in their development and implementation of operational strategies, tools and systems in the control room to support integration of wind generation. The nine utilities featured in this report have shown excellence in several different areas. While there are differences in operations, regulatory, electricity markets design, system topology and more, the collection of tools deployed to date clearly represent industry best practices. Because of the diverse global nature of this sample, the tools and solutions are in fact the best known reference for defining the basic set of requirements for integrating wind energy in any control center.

This section lists the areas which each operator has demonstrated excellence, including any unique challenges related to wind integration which they have learned to cope with, and the tools and solutions that were used. To read the more detailed description about each area, please refer to Appendix A.

50Hertz (Germany)

- Unique operational challenges with wind integration, especially under low load conditions.
- High penetration of wind generation at the distribution system level.
- Centralized wind power forecasting system and multiple forecast providers.
- Integration of wind power with grid operations.
- Congestion management and wind curtailment.
- Planning for future system ramps.

AESO (Canada)

- Stakeholder engagement process.
- Centralized wind power forecasting and a single forecast provider.
- Simulating of wind power impacts on system operations.
- Integrating wind power in grid operations with the Dispatch Decision Support Tool (DDTS).

BPA (USA)

- Centralized wind power forecasting.
- Wind generation monitoring and information dissemination.
- Calculating and monitoring of deployed reserves.
- Integrated curtailment and re-dispatch system.
- Visualization of uncertainty to improve situation awareness.

Eirgrid (Ireland)

- Operating island power systems with high penetration of wind generation.
- Centralized wind power forecasting with a single provider.
- Industry recognized wind integration studies.
- Frequent updates of grid codes and operation procedures.
- Early involvement of operators and dispatchers in tool's design.
- Dispatching wind generation with the Wind Dispatch Tool (WDT).
- Assessment of wind power on system security.

Energinet (Denmark)

- Impact of long-term energy policy.
- Interaction of TSO with DSOs and other market participants.

- Integration of distributed wind generation in transmission operations.
- Centralized wind power forecasting and multiple forecast providers.
- Operational planning with look-ahead capability.
- Wide-area situational awareness with the Nordic Operational Information System (NOIS).
- Multi-TSO and coordination of operating reserves.
- Planning for future electricity grids and markets.

ERCOT (USA)

- Centralized wind power forecasting and single forecast provider.
- Wind integration in the Integrated in the Market Management System (MMS).
- Decision support tools for wind integration:
  - ERCOT Large Ramp Alert System (ELRAS).
  - ERCOT Risk Assessment Tool (ERAT).
- Correlating ramp events with meteorological phenomena and weather regimes.

New York ISO (USA)

- Centralized wind power forecasting and single forecast provider.
- Wind generation integrated in the MMS.
- Visualization and Situation Awareness solutions.

Red Eléctrica de España (Spain)

- Unique pioneering control center for renewable energy.
- Improving wide-area situational awareness.
- Centralized wind power forecasting.
- Use of multiple forecast providers.
- Wind forecast management process and a dedicated team to manage the forecasting system.
- Advanced decision support tools for maximizing wind power integration.

RTE (France)

- Integrating wind forecast in real-time operations.
- Centralized wind power forecasting and multiple forecast providers.
- Collaboration between RTE and the DSOs.
- Wide-area situational awareness with look-ahead capability.

7. INTEGRATING WIND POWER IN CONTROL ROOM OPERATIONS

With the amount of wind generation in power systems growing in capacity, it is important that strategies and decision support systems used in control room operations be enhanced to account for the increased uncertainty and variability. The analysis of the questionnaire results in Chapter 5, and of the areas of excellence identified for the grid operators featured in Chapter 6 and Appendix A, highlights the different applications and processes in the control room which, when incorporated with wind power forecast, can be extremely valuable for integrating wind energy. Several of the survey respondents are already implementing changes to the tools in their control rooms in order to cope with wind generation, or they have plans to do so. This chapter provides a detailed discussion of the changes in basic applications of the EMS and the MMS.

In addition to software tools and processes, many respondents agree that higher penetration of wind generation on the grid, coupled with the constant stream of large volumes of operational and non-operational system data from a disparate array of sources will change the roles and responsibilities of dispatchers and other personnel in the control rooms. New potential job positions could also emerge. Grid operators are aware of this highly feasible scenario which is already a reality in some cases. Many operators are now investigating how to deal with this change while others have already begun to take such measures as implementing a new position in the control room. This section will introduce what is generally referred to as a Wind Operator Desk (WOD). This section will also feature various aspects and different variations of the scenario as it currently exists in some control rooms.

A critical finding in this project is the importance of providing operators with tools and systems to ensure that they achieve and maintain the highest level of situation awareness (SA). This SA is subject to a manifold of uncertain sources such as more wind and other VERs connected to the grid. The last section of this chapter addresses wind energy and SA in power system operations. That discussion then posits and explores a new operating paradigm emerging in the control center. Many researchers and several grid operators believe this paradigm will be necessary to cope with greater variability and the absence of absolute certainty in power systems operation.

7.1 Energy Management System

The EMS is an indispensable technology for operating power systems. It consists of hardware and highly specialized software, as well as communications and telemetry to monitor and control the real-time performance of the power grid. The EMS helps the grid operators and dispatchers make real-time decisions to maintain system reliability. It is constantly and automatically sending command signals to generators and other devices in the transmission network; adjusting the output and connectivity so that the system remains in balance.

In power systems with negligible or no wind generation, the standard EMS-related applications used for real-time operations (i.e., CA, ED, UC, tools for scheduling and regulation) are designed under the widely accepted assumption that the load or demand, faults in power network, and outages of conventional generator were the main sources of variability and uncertainty. Historically, this assumption has shown to be reasonable. However, as the penetration of wind energy on a system increases, the conventional EMS applications are affected in many ways, which can then impact grid operations. The old assumption regarding the traditional uncertainty culprits no longer holds true. Instead, the high inter-temporal variability and limited predictability of wind power are known to affect UC, ED, CA and a host of other applications and operational policies.

Typically, wind power forecast is more accurate in the shorter time frame (1-6 hours) and less predictable in day-ahead time frame (24-36 hours). Several different studies and data from actual grid operations with wind generation have proven this fact. Thus, the incorporation of wind power forecast uncertainty into power system dispatch and unit commitment procedures in control centers is becoming more critical as discussed in (Markerov, et al., 2010). The remainder of this section will examine EMS applications that wind generation impacts. Refer to Figure 29 to see the percentage of respondents that have integrated wind power forecast in different EMS applications.

7.1.1 Unit Commitment

Unit Commitment (UC) is a process that involves scheduling and committing the generators that must be available to supply energy that consumers demand. It also ensures that the appropriate amounts and types of generation reserves necessary are available to compensate for any perturbations in load or loss of a large generating unit due to faults in the system.

Several of the survey respondents advocate that UC should be run every 4 to 6 hours, or each time a new wind power forecast is provided to the grid operators. Others indicate that, with high penetration of wind energy expected in the future, UC should be run at even shorter intervals.

Above all else, UC will not be efficient if the wind power forecast is not taken into consideration. Several respondents with a high penetration of wind expressed concern about the usefulness of day-ahead commitment decisions, which neglect the wind power forecast. Bad system forecasts and the resultant decision errors may potentially increase operational cost and impact reliability. The challenge of making enhancements to UC to cope with wind power is attracting grid operators' attention. Several new approaches also are under consideration.[47] Future UC solutions will have to be robust and flexible to account for different wind regimes and varying levels of forecast confidence under different operating conditions.

7.1.2 Stochastic Formulation of Future EMS Applications

As more wind generation is connected to power systems, many researchers predict that, with increase computational power, future EMS applications will be formulated using stochastic modeling techniques. Stochastic Security Constrained Unit Commitment (SSCUC), Stochastic Security Constrained Economic Dispatch (SSCED) and Stochastic Optimal Power Flow (SOPF) are examples of topics receiving a lot of research attention. However, as the results in Chapter 5 show, no respondent has implemented stochastic formulation of any applications yet. By 2030, advances in computational techniques could facilitate the development of stochastic EMS applications for managing high wind generation.

7.1.3 Economic Dispatch

Grid operators use a process known as Economic Dispatch (ED) to determine how dispatch generators produce electricity at the lowest cost. This cost is subject to any reliability requirements and operational limits on generation and transmission facilities. ED was introduced in utility control rooms around 1970. The initial

[47] The Federal Energy Regulatory Commission held a Technical Conference in 2010 which focus on different state-of-the-art unit commitment models and techniques. The speakers included not only researchers from academia but also several experts and practitioners from utilities. Each group gave presentations of the actual implementation of advanced UC techniques to account for uncertainty.

implementations of ED in the EMS focused only on the real-time conditions of the system. Since then, it has continuously evolved as advances in the optimization algorithms have streamlined the process. Changes in power systems infrastructure, utility unbundling, and industry deregulation, and the creation of wholesale electricity markets has driven this evolution in ED. For example, with deregulation, the traditional role of grid operators in many parts of the world was expanded to also include operating electricity markets. This new responsibility meant that market-based approaches had to be used to dispatch generators, and to manage congestions on the transmission grids. Grid operators are currently using ED solutions such as Security Constrained Economic Dispatch (SCED). According to Chapter 5, several respondents indicated that they currently use or plan to implement SCED.

Today, ED has already moved into the next phase in its evolution. The two drivers are: an increase in high penetration of variable renewable generation and the deployment of demand respond and smart grid applications. Emerging ED solutions will have to address many new issues, the inter-temporal variation and uncertainties of wind generation, which can affect the design and implementation of ancillary services markets. The new ED solutions will have to be smart enough to account for wind induced operational uncertainties. One new ED approach steadily gaining attention is based on the so-called look-ahead formulation. With this formulation, dispatchers will run power systems in a more predictive mode, ensuring that better decisions are made on how to allocate and deploy resources and mitigate any operational risks. Look-ahead and predictive mode will be discussed in more detail in Section 7.4.5 of this chapter. Smarter ED solutions also will need to accommodate variability and uncertainty of the net load, generation, interchange and transmission security limits simultaneously on a real-time and near real-time basis (Cheung, Wang, & Sun, 2009).

7.1.4 Contingency Analysis

Contingency Analysis (CA) performs an impact assessment of potential events that could occur in the system. For example, grid components such as generators, transmission lines or other equipment can malfunction and trip under certain operating conditions. If this occurs, it presents a varying degree of severity for system security. CA, like all other applications, is always subject to some inherent uncertainty. In this case only those events that can be guarded against or planned for causes this uncertainty. System disturbances not accounted for in the CA analysis pose a risk to the system, in that the impacts are not known a priority. Based on the survey results, some grid operators are beginning to change the CA application in their EMS to accommodate for wind generation.

In conventional CA, contingencies are modeled as outages of different grid components. CA computations must occur fast enough to allow the dispatcher to determine a new operating point, and to plan and execute appropriate actions that will continue to safely operate the system. With high levels of wind penetration, use of accurate wind forecast can reduce, but never eliminate, the risks of unanticipated contingency. The set of EMS contingencies must be augmented with wind resource related contingencies. Examples of these new contingencies are un-forecasted extreme events that may be caused by up or down wind ramps, which affect the wind generation output or may even cause a wind farm to trip. For more on wind ramp, refer to Chapter 5.8.1.

Wind forecast is required to determine wind-related contingencies. Performing look-ahead studies to simulate various scenarios and present probable worst case conditions to operators is also needed.

7.1.5 Generation Control and Frequency Regulation

Deviation in frequency is an indication of the imbalance between system generation and load. To ensure the supply-demand balance such as frequency stability, special controls are deployed to adjust the generation output in response to load deviations. The primary and secondary controls are the two main types of controls. Primary controls are fast, autonomous and designed to respond within seconds to a minute. Secondary control, often called Load-Frequency Control (LFC) or Automatic Generation Control (AGC) is a centralized system designed to regulate the power output of selected generation units and correct the exchange of power on interlinks between different power systems or control areas. While historically set points instructions to generators were historically manual, these are often automated today.

In a power system with high wind penetration, it is important to study the influence of wind variability on the performance of the AGC controls and the system as whole. Island systems in Ireland, Tasmania, Hawaii, and New Zealand, or those with weak interconnections to neighboring systems, e.g., ERCOT, are susceptible to frequency stability problems. AGC controls are mostly implemented on conventional generators. However, system operators are increasingly designing a centralized wind power management system, which sends set points to wind generators that curtail their output. By doing so, the overall system performance will be affected. Given the SCADA systems and rapid control abilities in modern wind power plants, the capability of wind plants to provide regulation and other ancillary services should also be considered. Examples of wind power management systems currently deployed in control centers are discussed in Appendix A. Another way to address the wind variability is to design new or modify existing AGC algorithms based on the wind power forecast.

7.2 Market Management System

Deregulation and the emergence of competitive markets for electricity not only changed the grid work operators, but also led to the introduction of Market Management System (MMS) in control rooms. This is especially the case for power systems where some or all aspects of market operations are also the responsibility of the grid operators. The MMS consists of a set of advanced analytical computational software applications. The applications provide participants with efficient methods of conducting different market transactions such as submitting bids and offers to buy or sell various market services and products for energy, balancing, reserves, capacity etc. The EMS and MMS are closely tied together and exchange data between their various applications, which are designed to ensure that the market performance does not adversely affect the reliability of the power system. In the words of an operator of both the grid and the market, “reliability always comes first.”

MMS applications are designed based on the rules and protocols that govern the market. As markets evolve, so do the rules. Consequently, MMS systems must also change and be redesigned to implement these new market rules. Part of the challenge of integrating wind energy into power system with electricity markets is ensuring that the market rules do not create barriers for the wind generators. Guaranteeing that the limited predictability of wind does not have negative impact on the performance of the market is another part of the challenge.

Several respondents who are operating systems in regions with or without full wholesale and retail competitive markets indicate that proper design of electricity markets can mitigate some impacts of wind power uncertainty. It may also remove some potential barriers for wind generators. For example, intraday markets which permit more frequent scheduling and adjustments of resources after the day-ahead market closes can reduce the impact of forecast uncertainty. Intra-hourly market clearing intervals also facilitate wind energy integration. Fifty percent of the U.S. has 5-minute energy markets today. While these markets were not initially designed to cope with a high penetration of wind, MMS applications should and, in many cases, are being enhanced to account for wind variability and uncertainty. Examples of changes that RTO/ISOs have made in MMS to accommodate wind generation are discussed in Appendix A.

7.3 Wind Operator Desk

This study has also explored the interest and viability of a so-called “wind operator desk” (WOD) within the control room. In general, minimalist control rooms for transmission system and market operators will have separate desks or positions where human operator/dispatchers responsible for different functions sit. Depending on the various tasks and functions, operators will have access to the different decision support tools, e.g., EMS or MMS. Typical job functions include security coordinator, scheduling coordinator, market operator, and generation dispatcher. The number of desks in a control room will depend on the roles and responsibilities of the grid operator.

In view of the unique characteristics of wind generation, grid operators are concerned that with the higher penetration of wind and other variable energy resources in power systems and new challenges, it may not always be practical for one individual at a single desk or position in the control room to manage conventional as well as wind generation. The fact that the decision support tools also differ suggests that a special desk dedicated to wind generation could be warranted.

Several of the respondents indicate that there will be a need for some kind of WOD in the future. However, there is no common approach on how this should be implemented in the control room. Perhaps one of the most advanced and world-renowned implementation of a desk is the Control Center for Renewable Energy (CECRE) at Red Eléctrica de España. See Appendix A.8. Grid operators in the U.S. and around the world are now discussing an idea for a similar desk. For example, BPA, located in the U.S. Pacific Northwest, sought to develop what the role and responsibilities of the operator at a Wind Desk would be, in one of its pilot R&D projects launched in 2009. Not all versions of the WOD would require a full-time human operator and a physical position in the control room. Instead, some utilities are already considering other approaches, hereafter referred to as the “Virtual Wind Operator Desk” (VWOD). AESO in Canada and RTE in France have developed versions of a potential VWOD. These approaches are discussed in Appendix A.

7.4 Wind Power and Situation Awareness in the Control Room

SA and SA-related factors were mentioned in responses to survey questions. The expected increases in wind generation in power systems will inevitably affect SA in control centers. How and to what extent is the question? In this section, the subject of wind power and SA in the control room will be discussed in detail. The goal is to highlight SA in the context of wind integration and provide a basis upon which grid operators will prioritize tools to enhance SA under conditions of increased variability and uncertainty due to wind power.

In spite of the importance of SA in power systems operations, SA historically comes to the forefront of discussions among grid operators, regulators and policy makers following major events, such as blackouts or other incidents that have tragic consequences. Therefore, this section begins with a brief discussion of power blackouts caused by the lack of SA.

7.4.1 Power Blackouts and Inadequate Situation Awareness

In a final report issued on April 5, 2004, the joint U.S.-Canada Power System Outage Task Force identified four major causes of the 2003 North American blackout. *"Inadequate situation awareness"* was one prominent cause found. The joint task force remarked that training deficiencies, ineffective communications, inadequate reliability tools and defective back-up capabilities all contributed to a lack of SA for the operators involved. Similarly, in the aftermath of a power blackout on November 6, 2006, which left 15 million EU citizens without power for several hours, the German Utility EON reported on the incidents and causal factors as the lack of coordination and miscommunications—factors that impact *team situation awareness*.

In many other major power outages, the root cause is a lack of SA and the inability of grid operators, reliability coordinators and others to visualize events across the entire system while also considering current and anticipated future impacts. For example, findings from the July 13, 1965 blackout in the Northeast U.S. and Canada included the following: *"System control centers should be equipped with display and recording equipment, which provide operators with as clear a picture of system conditions as possible."* During the blackout on the U.S. West Coast on December 22, 1982, system operators could not assess the extent of the disturbance or what corrective action should be taken, due to the volume and format in which data were displayed. This challenge made real-time evaluation of the situation even more difficult. The DOE provided recommendations in response to the electrical power outages of July 2–3, 1996 that a *"system operator must… effectively monitor and assess the state of the transmission and distribution systems*."[48] Blackout incidents in other countries, such as in Denmark, Sweden and England in 2003, and Australia in 2006, have been partly attributed to poor mental models about types of operations and the health of transmission and distribution (T&D) equipment.

As a result of these events and the societal impacts, SA has become an important priority for policy makers and electricity regulators in recent years. In the July 2009 Smart Grid Policy[49] statement issued by FERC, wide-area SA was identified as one of four smart grid priority applications.

7.4.2 What is Situation Awareness?

The NERC Real-Time Tools Best Practices Task Force defined SA as: "Ensuring that accurate information on current system conditions is continuously available to operators. This includes information on the current state of bulk electric system elements as well as on the potential impact of contingencies that might affect these elements. This information must be accurate, dependable, timely and comprehensive enough for operators to rapidly and fully understand actual operating conditions and take corrective action when necessary to maintain or restore reliable operations." (North American Electric Reliability Corporation, March 2008)

Mica Endsley provided one of the earliest, and perhaps most formal and widely used definitions of SA, in 1988 describing it as the "*perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*" (Endsley M. R., 1988). According to this definition, SA is comprised of three levels: (1) perception, (2) comprehension, and (3) projection. See Figure 47 Level 1 SA is perception and involves the sensory detection of vital cues in the environmental. For example, operators need to be able to see relevant displays or hear an alarm sound.

[48] See page 90 in *The Electric Power Outages in the Western United States, July 2-3, 1996.* Available at http://www.nerc.com/docs/docs/pubs/doerept.pdf.
[49] Available at www.ferc.gov/whats-new/comm-meet/2009/071609/E-3.pdf.

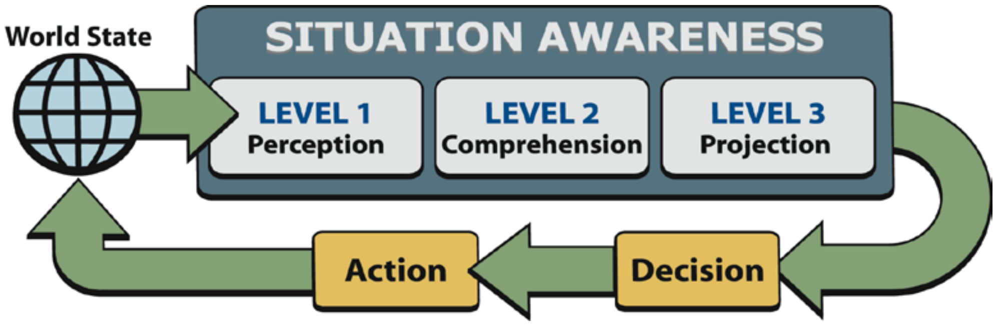

Figure 47. Situation Awareness – The Key to Good Decision Making (Courtesy of Mica Endsley)

However, SA entails more than the perception of a multitude of data by grid operators. Comprehension of the meaning or significance of that information in relation to the operators' goals is also important. This process includes developing a comprehensive picture of the world with emphasis on what most affects the individual, including power grid operators. For example, grid operators with good Level 2 SA are able to understand that a particular voltage value is "over the limit" or comprehend the impact of a new system outage on other parts of the system (Connors, Endsley, & Jones, 2007).

Projection, the highest level of SA, involves the extrapolation of projected information to determine how it will affect future states of the operating environment. Projection combines what an operator knows about the current situation with his/her mental models of the system. In doing so, they may be able to predict what is likely to happen next. For example, being able to project the impact on the system of taking a piece of equipment offline for maintenance or of a wind ramp event can be critical. A typical process for creating these projections in power system control rooms is to perform a Contingency Analysis in order to determine the set of events, e.g., wind ramps, generation outage, transformer failure, line outage, for which the system will remain stable. The higher levels of SA (comprehension and projection) allow operators to function in a timely and effective manner, under very complex conditions and with challenging tasks, in a dynamic environment.

Uncertainty is an important element of decision making. As the fundamental component of SA, uncertainty, doubt or the lack of confidence in the information provided to operators has a direct impact on what decisions are made (Endsley, Bolte, & Jones, *Designing for Situation Awareness*, 2003). This report has established that a higher penetration of wind energy will introduce more variability and uncertainty in power system operations and control. Thus, managing this increased uncertainty must be of critical concern for grid operators because of the potential impacts on SA.

In the context of integrating wind energy in control centers, little work has been done to design sufficient decision support tools and processes to manage and help mitigate uncertainty. Throughout the survey and during interviews, several respondents expressed concern that, as wind energy increases, operators will have difficulty determining how much uncertainty exists in the control room environment without the appropriate tools and systems to assist with this need. For example, tools are needed that will help operators better understand the uncertainty cone, described in Chapter 5.3, and manage that uncertainty so as to mitigate operational risk. Several responses to Questions 19, 28 and 32 found in Table 7, Table 10 and Table 13, respectively, identify factors that affect SA.

7.4.3 Visualization for Situation Awareness

Visualization is important for operators to develop all levels of SA. The need for improved interfaces and better visualization capabilities within decision support tools was emphasized in the August 14, 2003, blackout task force report.[50] Wind forecasts provide operators with projections of wind availability and are important for SA. Displaying wind power forecasts in control centers should directly support the operators' need to assess the quality of information and resolve potential operational conflicts and manage uncertainty. With a higher penetration of wind energy in the power grid, interest in the visualization requirements for situation awareness (EPRI, 2009) is growing. According to Figure 38, 55% of survey respondents ranked the value of visualization systems in integrating wind energy HIGH, and about 25% ranked it as MEDIUM. In Appendix A, several examples of visualization tools and displays of wind forecast information in control rooms of grid operators in Europe and the U.S. are presented.

7.4.4 Support for Managing Uncertainty

Confidence in wind forecast information, which leads to greater certainty, is an important component of SA (Endsley, Bolte, and Jones, *Designing for Situation Awareness*, 2003). Operators that understand forecast uncertainty will act on information confidently and appropriately. Those operators who do not correctly calibrate how reliable such forecasts are will run the risk of either acting too rashly (counting on wind energy that will not materialize) or too conservatively (not taking advantage of what the wind resources can provide). Thus, correctly understanding how accurate uncertain information, such as wind forecasts are, will directly affect the likelihood that operators will properly react to that information.

The level of confidence or certainty that grid operators place on information when assessing a situation in the control room is a key variable in decision making. With increasing amounts of wind energy, it is important that systems and tools which integrate wind forecast be designed to directly support operators in making this assessment. Some of the control centers that the investigators visited have started to take the impact of wind uncertainty and variability into consideration when specifying or designing specific tools and systems for operators. Based on interviews, respondents placed an inconsistent emphasis on SA. While the majority of respondents agree it is critical to have a high level of SA, many are not yet taking concrete actions to improve and achieve higher levels of SA as it relates to wind power.

7.4.5 Look-Ahead and Predictive Operations of Power Systems

From the perspective of the control room, there are four basic modes of operating power grids, based on systems operators' actions: (1) reactive, (2) preventive, (3) predictive and (4) proactive. Basically, predictive operation allows the operator to monitor if the system is headed for trouble. In proactive mode of operation an action is taken based on the predictive information so as to avoid the trouble Figure 48 is an illustration of the look-ahead and predictive operations. In this example, a plot of the system trajectory demonstrates that without the ability to look ahead and see the future state, the operator would make the erroneous assumption that the system is going to be stable in the future when in fact, it would become unstable. In most cases, today's modus operandi is reactive and preventive. However, in order to achieve higher levels of SA, system operators should

[50] In the aftermath of the August 14, 2003 blackout, the need to improve the interfaces and decision support systems used in grid control rooms was discussed in "Improved Interfaces and Decision Support", found in Appendix B5: A Systems View of the Modern study conducted by the National Energy Technology Laboratory for the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, March 2007. The report is available for download at http://www.netl.doe.gov/smartgrid/.

be equipped with tools that allow more predictive and proactive actions from operators. This shift will be particularly necessary as more wind generation is connected to the power grid.

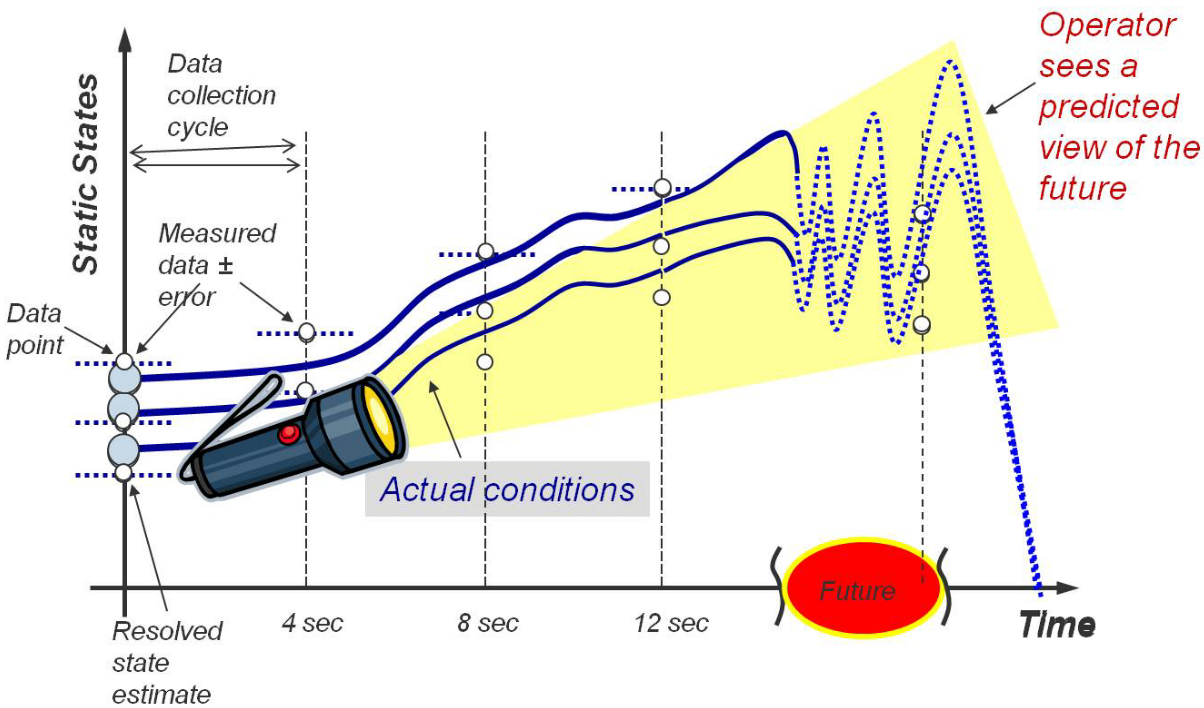

Figure 48. Look-Ahead and Predictive Mode of Grid Operations[51]

A majority of the respondents have indicated that increased wind power will inevitably lead to a new operational paradigm shift in grid operations, one that is more predictive and proactive and less reactive. For example, uncertainty about the timing, duration and quantity of sudden large wind power changes makes it necessary for grid operators to have either enhanced decision support tools or newer ones which can support predictive operations that lower the operational risks.

Since the 1960s, control center computer applications for analysis and decision-support have constantly evolved. The first generation of applications focused on the basic tasks grid operators performed— monitoring, control and information gathering. The second generation of tools targeted decision-making and taking action. The industry is now about to undergo another transformation due to high levels of wind generation. Based on the feedback from respondents, more wind power on the system is expected to hasten the development of the third generation control center applications. These applications will likely require predictive analytical techniques and visualization tools to assist operators in coping with exposure to increased variability and uncertainty.

Operational risk management will clearly require applications that allow operators to look-ahead and assess the next system conditions before they occur. This ability to project into the future provides the highest level of SA. Today, SA is achieved in control centers with different EMS applications such as state estimators and contingency analysis. However, these tools do not provide an early look at future operating conditions in a timely manner. A strong reliance on the operator to make final operational decisions, often in a reactive mode,

[51] Adapted from an original figure by JD Hammerly, formerly with Alstom T&D (now Alstom Grid Inc.).

still exists. With increased variable generation, the new operational paradigm in control rooms must evolve from reactive to predictive and proactive decision making, facilitated through these better tools. These new tools must help operators update their mental models (Woods & Sarter, 2010) about how the system will evolve based on wind forecasts. New predictive and proactive operational paradigms will require the use of advanced analytical tools including data mining, pattern recognition, faster and more accurate real-time forecasting from multiple providers, and ultra-fast simulators that can correctly mimic the interaction between variable generation and the rest of the system.

Wind forecasts are developed using weather models that contain abundant geographically distributed data. This data provides information needed to support decisions, as well as input for other forecasting tools such as load and transmission line thermal limit forecasting. Weather situational forecasting, see Figure 26, can be used to develop early warning systems that alert grid operators to the likelihood and impacts of extreme weather events.

Look-ahead and predictive solutions in the control room will enable operators to achieve Level 3 SA. However, it is important that new tools in the control room are designed using methods which consider the potential impacts of increased wind energy on SA. While techniques to design a system for SA enhancement have been applied to other complex real-time domains (e.g., aviation, air traffic control, military command and control systems), more research and development into how best to apply these methods to power system control room design is needed. See (Endsley, Bolte, & Jones, *Designing for Situation Awareness*, 2003).

It's not possible for a perfect forecast as that would mean absolute certainty. Power systems will always be operated subject to a time-varying cloud of uncertainty. Some irreducible uncertainty in power systems operations, and therefore, operational blind spots (Byers, 2011) will always be there. Look-ahead and predictive operational paradigms are not intended to completely eliminate uncertainty or remove the blind spots. Instead, it will enable operators to quickly examine operational blind spots, plan for and make better decisions. Uncertainty is always present with or without wind and other variable energy resources.

8. SUMMARY OF BEST PRACTICES AND LESSONS LEARNED

This section summarizes best practices tools, processes and procedures based on the findings in this study. Both current and emerging were identified. By analyzing results from the questionnaire, the visits to control centers, interviews with the staff at control centers and survey respondents, and a review of existing literature, investigators were able to discern these practices.

This collection of practices is an excellent starting point to further expand the general requirements for the development of new or enhancement of existing tools for wind integration. While certain aspects of these practices have been identified, it is important to note that the survey responses reflect the current views of the grid operators in an otherwise very dynamic and changing environment. The practices therefore offer important guidance in helping grid operators, policymakers and other industry stakeholders determine how to proceed with integrating high levels of wind energy in the their system. Application of these best practices must always be examined in the proper context. This examination should consider the differences in the power system and the electricity market within which it operates.

The applicability of best practices does not mean exact imitation of what other grid operators have done. While these practices have yielded good results, how they are actually implemented will differ from one grid operator to another.

The best practices have been put under six different categories: tools, data, SA, wind power forecasting training, and processes/procedures.

Tools

This report identifies and describes nine current best practice tools and decision support systems used to integrate and manage wind energy. These tools that have been deployed in control centers in the U.S. and Europe are:

- Dispatch Decision Support Tool (DDST) at the Alberta Electric System Operator, Canada
- Integrated Curtailment and Re-Dispatch System (iCRS) at the Bonneville Power Administration, USA
- Wind Security Assessment Tool (WSAT) at Eirgrid, Ireland
- Nordic Operational Information System (NOIS) at Energinet, Denmark
- Drift Planlægnings System at Energinet, Denmark
- Ercot Large Ramp Alert System (ELRAS) at the Electric Reliability Council of Texas, USA
- Generación Eólica Máxima Admisible en el Sistema (GEMAS) at Red Eléctric de España, Spain
- Centro de Control de Régimen Especial (CECRE) at Red Eléctric de España, Spain
- Insertion de la Production Eolienne dans le Système (IPES) at RTE, France

Other practices as it relates to tools include:

- Integrate wind power forecast and uncertainty in the EMS, MMS, Unit Commitment, and other control center software.

- Modify the primary controls, i.e., AGC, to account for wind variability.
- Implement forecast error management tools to compute and track forecast performance metrics to ensure errors are constantly reduced.
- Use both deterministic and probabilistic techniques to determine system reserves.
- Integrate wind power forecast with congestion management tools.

Data

- Standardize the minimum data requirements (e.g., turbine and meteorological) and create a process to certify the data.
- Develop an information portal to provide wind energy-related data to the various stakeholders.
- Develop a guide which describes the complete set of data required of the wind generators.
- Implement a real-time collection, analysis, monitoring and achieving of wind generation performance data.

Situational Awareness

- Develop dashboard overview displays for operators to monitor all wind characteristic and system performance including:
  - Net load (Load – Wind)
  - Wind power output
  - Wind speed
  - Wind direction
  - Propagation of ramp events across the system
  - Forecast error
- Develop a reserve monitoring system to track how much reserve capacity has been used and how much is left.

Wind Power Forecasting

- Implement a centralized forecasting program.
- Use multiple wind power forecast providers and develop an internal ensemble forecast as a means to reduce errors.
- Perform comparative analysis of the forecast provided by different third party forecasting services.
- Update wind power forecast in the control room and to applications frequently.

- Establish a wind forecasting management team (one or several persons) fully responsible for the forecasting program. As an incentive, link the forecast performance improvements to the team members' performance objectives.

Training

- Integrate wind forecast in training simulators.
- Deploy training simulators enhanced with appropriate wind plant models between 6–12 months and train operators on new functionalities in decision support tools in the production version of the EMS.
- Train dispatchers and operational engineers on the fundamentals of meteorology and the impacts of different weather regimes on wind.

Processes and Procedures

- Perform more frequent scheduling and dispatch of resources.
- Integrate wind power forecast in congestion management and other processes.
- Wind plants should receive dispatch instructions directly from the Security Constrained Economic Dispatch (SCED) tool.
- Implement a change-management process in the control room to facilitate wind integration:
  - Stakeholder Buy-in
  - Wind Integration Champion
- Perform various operational impact studies with strong participation from the internal engineering staff. Use the time-simulation based method which simulates all of the minute-by-minute deviations as they relate to system operations, including computing the critical system performance indicators such as the Control Performance Standards (CPS).
- Constantly update grid interconnection codes to account for new reliability criteria.[52]
- Perform an annual review and update of operational guidelines as more wind generation is connected to the system.
- Keep historical records of wind power forecasting errors. Show this information to operators in order to increase their confidence of the forecasting system.
- Enact a fully or semi-automated wind curtailment procedure to reduce the operational burden for operators especially under extreme ramp events.
- Perform more frequent scheduling and dispatch of resources.
- Integrate wind power forecast in congestion management and other processes.

[52] It should be noted that, in the U.S., grid codes should be developed subject to NERC and FERC approval.

9. RECOMMENDATIONS

This following is a set of recommendations to support the integration of wind energy from the perspective of utility control rooms. Some of the recommendations are matter-of-fact statements while others provide a more detailed explanation and further rationale for implementation. While these recommendations initially are focused on wind energy, most can be applied to integrating other variable energy sources such as utility scale solar generation.

Three categories of recommendations are provided. They are: *Short Term*, *Medium Term*, and *Research*.

- *Short Term:* "Low hanging fruit" actions utilities can implement to successfully integrate wind energy into control rooms. They are not dependent on new regulatory or policy measures, additional research or other catalyst activities.
- *Medium Term:* Recommendations that depend on new regulatory and public policy measures, or that require additional technology development and demonstration before implementation can proceed.
- *Research*: These activities require more basic or advanced research with the support of public-private partnerships, and through collaboration between industry, national laboratories and academia.

9.1 Short Term Recommendations

- **Centralized Forecast –** Implement a centralized wind power forecasting program.
- **Multiple Forecasting Providers –** Use ensemble forecasting which combines wind power forecast from several third-party forecasting providers.
- **Visualization of Wind Power Forecast –** Develop displays that allow operators to compare actual wind generation with wind power forecast data. Also, build displays to monitor net load across the system (i.e., load minus wind) in real-time.
- **Integration of Wind Power Forecast –** Enhance the EMS and other control room decision support tools incorporating wind power forecast data. The nine best practice tools presented in this report is an excellent starting point for defining initial functional requirements.
- **Rapid Update of Wind Power Forecast –** Provide rapid and more frequent updates of wind power information to control room operators and the applications they utilize. This will reduce the degree of uncertainty impacting real-time decision making.
- **Reserve Monitoring –** Implement a tool to monitor operating reserves.
- **Control Room Improvements –** Deploy new visualization tools and other decision support capabilities to enhance situational awareness in control rooms.
- **Look-Ahead and Predictive Operation –** Implement look-ahead and predictive operational capabilities in the control room. This can be accomplished by connecting the real-time production EMS with an ultra-fast dispatcher training simulator (DTS). The DTS includes replica models and algorithms of the real-time EMS. It must have the proper model of wind plants, such as a time series model with actual or simulated wind power forecast.
- **Change Management Process –** It is necessary to develop and follow a detailed change management process when integrating wind forecast in control rooms. For some operators and dispatchers, integrating

wind can be a difficult cultural change. Successful integration of wind energy in the control room requires operators to be involved early in the process.

- **Wind Forecast Management –** Assign a dedicated team to manage the wind power forecast. As part of the activities, the team should, at a minimum, generate weekly and monthly performance reports including different forecast errors for the various wind forecasting products used.
- **Operator and Dispatcher Training –** Conduct training on how wind plants function and how wind forecasting can better support operational decision-making. Appropriate training tools for integrating wind power forecast will help operators develop a better understanding of how wind plants operate and how they can interact more effectively with the system. The training simulators should mimic the actual system and include representations of wind generation assets.
- **Industry Wide Training –** Federal and State governments, in partnership with utilities and other private sector parties, should invest in power engineering programs at universities and colleges, in addition to other forms of accelerated specialized training programs that produce the requisite number of engineers and technical workers to replace experienced technicians approaching retirement. More skilled engineers and technicians are needed to ensure a secure and reliable operation of the U.S. power grid infrastructure, which faces major challenges such as increased power generation from wind and other variable energy resources. Modernization of the nation's electricity delivery (transmission and distribution) system with smart grid technologies also will require new technical workers. Training of the workforce must start now, long before retirements begins draining control room expertise, in order to ensure a smooth transition and business continuity.
- **Information Dissemination –** Grid operators should develop a website portal to provide relevant wind and system information to key stakeholders such as wind plant operators, regulators and researchers. Examples of information that should be delivered via this portal include forecasted versus actual wind power generated on a system and regional level, and other performance metrics. Several utilities featured in this report have deployed web portals dedicated to wind generation.

9.2 Medium Term Recommendations

- **Faster Electricity Markets –** New policies for operating power systems in market and non-market regions should be designed to support the frequent scheduling (e.g., sub-hourly) and dispatching of generation and transmission resources. These policies will facilitate better integration of wind generation.
- **Larger Electricity Markets –** Regulatory policies should be designed and implemented to support the development of multi-regional markets for ancillary services and reserves. This will foster a more flexible use of resources at both the local and global level.
- **More Transmission Capacity –** Inadequate transmission capacity is a key obstacle to integrating more wind energy into existing power grids. Grid operators in this survey cited the need to build transmission as one of the changes needed to increase the share of energy that comes from locationally constrained wind resources. Federal and State regulatory policies should be enacted to accelerate the building of more transmission capacity. Regional transmission planning processes should be modified to accommodate alternative transmission solutions that support harnessing the huge potential of offshore wind resources in the U.S.
- **Dashboards in Control Rooms –** Increased uncertainty and variability in grid operations will require that new decision support systems be designed with Intelligent User Interfaces, in order to improve the

communication between the operator and the computerized tools used in control rooms. By 2030, an avalanche of anticipated data, which operators must cope with, will require interfaces that can naturally be personalized and dynamic. Dynamic dashboard technologies will be needed to help operators develop higher levels of SA through the creation of new displays. These displays will be extracted from a geographic overview of a wide area, and will allow operators to zoom in and monitor an area with large wind plants and where extreme ramp events are predicted to occur.

- **Design Systems that Enhance Situational Awareness (SA) –** New control room tools should be designed to enhance SA. The requirements for achieving higher levels of SA must be taken into consideration during the design and not after.
- **Wind Event Warning System –** Develop a high wind event warning system in the control center, which will allow operators to visualize such events and take the steps necessary to protect the system.

9.3 Research Recommendations

- **System Flexibility –** Develop more rigorous methods and tools to accurately quantify, monitor and assess the degree of flexibility in a given power system for a given level of wind power penetration. Collaboration between grid operators and the research community should foster such efforts.
- **Total Value of Wind Forecasting –** Conduct more research into how operational processes and procedures are affected as a result of using accurate wind power forecast. By doing so, operators can demonstrate the total value of the investments that should be made for continuous improvements in the performance of the wind forecasting system. Grid operators and commercial forecast providers should collaborate on these efforts.
- **Develop Tools to Make Better Use of Probabilistic Information –** While the operating conditions under which grid operators make decisions is clouded with varying degrees of uncertainty, the actual decision is deterministic and binary. To address the uncertainty related to wind forecasting, many researchers and power system practitioners suggest that probabilistic information be used. Research must consider how to best integrate probabilistic tools with conventional deterministic tools in the control room. More importantly, research also should examine how probabilistic information should be presented to system operators. Research also should be conducted on the use of stochastic methods for unit commitment, economic dispatch and other processes.
- **Risk-Based Decision Making –** With the onset of increased variability and uncertainty in power systems due to wind and other variable generation, the need to integrate a risk-based approach with decision-making in the control room is critical. Unlike the deterministic approach, a risk-based technique accounts for differing probabilities and grid contingencies. Research is needed on how to quantify relative operational risk and severity of contingencies such as extreme ramp events. Decision-support tools must be designed to incorporate the risks related with varying degrees of uncertainty in wind power forecasts.
- **Extracting Value from the Deluge of Data –** Research should be conducted in the application of advanced techniques such as data mining and pattern recognition in power systems operations. Operators have developed data-driven mental models around the power system. The uncertainty introduced by wind generation and other sources leads to unpredictability in power flow and other unfamiliar operating conditions represented by more data. Operators do not have the proper tools to extract any intrinsic values locked the large volume of data, and then develop new mental models. Research should be conducted to develop new decision support tools based on data mining and pattern recognition techniques.

- **Improvements in Boundary Layer Forecast –** The U.S. should invest in improving its boundary layer weather forecasts at the national level. A collaboration of the public and private sectors is critical to improving the atmospheric observations, modeling, and numerical weather predictions needed to support a large-scale integration of national wind energy. Improvements of boundary layer weather forecasts will support integration of large-scale wind energy into the nation's electric grid. From the public sector, National Oceanic and Atmospheric Administration (NOAA) should reduce errors in relevant meteorological parameters, such as wind speed and direction in the turbine layer, thereby allowing for improved, foundational weather forecasts available for public consumption. The private sector parties, such as commercial forecasting service providers, should be responsible for providing value-added products and tailored forecasts of wind power to grid operators. Both the public and private sectors should contribute to the design and deployment of a national observation backbone network to support better boundary layer forecasts. While NOAA should provide an improved foundational weather forecast, the private sector must be the sole provider of wind power production forecasts and the related forecasting products. Investing in an improved foundational, boundary layer forecast will support many industry and national goals, including the addition of more wind and other renewable energies.
- **State-of-the-Art in Centralized Forecasting –** As more grid operators around the world gain experience from centralized wind power forecasting, it is important that lessons learned are captured and disseminated to the broader industry. Because of the benefit to the industry at-large, a new comparative study of centralized wind power forecasting should be conducted. While previous studies focused on grid operators in North America, a new study should consider the programs deployed by grid operators in other countries. Both public and private sectors should provide support for such a study.
- **Knowledge Management to Cope with the Aging Workforce –** The reality of an aging workforce will likely cause many utilities to lose experienced operators, along with vast amounts of undocumented knowledge of how the grid works. Simultaneously, utilities will have to hire new, less experienced operators, who must manage the grid in a hybrid state with both old and new equipment, most notably a mix of conventional and variable energy resources. Grid operators must begin documenting the operational knowledge and experience of existing staff before they retire. Once this information is stored and archived, sophisticated search engines and retrieval tools will be needed in the control rooms to integrate historical data with real-time operations. Being able to incorporate documented knowledge about historical grid operating conditions and critical equipment with other, more current information, will further reduce operators' uncertainty, thus enabling proper diagnosis and timely decision-making. This will lead to the emergence of a Knowledge Management System (KMS) in control rooms. Research into advanced information systems, analytical software and search engines should be conducted to specify requirements and recommendations for the implementation of advanced KMS applications. The research should be supported with investments from the public and private sectors.

10. CONCLUSIONS

This report comprises a comprehensive and detailed global survey of methodologies for integrating wind power forecasts into decision-support tools used by electric utility control centers operating systems with a high penetration of wind energy. It outlines current and emerging best practices that serve as the basis upon which grid operators can begin building strategies for enhancing existing control center tools and processes, and formulating new ones to meet the needs of an evolving grid. Specific conclusions that can be drawn from this investigation include the following:

- ***More and more grid operators are interested in applying industry best practices and examples of excellence as the starting point for deploying their own decision support systems built specifically to address wind energy integration at the control center level.***

  The collection of practices in this report is an excellent starting point to further expand the general requirements for the development of new or enhancement of existing tools for integrating wind and other VER's. While certain aspects of these practices have been identified, it is important to note that the survey responses reflect the current views of the grid operators in an otherwise dynamic environment. The practices therefore offer important guidance for grid operators, policymakers and other industry stakeholder to use in determining how to integrate high levels of wind energy in specific systems. Application of these best practices must always be examined in the proper context. This examination should consider the differences that exist across power systems and the electricity markets in which they operate.

- ***Realizing a scenario of 20% wind energy by 2030 in the U.S. will be difficult if existing decision support tools do not evolve to meet the new challenges.***

  That difficulty will be magnified if grid operators and dispatchers are not provided with meaningful, actionable wind power forecast information. Effectively and efficiently integrating wind forecast data into control rooms in a manner tailored to the needs of operators and dispatchers is a means to accommodate additional wind generation supported by reliable power system operations.

- ***Grid operators worldwide are increasingly positive about integrating wind generation as they share best practices and learn about the successes of their peers.***

  In the past, grid operators were often cautious and apprehensive about connecting wind energy to power systems. The findings in this report indicate this attitude is changing, as grid operators around the world are successfully addressing many of the early concerns. To continue reversing the misconceptions and misinformation about the impact of wind generation on the power grid, operators should continue to share best practices, lessons learned, and examples of excellence as illustrated by this report. In addition, operators also should share the promising practices of their peers who operate power grids that have higher penetration of wind generation in their system and have developed expertise in coping with operational challenges inherent to wind.

  The nine utilities featured in this report have shown excellence in several areas. While there are differences in operations, regulatory environments, electricity market designs, system topologies and more, the collection of tools deployed to date clearly represent industry best practices. Because of the diverse global nature of this sample, the tools and solutions are in fact the best known reference for defining the basic set of requirements for integrating wind energy into any control center.

- ***Wind power forecasting is indispensible for successful wind integration.***

  An overwhelming majority of respondents identified wind power forecast as a critically important prerequisite for the successful integration of wind energy. Predictability of wind plant output is the key to managing uncertainty. A paramount concern for grid operators is the accuracy of the wind forecast. 94% of the respondents indicated that integration of a significant amount of wind power will ultimately depend on the accuracy of the wind forecast. The combination of centralized and ensemble forecasting using multiple wind forecast providers is clearly the best approach currently available. More and more, grid operators in the U.S., Europe and other parts of the world have a centralized wind forecast system or are in the process of implementing one.

- ***Efficiently integrating wind energy in power systems requires that forecast and uncertainty information be incorporated into real-time decision support systems and planning tools.***

  Grid operators around the world have, to varying degrees, integrated wind forecast in different processes and tools used in real-time operations and planning. Respondents have incorporated wind forecast in real-time applications that are part of the EMS and in processes for managing congestion, voltage stability and unit commitment etc. Several grid operators already are implementing changes to the tools in their control centers to cope with wind generation, or are planning to do so.

- ***Higher levels of wind generation have shown to create uncommon system conditions and consequences that operators must learn to manage.***

  The best practices presented in this study are related to those aspects of maintaining reliability which will become difficult as more wind power is connected to the grid. The key challenge areas highlighted in the results of this report are:

  - Procuring the flexible resources necessary to cope with increased system variability.
  - Managing congestion.
  - Forecasting ramp events.
  - Efficient electricity markets.
  - Determining adequate operating reserves and transmission capacity.
  - Unit commitment and economic dispatch that account for the transmission network.

- ***Efficient integration of wind energy requires grid operators to have access to a proper mix of flexible resources ranging on the supply-side, delivery-side and demand-side.***

  Several of the changes in operational processes required for wind integration are related to measures known to provide flexibility to power systems. In their survey responses, grid operators across the board stressed the need for more flexible resources to cope with wind-induced variability on the system.

- ***Smart grid technologies can aid wind integration by providing additional system flexibility.***

  More flexible resources are needed to cope with higher penetration of wind energy into power systems. The amount and type of flexible resources needed depend on the differing behavior of variability and uncertainty of wind power, and of the system as a whole. By increasing the observational accuracy, controllability, and maneuverability of certain loads, generation and transmission resources, smart grid technologies can generally improve power system flexibility. Several grid operators with wind energy connected to their system are seeing the benefits of smart grid applications. While some of these applications are relatively well developed, others still require more technology enhancements to become economically viable.

- ***Having skilled operators is necessary for wide-scale deployment and the integration of wind and other variable energy resources.***

  The industry needs to develop training focused on preparing control center personnel to better utilize wind forecasting information. Unless operators gain more confidence and experience in managing increased uncertainty and variability, the result could be overly conservative and suboptimal system operations. In the context of an aging workforce, it is vital to reduce the learning curve for grid operators and dispatchers so they can acquire the requisite knowledge and expertise in running power systems and electricity markets with large amounts of wind generation. It also is imperative they learn the intricacies of wind forecasting so they are able to successfully cope with the fast pace at which wind power is expected to be connected to the grid. A better understanding of the best practices, lessons learned and examples of excellence profiled in this report will give grid operators higher levels of confidence in the management of variability and uncertainty inherent to wind generation. Operators will be more inclined to run systems less conservatively, thereby placing a greater percentage of wind power on the system for dispatch. Consequently, this application of best practices could enable the broader adoption of wind generation.

- ***Achieving and maintaining the highest levels of situational awareness in control centers is, in general, of pivotal importance to grid operators and will be the case especially for systems characterized by high penetration of wind energy.***

  This report has established that a higher penetration of wind energy will introduce more variability and uncertainty in power system operations and control. SA is affected by uncertainty. The findings in this project underscore the importance of providing operators with tools and systems to ensure they achieve and maintain the highest level of situation awareness. Thus, managing this increased uncertainty must be of critical concern for grid operators because of the potential impacts on SA.

- ***Integrating wind generation could require changes in the physical grid, as well as changes in operational business processes and information technology solutions at work in control centers.***

  Some of these changes require new electricity regulation and market protocols (e.g., faster electricity markets, more flexible conventional generation, larger balancing areas, dynamic interchange scheduling, controllability of load resources, surgical load shedding). Others may need local or national policy measures (e.g., building new transmission), which may take longer to implement. That said, grid operators can implement some short-term changes such as more accurate wind forecasting, automated decision support tools and visualizations of system conditions.

- ***Grid reliability standards and regulatory policies as well as laws enacted at the local, state, regional, national and multi-national levels affect the integration of wind generation in the control center.***

  Seventy-nine percent of respondents agree or strongly agree that integrating a significant amount of wind generation will largely depend on the operating policies deployed to support operators in the control room. Respondents who are in agreement with various policy statements have high wind penetration levels, while most of those who did not agree have low penetration of installed capacity. The findings in this report have shed light on the importance of coherent and consistent long-term energy policy as a driver for the industry. This is illustrated by comparing the strong correlation between government and regulatory policies and the cumulative growth of wind generation in power systems. Grid operators in different countries saw significant increase in the wind generation capacity at times when supportive public policy measures were enacted.

- ***The industry is on the verge of a new operating paradigm as high levels of wind and other variable generation and increasing operational uncertainty become the norm today and even more so as we move towards 2030.***

  A majority of the respondents indicated that increased wind power will inevitably lead to a new operational paradigm shift in grid operations, one that is more predictive and proactive and less reactive. For example, uncertainty about the timing, duration and quantity of sudden large wind power changes makes it necessary for grid operators to have either enhanced decision support tools or newer ones which can support predictive operations that lower operational risks. Based on the feedback from respondents to the survey, more wind generation on the power system has already sparked development of the third generation of control center computer applications; these new applications will support look-ahead and predictive operations and enable operators to achieve higher levels of SA.

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APPENDIX A.

EXISTING EXAMPLES OF EXCELLENCE AT CONTROL CENTERS

This appendix explains the findings and examples of excellence identified at the six utilities visited, namely: BPA (USA), Eirgrid (Ireland), Energinet (Denmark), ERCOT (USA), NYISO (USA) and Red Eléctrica de España (Spain). It also includes practices and areas of excellence demonstrated by three other utilities that were not visited whose wind integration activities are notable. These are AESO (Canada), 50Hertz (Germany) and RTE (France). A brief description of each utility's grid, the rationale for selection and how the utility met the selection criteria is given. During the control center visits, investigators interviewed engineers, operators and managers. This appendix also describes tools and operational procedures that are considered examples of excellence and illustrates some of the identified best practices.

The number of other utilities and industry stakeholders who have visited the selected sites and seen what they have achieved or referenced in their work is another good indicator that a utility has shown an example of excellence in addressing a given problem. That is the case for all of the nine utilities highlighted in this report.

A.1 50Hertz Transmission GmbH (Germany)

50Hertz Transmission GmbH (50Hertz) is a transmission grid operator and is 60% owned by the ELIA Group. The group also owns the Belgian TSO ELIA. As one of four TSOs in Germany, 50Hertz operates in the northern and eastern parts of the country. See Figure 49. Its power grid covers about 9,800 km, and operates in the German states of Berlin, Brandenburg, Hamburg, Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt and Thuringia. 50Hertz has electrical interconnections to neighboring TSOs within Germany and externally with Denmark, Poland and the Czech Republic.

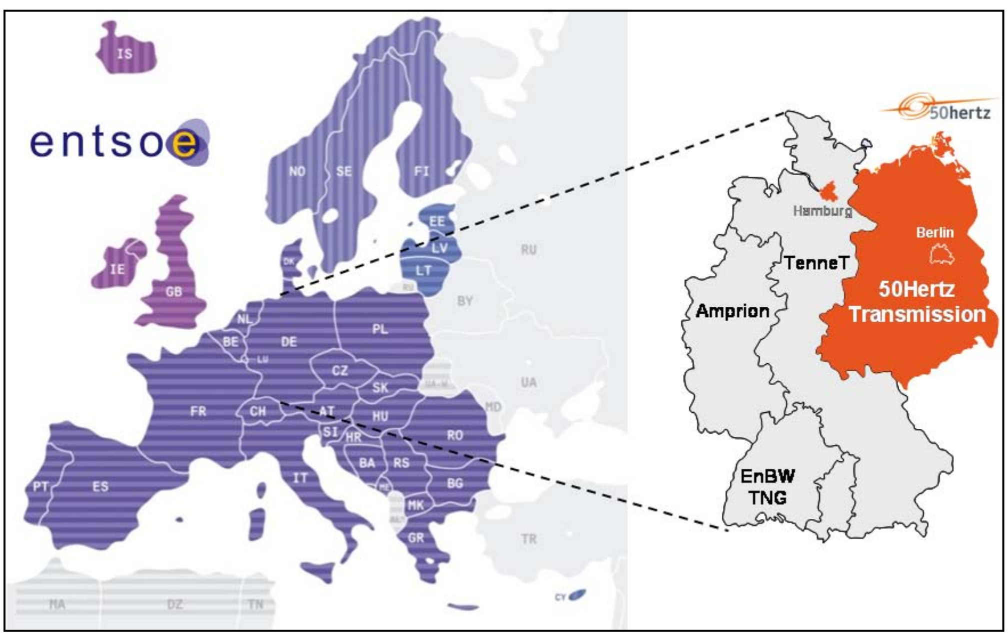


Figure 49. Map of the synchronous network areas belonging to ENTSO-E and zoom with focus on 50Hertz and the three other German TSOs (Source: 50Hertz)

At the end of 2010, the installed wind power capacity in its grid was just above 11,500 MW (preliminary value), which is about 42% of the total wind capacity of Germany. Figure 50 shows the cumulative installed wind capacity in the system from 1995 to 2010.

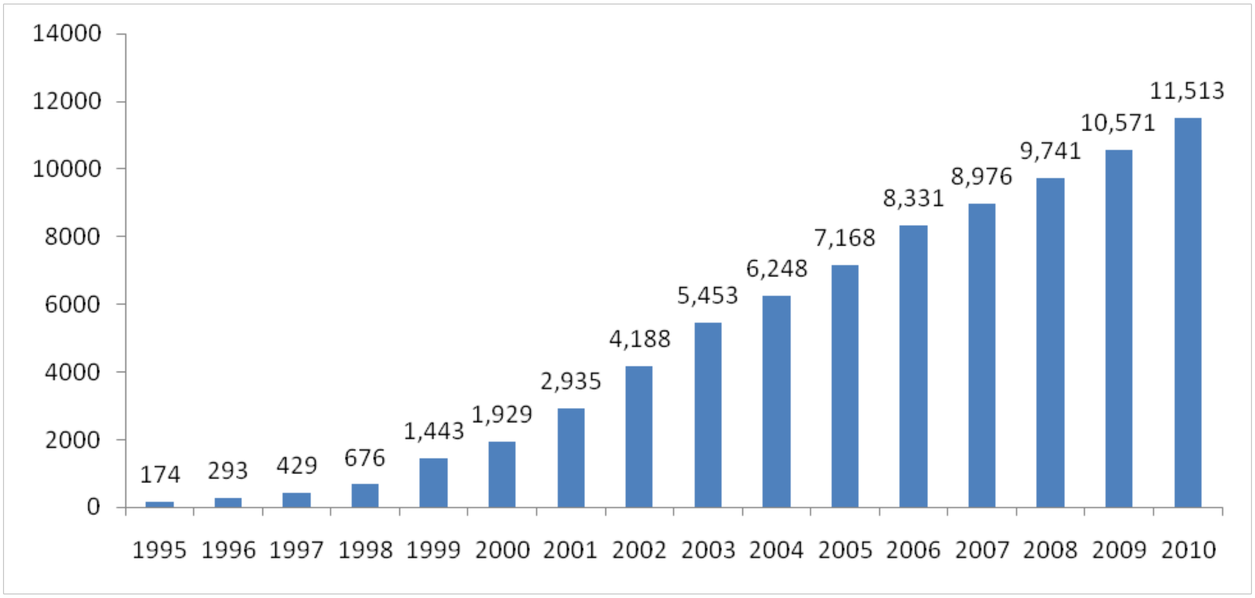


Figure 50. Cumulative Installed Wind Capacity (MW) in 50Hertz control area (Source: 50Hertz)

In meeting the European Commission 20-20-20 objectives, among others, generating 20% of energy from renewable energy sources, the National Renewable Action Plan (NREAP), which Germany provided to the EU, targets 39% of renewable energy by 2020. This percentage is equivalent to 111 GW, of which about 46 GW will come from wind power. As shown in Figure 51, a substantial amount of this capacity is projected to be built within the 50Hertz power system.

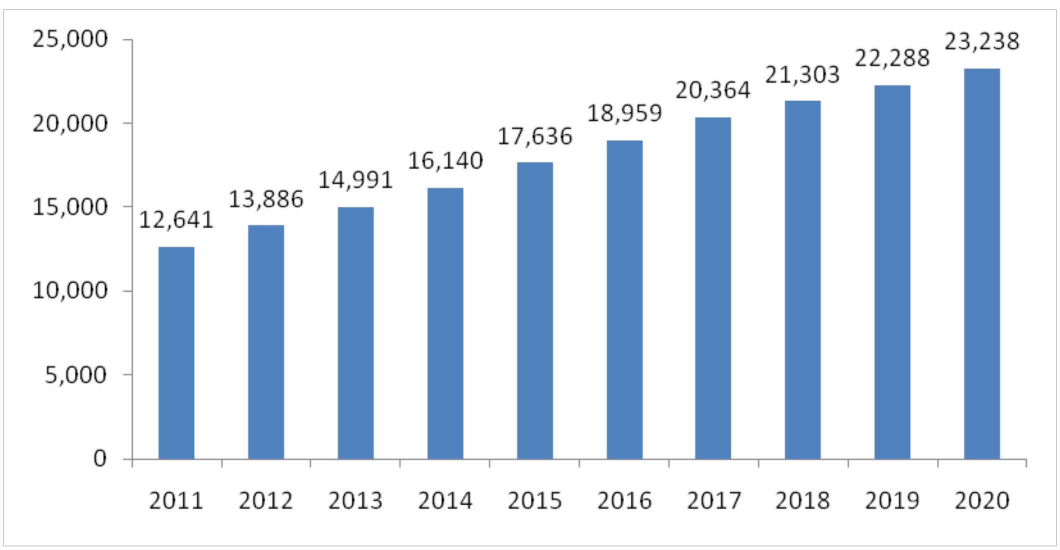


Figure 51. Projected Wind Capacity (MW) in 50Hertz control area, 2011 – 2020 (Source: 50Hertz)

A.1.1 Unique Operational Experience of Wind Integration

50Hertz has a generation mix and operational conditions, which make it very unique in the world wind power industry. At the end of 2010, the total installed generation in 50Hertz control area (i.e., including the share connected to related distribution grids) was about 38,000 MW, of which about 30% was wind. The peak load in 50Hertz control area is only about 17,600 MW (value for 2009). This currently makes 50Hertz the only known power system in the world that has this level of wind power capacity, relative to both peak load and generation. This constellation has caused several operational challenges in 50Hertz control area, especially when the actual wind power infeed exceeded the demand such as during low load conditions.

Due to the EU energy directive, 50Hertz, and other TSOs must take necessary grid and market-related operational measures to ensure priority access is granted to renewable energy generation and to minimize the curtailment of wind generation (Andrea, 2010). 50Hertz operators have developed expertise, operational processes and guidelines over the years to cope with low demand and high wind production conditions, subject to regulatory constraints imposed from the EU energy policies.

Another important aspect of wind integration in 50Hertz system is the fact that about 90% of all the wind generation is connected to the distribution system level, which is not operated by 50Hertz. 50Hertz operators, therefore, do not have access to all of the actual wind injections to the system in real-time. This lack of observability regarding instantaneous wind power means that operators must make decisions with incomplete information, thus introducing more operational uncertainty.

A.1.2 Centralized Wind Forecasting at 50Hertz

Wind forecasting is currently being used in the 50Hertz control room. 50Hertz uses three different forecast tools. It receives wind power forecast data from four different forecast service providers. Forecasts are provided for the entire 50Hertz area in Germany, and the regions within 50Hertz control's area. The forecast horizon is 96 hours and beyond that and it's updated twice a day. That information is combined using a weighted sum. Dispatchers use the information to develop an operational forecast.

A.1.3 Congestion Management and Wind Curtailment

Congestions do occur temporarily in the 50Hertz grid as a result of varying wind patterns and other events. As results from the survey indicate, congestion management is one of the processes in which wind power forecast is taken into consideration. During periods of congestion in the grid, 50Hertz redispatches power plants to manage overloads. European Commission Renewable Electricity Directive requires that wind generators are guaranteed priority dispatch, except for those conditions that affect the stability of the electricity grid. To ensure a reliable and secure electricity supply, the Directive states that wind production can be curtailed if the grid is endangered. As part of the process, curtailment orders are determined using information about generators that have the most impact on the congestion at the time. As the majority of wind plants in 50Hertz are connected at the distribution level, 50Hertz has no direct control over this major wind share. However, this curtailment only occurs during heavy flows of power. As a last measure, 50Hertz manually curtails winds by informing the respective distribution system operators about the required amount of power to be curtailed and for how long.

A.1.4 Integration of Wind Power with Grid Operations

Over the years, 50Hertz has proven to have successfully integrated wind energy management into their control room operations under a variety of challenging system conditions. Wind generation in 50Hertz control area has been shown to cause:

- Overload on control area internal power lines but also lines that interconnect 50Hertz with the neighboring control areas (e.g., the Polish TSO).
- Overloads of transformers linking the transmission level with the distribution level.
- Problems with local voltage stability.
- Problems with frequency stability/system balance.

In addition, periods with minimal load conditions frequently occur. During these times, the excess wind capacity in 50Hertz has to be transported to neighboring TSOs, where the electrical demand is much higher. This transport requires a very close coordination between 50Hertz and neighboring TSOs in and outside of Germany.

From the years of operating the system with high wind penetration, 50Hertz has developed and successfully implemented various remedial actions schemes (RAS) in order to alleviate congestion and cope with such conditions.

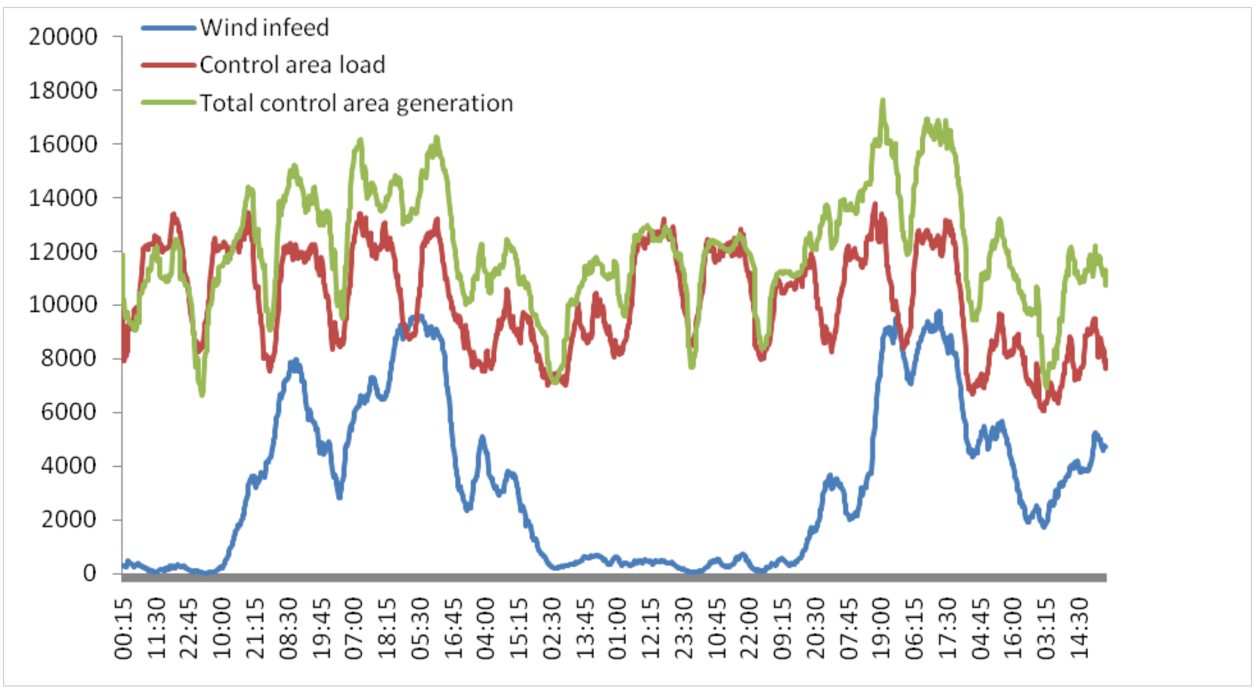
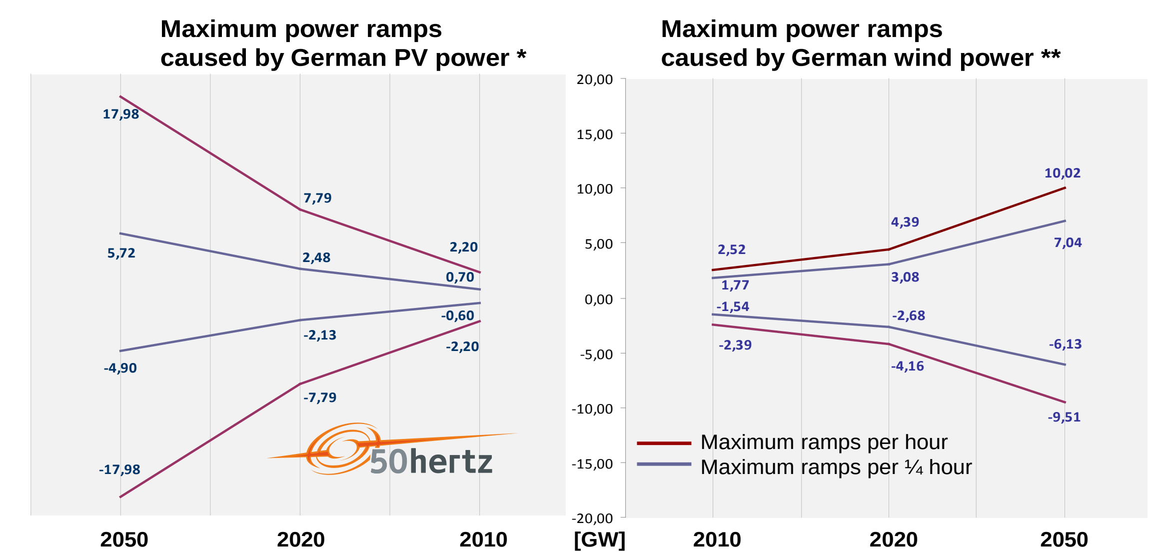


Figure 52. Wind Infeed, Total Generation and Load in MW in 50Hertz Control Area for a 72 Hours Period (provided by 50Hertz)

Figure 52 shows actual wind power generation, total generation and load in 50Hertz control area for a three-day period. The data is sampled on 15-minute intervals. The wind profile clearly illustrates an example of the operational challenges that operators must cope with to keep the system in balance. For example, besides the very challenging wind power ramps that occur over the 72 hours period, the duration of the high wind infeed periods, which last for several hours, should be noticed so that even the support from pumped storage power plants (nearly 3 GW in 50Hertz control area) can have only very limited effects. Moreover, the figure also shows an example of the total wind power infeed exceeding the total consumption. 50Hertz has demonstrated excellence in its ability to operate the system with this level of wind generation relative to total generation and load.

A.1.5 Planning for Future System Ramps

Figure 53 shows a 50Hertz outlook for power ramps in Germany's electricity system by the year 2050. The power ramps are expected to be caused by both wind power (up to 10 GW per hour) as well as Photovoltaic (PV) power (up to 18 GW per hour) and will pose new operational challenges. Although the German system is embedded in the European system, it is clear that the future electricity system must be based on other technologies and principles, in terms of power transmission and operation, in order to cope with future system ramps. Large-scale and decentralized storage as well as demand response from industrial and residential consumption provide flexibility and will be an important consideration when seeking solutions to cope with future system ramps. This type of ramp outlook provided from 50Hertz is a promising practice that other grid operators should consider.



* Installed **German PV power** 2010 as of **6/09/2010** (**14,48 GW**) and respective ramps (source: sma.de) as basis for linear extrapolation to **2020** (**52 GW** according to German National Renewable Action Plan 2010) and **2050** (**120 GW** according to 2010 study of German Federal Environment Authority "Umweltbundesamt", 100% RES scenario).

** Installed **German wind power** as average value for **2010** (**26,40 GW**) and maximum German wind power ramps in 2010 as basis for linear extrapolation to **2020** (**46 GW** according to German National Renewable Action Plan 2010) and **2050** (**105 GW** according to 2010 study of German Federal Environment Authority "Umweltbundesamt", 100% RES scenario). Updated analysis, status quo: 5th May 2011.

Figure 53. Forecast of Power Ramps in the German Electricity System caused by Wind Power and PV (Source: 50Hertz)

A.2 Alberta Electric System Operator (Canada)

The Alberta Electric System Operator (AESO) operates the Alberta Interconnected Electric System (AIES) and the wholesale electricity market in the province. As of January 2011, the total installed wind power generating capacity connected to the AIES is 777 MW, or 5.7% of the total installed generation. This capacity is planned to exceed 1,100 MW by Q2, 2012. Several thousand megawatts of wind power could be built in the coming decade.

Since 2000, when it became clear that policy and regulatory changes would result in increasing amounts of wind generation in Alberta, AESO began to develop strategies for how to integrate wind into its system. Several aspects of this strategy where AESO has demonstrated exemplary industry leadership will be discussed. These examples include wind forecasting and how it is used in grid operations, stakeholder engagement, technical studies and development of tools for grid operators and dispatchers.

A.2.1 Stakeholder Engagement

AESO has been working with wind generation developers and other stakeholders to address integration issues related to wind generation. This process involves constantly seeking the involvement and feedback from stakeholders. The process holds true especially in the development of the technical rules for interconnecting wind plants to the grids, while simultaneously addressing key issues such as wind power forecasting capability, power limiting, and ramp rate limiting. Successful implementation of these new rules is a prerequisite in ensuring that wind plants meet all wind power forecasting and data requirements to enable the AESO to better manage and cope with wind generation.

The AESO also provides information about all aspects of wind integration in the province to the public from its corporate website. Different operational data such as wind forecast and power transfers on transmission interconnectors to the U.S. and within Canada can be accessed directly from the website.

The AESO conducts technical studies examining the operational impacts of wind generation. In order to efficiently manage the wind variability and uncertainty, AESO has for several years worked to address the need to incorporate wind power forecast and forecast uncertainty into system operations for several years. In spite of a relatively small amount of installed capacity several years ago, AESO began developing the tools and processes necessary to gain the experience in integrating wind power.

A.2.2 Centralized Wind Forecasting at AESO

Most of the base-load generation is located in the northern part of the province, while other significant loads and interconnections to neighboring utilities are in the south. Under certain operating conditions, transmission flows on the AESO grid in the north-south direction can be constrained. This and other potential operational impacts identified from studies conducted by AESO concluded that an accurate wind power forecast would help operators better allocate reserves and manage wind integration on the system. AESO commissioned a wind power forecast pilot project in 2007. In January 2010, AESO contracted with a forecasting company to provide a centralized wind power forecast for Alberta. As part of the first phase, six day-ahead aggregate forecasts based on global weather information about the installed wind power capacity is posted to the AESO website. In the second phase, which is currently underway, site-specific wind power plant information will be included. Figure 54 shows wind power forecast from AESO forecasting system.

An example of the aggregate wind power forecast report is given in Figure 54. It shows the amount of wind power that will be available to the Alberta grid six days (144 hours) ahead. It is based on the current installed capacity of 777 MW from 14 wind power plants. Site specific information is not included. The probability range is displayed at the bottom of the graph with the yellow line indicating the most likely forecast.

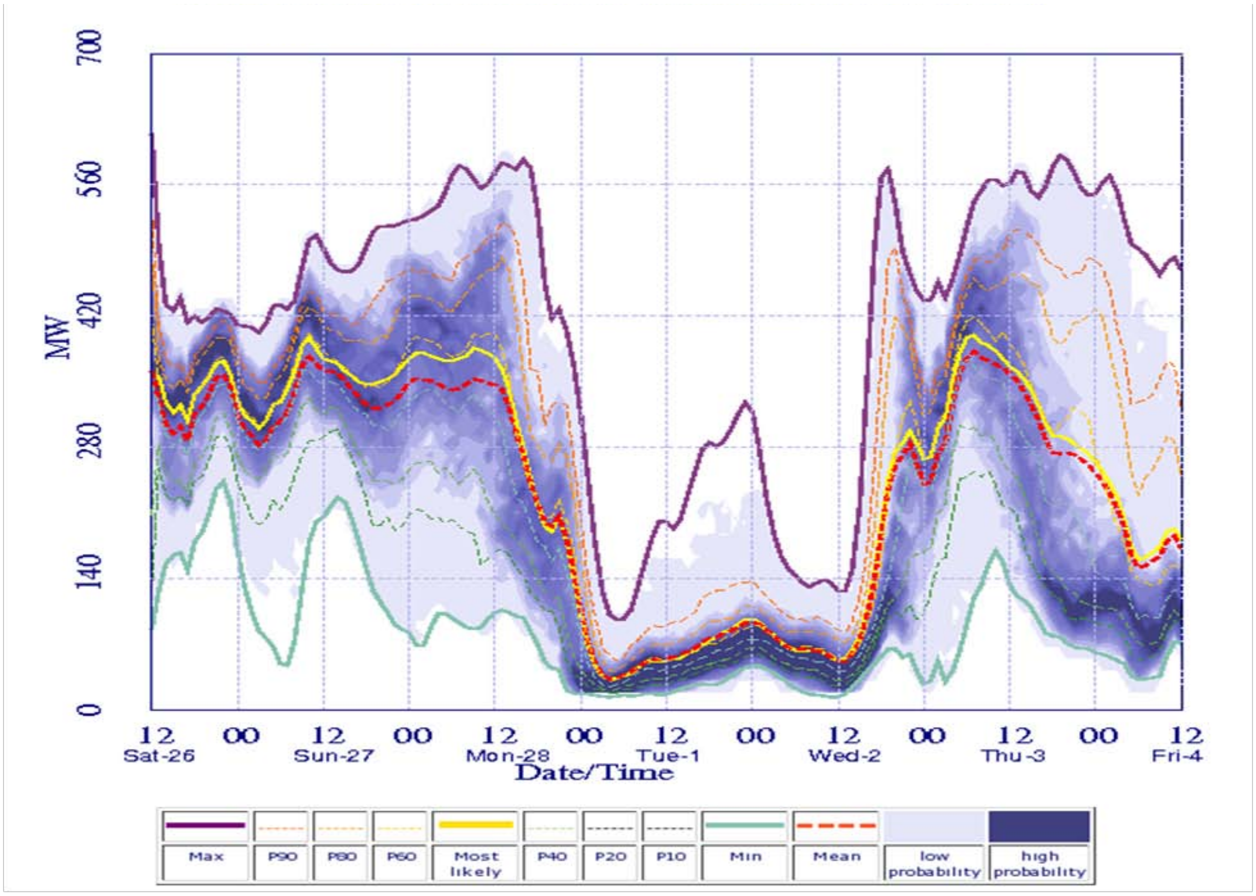


Figure 54. Alberta Six-Day Wind Power Forecast updated at 11 a.m. MST on February 26, 2011[53]

A.2.3 Simulating Wind Power Impacts on System Operations

The ability to study the impacts of wind power on system operations is important for the successful integration of wind generation. AESO recognized this fact early and, in 2005, developed a dispatch simulation model that was used to analyze and assess how wind power plants would impact system operation. The model was also analyzed for the effectiveness of its measures to mitigate the impacts. The dispatch simulation model emulates the actual behavior of the system before and after wind power is introduced. Typical operational impact studies based on statistical models examine wind power data, load data and the combination of the two. However, this does not capture the critical phenomena in the relevant timeframes for grid operations. On the other hand, the time-simulation based method simulates all of the minute-by-minute deviations as they relate to system operations, including computing the critical system performance indicators such as the Control Performance Standard (CPS) defined by NERC. See (Hu, Kehler, & McCrank, 2007) for a detailed discussion of methods, algorithms, and description of the simulation model and validation.

[53] This data was downloaded from AESO publically available information portal, www.aeso.com.

A.2.4 Integrating Wind Power in Grid Operations with a Dispatch Decision Support Tool (DDST)

In 2007, AESO presented the concept and a prototype version of its Dispatch Decision Support Tool (DDST). It has since attracted a lot of attention from peer utilities and others in the wind industry. The goal of the DDST was to incorporate wind power forecast into system operations (Hu & Kehler, 2009). That same year, work began to develop a production version. Several prototypes have been developed and tested with the involvement of the real-time operations staff in the control center. Based on discussions with engineers and managers at AESO, significant efforts have been made to integrate wind power forecast in the control centers. In 2009, a prototype model was installed in the control room and a validation test was conducted based on a real-time situation. In 2010, the DDST production version was installed in the control room and began to undergo beta testing.

Figure 55 shows a snapshot of displays from the DDST in production. An important and unique aspect of the AESO approach is the focus on operational forecasting. This approach involves forecasting operating variables like demand, supply and other system conditions such as variability and uncertainty. Wind forecast is therefore only one aspect of system operational forecasting.

DDST takes wind power forecast, wind power forecast uncertainty and load forecast into account, as well as other real-time operational information including actual load, interchange, reserves and the flexibility (i.e., capacity and ramp rate) of resources available in the energy market. The following legend explains the use of the different displays shown in Figure 55:

A. Shows ACE and AGC generation forecast.

B. Load forecast for the 60 minutes.

C. Wind power forecast for the next 60 minutes. It is currently based on a persistence forecast and will migrate to short-term forecast data following the second-phase work.

D. Interchange forecast for the next 60 minutes.

E. Forecast for the net system interchange.

F. Display used to assess energy market ramping capability and for balancing forecast system change.

G. Real-time “what-if” analysis to assess the energy market maneuver capability (flexibility to move the system up and down) that handle the system is uncertainty.

With the DDST, operators in the control room can manage and dispatch the energy market, as well as optimize the use of regulation reserve to cope with the variability and uncertainty of wind power during real-time operations. Based on the outcome of the DDST, operators can determine if there is a need to execute appropriate wind power management procedures to balance supply and demand.

In a separate independent report published by NERC, (NERC IVGTF Task 2.4, 2011), the DDST was also selected as an industry best practice for visualization and tools in support of wind integration.

Figure 55. Displays from AESO Dispatch Decision Support Tool (Provided by Ming Hu and John Kehler, AESO)

A.3 Bonneville Power Administration (USA)

The Bonneville Power Administration (BPA) is a federal nonprofit agency that is part of the U.S. Department of Energy. BPA is self-funded from the sales of products and services. Located in the Pacific Northwest, BPA markets wholesale electric power from the 31 federal hydro projects in the Columbia River Basin, one nonfederal nuclear power plant and several small nonfederal power plants. It supplies nearly one-third of the electricity used in the Northwest.

The mix of generation in the BPA system predominantly consists of hydropower. There is also thermal and wind energy, which is currently the fastest growing form of new generation. Most of the wind farms in BPA are clustered along the Columbia River near existing BPA transmission and other new transmission projects. As shown in Figure 56, wind generation installed capacity in BPA went from about 422 MW in 2005 to more than 3,372 MW by the end of 2010.[54] By 2013, the wind is expected to reach about 6,000 MW. In the long-term, BPA is planning for the future scenario of 10,820 MW of wind by 2020.

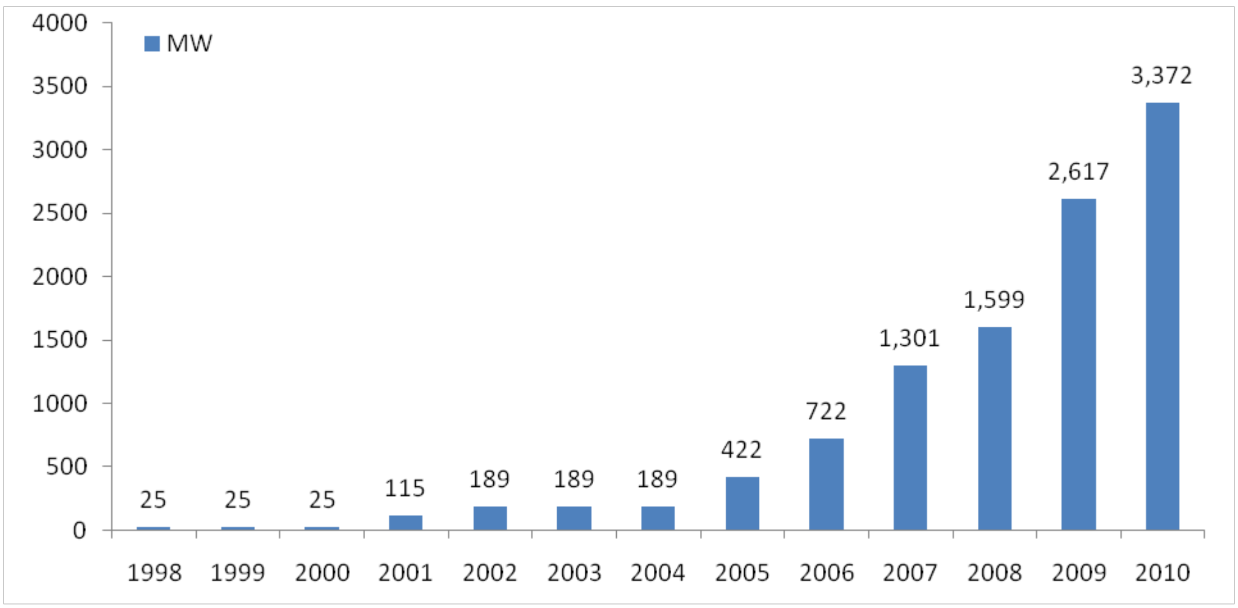


Figure 56. Cumulative Installed Wind Capacity (MW) in BPA (Source: BPA)[55]

Integrating large amounts of wind energy in a power grid that is heavily based on hydro poses a set of interesting operating challenges such as computing and managing reserves, forecasting and coping with wind ramps and environmental regulations on the use of hydro resources. BPA has been able to use the hydro to integrate wind with little or no impact on conventional generation.

BPA also manages the federally owned transmission lines and facilities in multiple states in the Pacific Northwest and other parts of the western U.S. More specifically, the BPA service territory includes Idaho, Oregon, Washington, and western Montana, parts of eastern Montana, California, Nevada, Utah and Wyoming.

[54] Data accessed on March 1, 2011 from http://transmission.bpa.gov/business/operations/wind/WIND_InstalledCapacity_CHART.pdf.
[55] *Id.*

A.3.1 Centralized Wind Power Forecasting at BPA

BPA is undertaking a project that will improve its ability to perform more accurate long-term and short-term wind power forecasts.[56] The forecast will be used to develop decision making tools in the transmission control center. Given the large amount of hydropower in BPA, tools that integrate forecast data will support scheduling and utilization of hydro-generation patterns, anticipate wind generation patterns and mitigate potential risk to grid operations. With better wind power forecast, BPA will more effectively manage the system reserves deployment, in response to a sudden increase or decrease in wind speed. Figure 57 shows a display of the aggregate a generation forecast, showing the highest and lowest forecasts from a BPA forecasting tool.

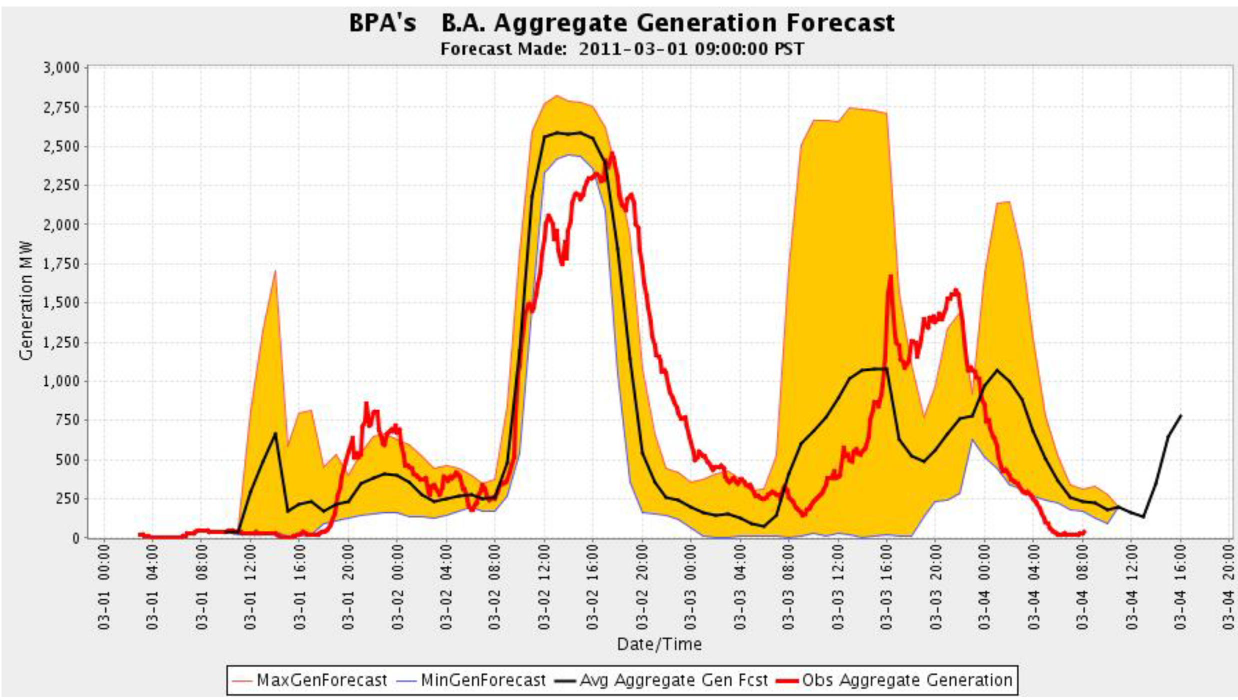


Figure 57. Prototype Display for Visualizing Wind Forecast Uncertainty (Provided by Bart McManus, BPA)

A.3.2 Wind Generation Monitoring and Information Dissemination

Today, wind energy is integrated into BPA's system operation based on schedules provided by wind generators. In addition to the schedules, the output from wind generators and other relevant plant data are sent to BPA via its SCADA system. An essential part of BPA's wind integration strategy is collecting real-time information about wind and other forms of generation, and making non-confidential information available to operators in the control room, and to generators and other interested stakeholders. As an example, Figure 58 shows seven days of historical data for load and total generation from wind, hydro and thermal plants. This information can be accessed from the section of BPA's website dedicated to wind power.[57] In addition to generation and load, historical information about deployed reserves, installed nameplate capacity, wind plant sites is also on the website.

[56] Refer to BPA wind power forecast pilot projects.
[57] See http://transmission.bpa.gov/Business/Operations/Wind/default.aspx.

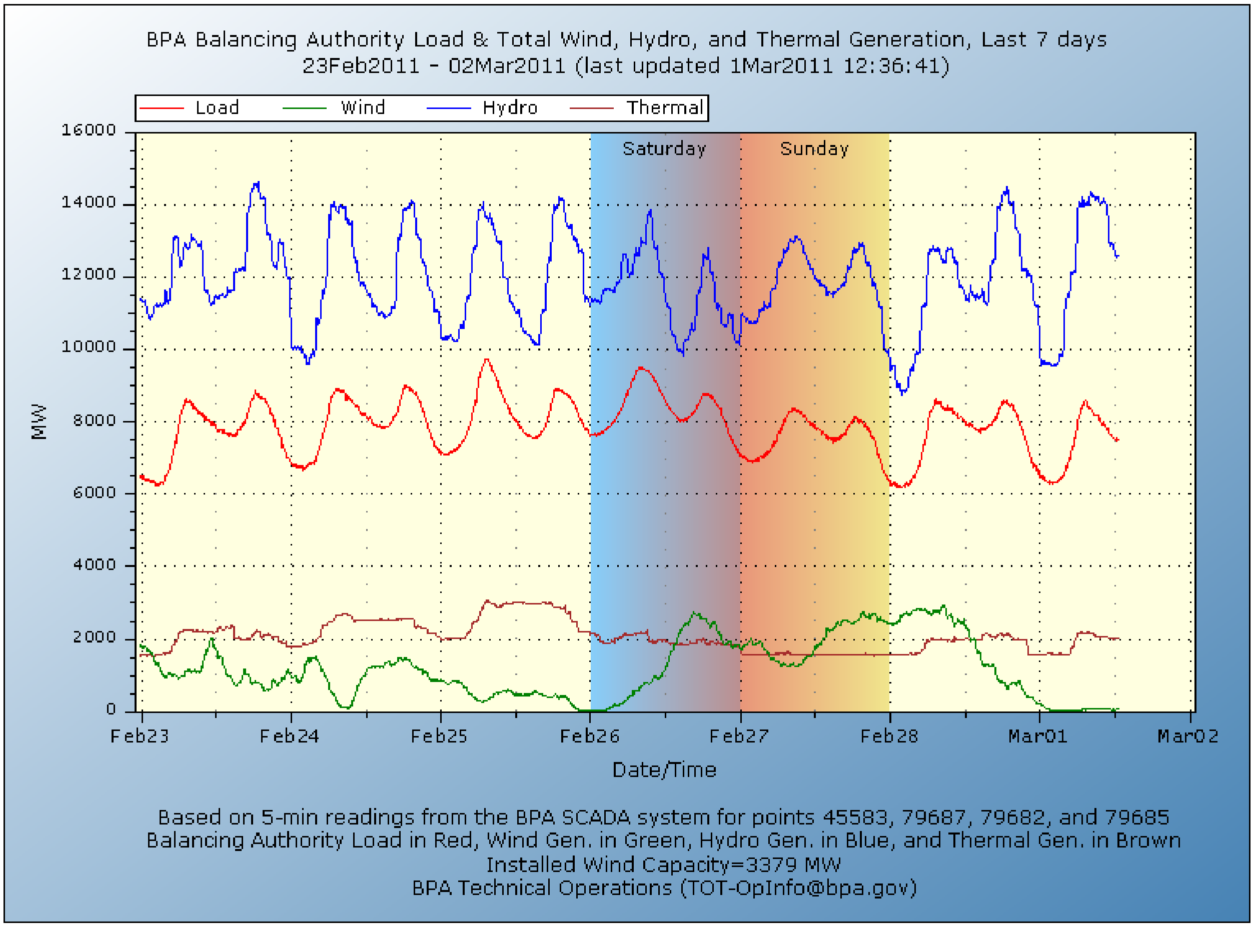


Figure 58. Load, Total Wind, Hydro and Thermal Generation for February 23 – March 1, 2011 (Source: BPA)[58]

A.3.3 Calculating and Monitoring of Deployed Reserves

A common and salient business practice of grid operators is to calculate the amount of generation reserves needed for the power system with a given load and generation under both normal and abnormal conditions. As noted previously in this report, a higher penetration of wind generation in power systems increases variability and uncertainty. Consequently, determining the amount of operating reserves under increased system variability and uncertainty is a very important task. BPA has tools to compute system reserves and display calculated reserves. While it is important to know the amount of operating reserves, it is also very useful to know how much of the calculated system reserves have been utilized. BPA developed Deployed Reserves, a unique practice to observe, measure, and monitor the reserves that have been deployed in support of system operations.

The basic process for determining the Deployed Reserves at BPA is as follows: For every hour, at approximately 15 minutes before the top of the hour, BPA accepts the next interchange schedules and new base points for generation. With that data together with the load and load forecast, BPA calculates where the system would have evolved to 10 minutes after the top of the hour or the end of the hourly ramp. During the

[58] Figure 58 can be automatically generated for download at BPA website.

course of the hour after the ramp has ended, any movement of the controlled generation (generation on AGC) is considered to be part of the total deployed reserve.[59]

To implement this practice, BPA has developed a software system known as Integrated Curtailment and Re-dispatch System (iCRS), which is implemented through BPA's Generator Advisor Web application. As shown in Figure 59 , the iCRS has a single GUI from which different information about BPA's balancing reserves, wind generation and other system-wide data can be monitored. The tool is used by operators in the transmission control center and offers a unique, intuitive and easy means to monitor reserves. With the GUI, operators can view information in Trend, Dashboard, Chart or Events.

Figure 59 shows the deployed reserves at 12:37:41 PST on March 4, 2011. The condition is normal, which is indicated with the positions of the Deployed Reserves and Wind Generation gauges. Figure 60, Figure 61, and Figure 62 show various balancing reserve, wind power and other systems data, all from the same Graphical User Interface (GUI).

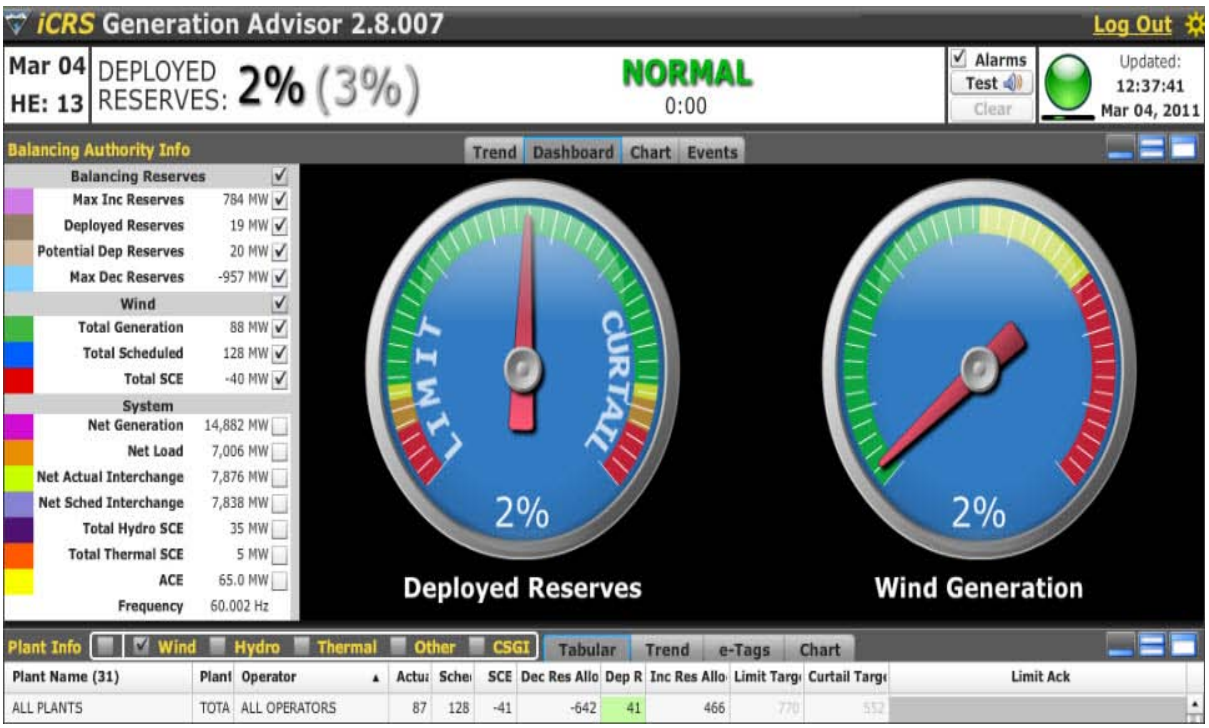


Figure 59. iCRS Generator Advisor Dashboard Display (Provided by Bart McManus, BPA)

[59] This basic description is based on information from, and discussions with, Bart McManus of BPA March 4, 2011.

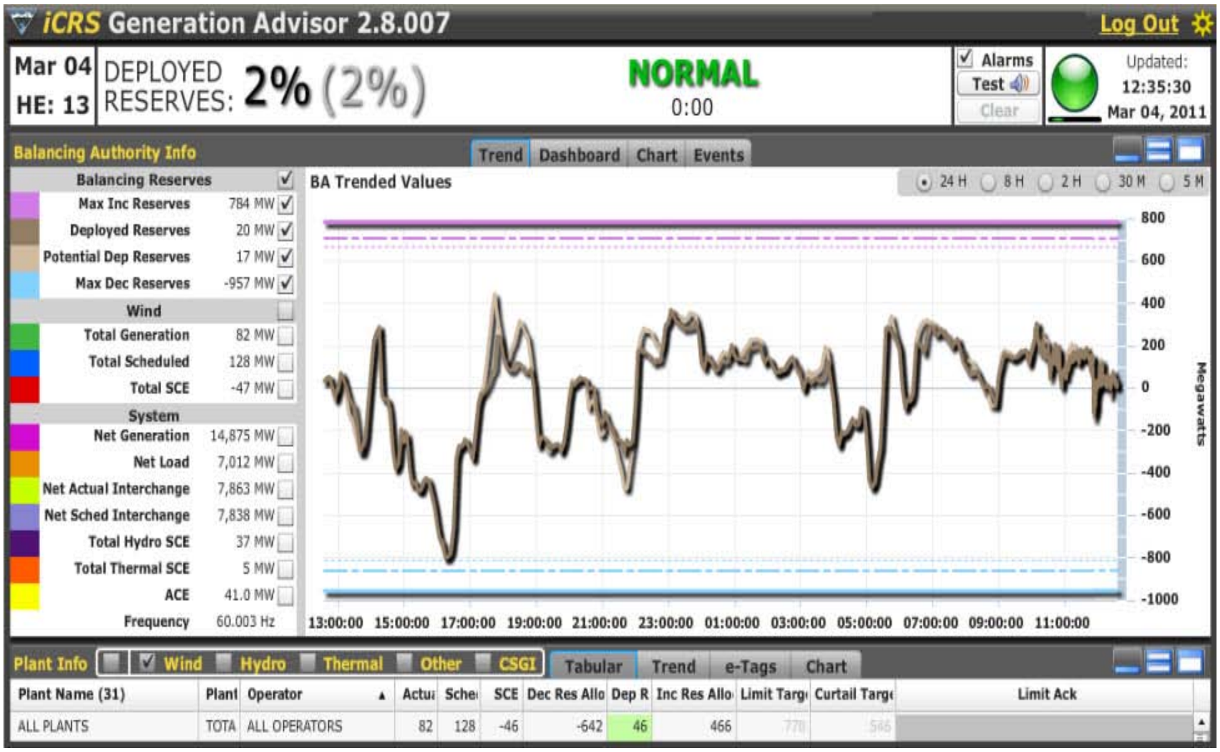


Figure 60. iCRS Generator Advisor Trend Display of Balancing Reserves (Provided by Bart McManus, BPA)

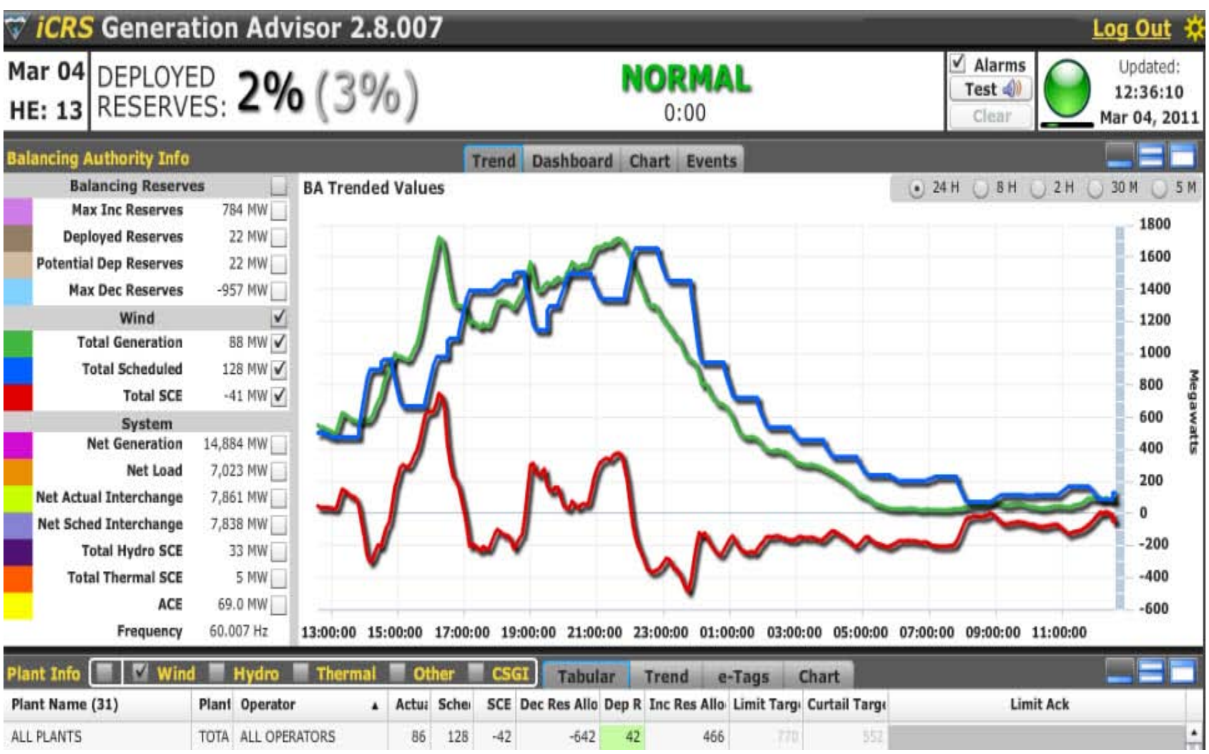


Figure 61. iCRS Generator Advisor Trend Display of Wind Information (Provided by Bart McManus, BPA)

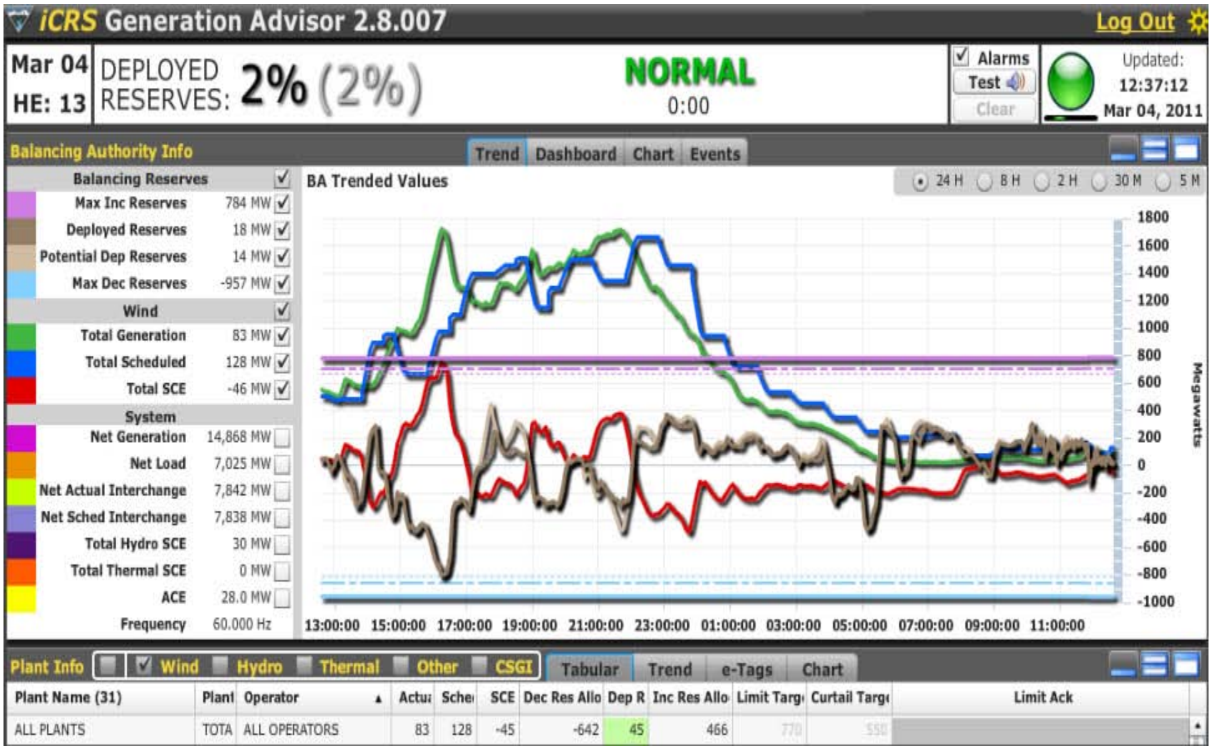


Figure 62. iCRS Generator Advisor Trend Display of Wind and Balancing Reserves Information (Provided by Bart McManus, BPA)

A.3.4 Research on Visualizing Uncertainty to Improve Situation Awareness

In anticipation of increased penetration of wind generation in the coming years, BPA is currently undertaking research to develop tools that visualize wind power forecast and uncertainty. BPA is also conducting work with technical support from Pacific Northwest National Laboratory (PNNL). Once completed, dispatchers will use these tools to obtain better views and improved situation awareness in real time. The new display will incorporate the application of both Human Factor Engineering (HFE) and Cognitive System Engineering (CSE). While dispatchers do not currently use these new displays, the following steps are taking place at BPA as part of the design:

1. Validate assumptions/hypotheses with operators.
2. Thoroughly evaluate data selected to be presented (and not presented) to each user in the control room, including operators.
3. Incorporate HFE / CSE in displays design. This should happen early in the process of system design or even before the new systems are conceived.

A.4 EirGrid (Ireland)

EirGrid is the TSO and Market Operator in Ireland. The company also owns the System Operator of Northern Ireland (SONI) Ltd. At the end of 2010, there was 1,425 MW of installed capacity in Ireland. The peak demand, recorded in December 21, 2010, was 5,090 MW. The Eirgrid system has broken many records in terms of installed capacity and actual electricity supplied from wind. For example, on the April 5, 2010 at 6 a.m., wind generation provided 50% of system demand. Total renewable output reached 55% at the same moment. Installed generation in the Republic of Ireland in 2010 including wind and other small renewable energies was 8,360 MW. As an island system, in light of the generation mix and penetration of wind relative to the total installed generation, the Eirgrid power grid is certainly prone to a number of operational challenges.

Like other member states in the EU, Ireland has defined targets to meet the EU requirements for renewable energy generation. In September 2010, Ireland submitted its National Renewable Energy Action Plan to the EU Commission, which details how it intends to reach the legally binding renewable target of 16% of total energy by 2020. In addition to the EU obligation, the country has also adopted a policy goal that requires 40% of generation by 2020 come from renewable energy sources, namely wind. It is expected that approximately 4,632 MW of wind generation will need to be installed by 2020 to meet the 40% national renewable target in Ireland. Figure 63 shows the indicative wind targets from 2010 – 2020. Note that, while the indicative target for 2010 was 1,796 MW, the actual total installed capacity was less.

Another 1,600 MW of wind will be required in Northern Ireland assuming that similar policy objectives are adopted. Combined, the system of Ireland and Northern Ireland could potentially seek to operate with more than 6,000 MW of wind on the joint power system by 2020.

A.4.1 Operating an Island System with High Wind Power Penetration

Based on discussion with staff at EirGrid, the impact of a large amount of non-synchronous generation on the island's power system will significantly affect its operation. In some cases, the existing levels of penetration already pose some operational issues and concerns. EirGrid and SONI are beginning to adapt to this new situation by investing in their control centers in Dublin and Belfast. These utilities are also developing a range of procedural measures and operational tools to integrate more wind on the system. While the Eirgrid system is small compared to several others studied in this project, peer utilities will look at it as an example of how an island system should operate with high penetration levels of wind generation.

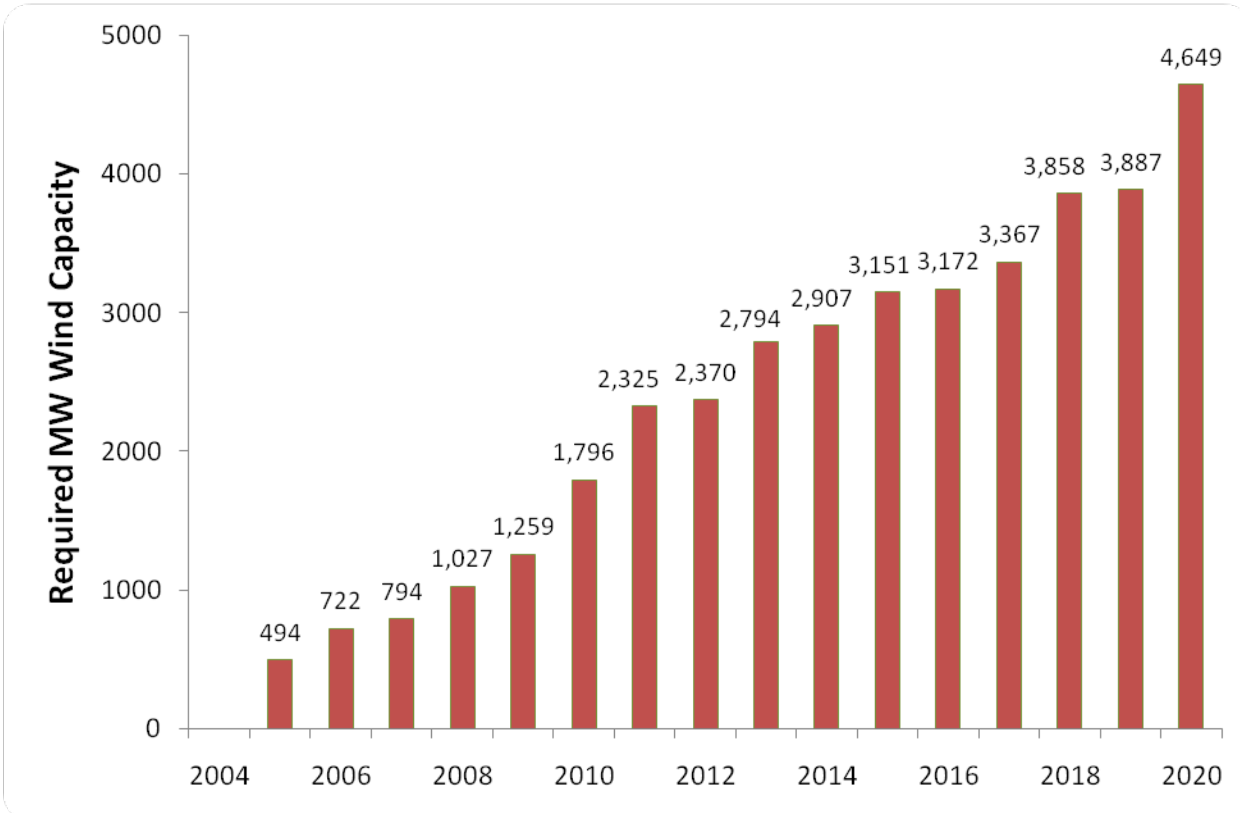


Figure 63. Cumulative Installed Wind Capacity to 2011 and Indicative Targets from 2010 – 2020 (Provided by Frank Groome and Jon O' Sullivan, Eirgrid)

More than 40% of the wind farms in Ireland are currently connected at the distribution level in the Eirgrid system. This fact means that the interaction between Eirgrid and the DSO is very important. Tools and processes are constantly improved, and new ones are developed to ensure that appropriate information is exchanged between Eirgrid and DSOs. This exchange is done in a timely manner to ensure system stability and reliability.

A.4.2 Industry-Recognized Wind Integration Studies

Eirgrid conducted several studies on the impact of wind generation as a benchmark and reference guide for both grid operators and system planners around the world. The *All Island TSO Facilitation of Renewable Studies* (Eirgrid, 2010) is one example. The study identified several issues related to operating the two power grids on the island at the projected penetration levels in 2020. The level of involvement of Eirgrid engineers and grid operators is unique to these studies. This involvement is in stark contrast to studies that some grid operators commissioned that are primarily conducted by external consultants with limited participation of the internal operational personnel. This participation of Eirgrid engineers ensures a strong link between interpretation and the application of the findings. Eirgrid's role as a leader in wind integration, in spite of the size of its grid, is also demonstrated by the tools being developed and deployed in the control room (e.g., the Wind Security Assessment Tool). Furthermore, Eirgrid's staff participation in conferences on wind integration, and the number of articles and reports written by its engineers, and published in international peer-reviewed journals is noteworthy.

A.4.3 Updating Grid Code and Operation Procedures

The development of the Grid Code for interconnecting wind farms to the power grid is an important activity at Eirgrid. It's also an essential part of its strategy to successfully integrate wind generation both to the physical grid and operationally in the control room. As more wind generation is connected to both the transmission and distribution networks in Ireland, and as these networks also undergo changes, it is important that the grid interconnection codes be updated to reflect new operating conditions. Eirgrid's grid code is continuously reviewed and updated in response to changing regulatory policy at the national and EU level.

A.4.4 Early Involvement of Operators and Dispatchers in Tools Design

Wind integration involves change management as the connection of significant amounts of wind generation can mean a change in the operational culture. Eirgrid's success in integrating wind energy is a result of the early involvement of system dispatchers in the process, when designing new tools for the control rooms or making changes in the operational guidelines. This involvement also increases the pace at which operators begin to use the new tools.

A.4.5 Wind Dispatch Tool (WDT)

Eirgrid must dispatch a wind generator under the Priority Dispatch, according to the Provisions in the EU energy directive. However, under operating conditions that could affect system stability and reliability, wind generators may be curtailed. To address both the issue of dispatching wind and system stability in the presence of wind, Eirgrid has developed two decision support tools that are used by operators and dispatchers in its control room.

Eirgrid's Wind Dispatch Tool (WDT) features two distinct forms of wind dispatch, *Curtailment* and *Constraint*. Curtailment is a global function that allows the Eirgrid operator to reduce the output of all participating Wind Power Stations (WPS) in situations where the total wind output is considered to be a threat to system security. Constraint dispatch allows the operator to reduce the output of particular WPS's, which is normally a result of local network constraints. It is possible to have both curtailment and constraint in operation simultaneously.

Curtailment Operation

From this WDT tool display shown in Figure 64, the operator enters the total required output of participating WPS's and requests the application to calculate revised set points for each unit. The total reduction required is allocated across the participating units ("Curtail Selected" flags) in proportion to their actual outputs and capacities. The set points are displayed to the operator for review (the operator may modify these, if appropriate). When satisfied, the operator issues the new set points and selects the "Issue Curtailment Set-points" option. The application first turns on "MW Set-point NCC Control" and then issues the set-point value. Application logic is provided to track the actual implementation of the set points and inform the operator via alarms of any implementation failures. All steps in the process are logged in a special application log, which is subsequently stored in the Historical Information System (HIS). This is necessary for audits and resolution of any disputes.

Constraint Operation

For constraint operation, the operator directly selects those units that need to be constrained ("Constrain Selected" flags), enters the desired set-points directly and issues them using the "Issue Constraint Set-points" option.

Removal of Curtailment/Constraint

By selecting the remove option, the curtailments or constraints in operation are canceled. The application has special logic, which ensures that the wind plant returns to free dispatch, based on the wind level at that time.

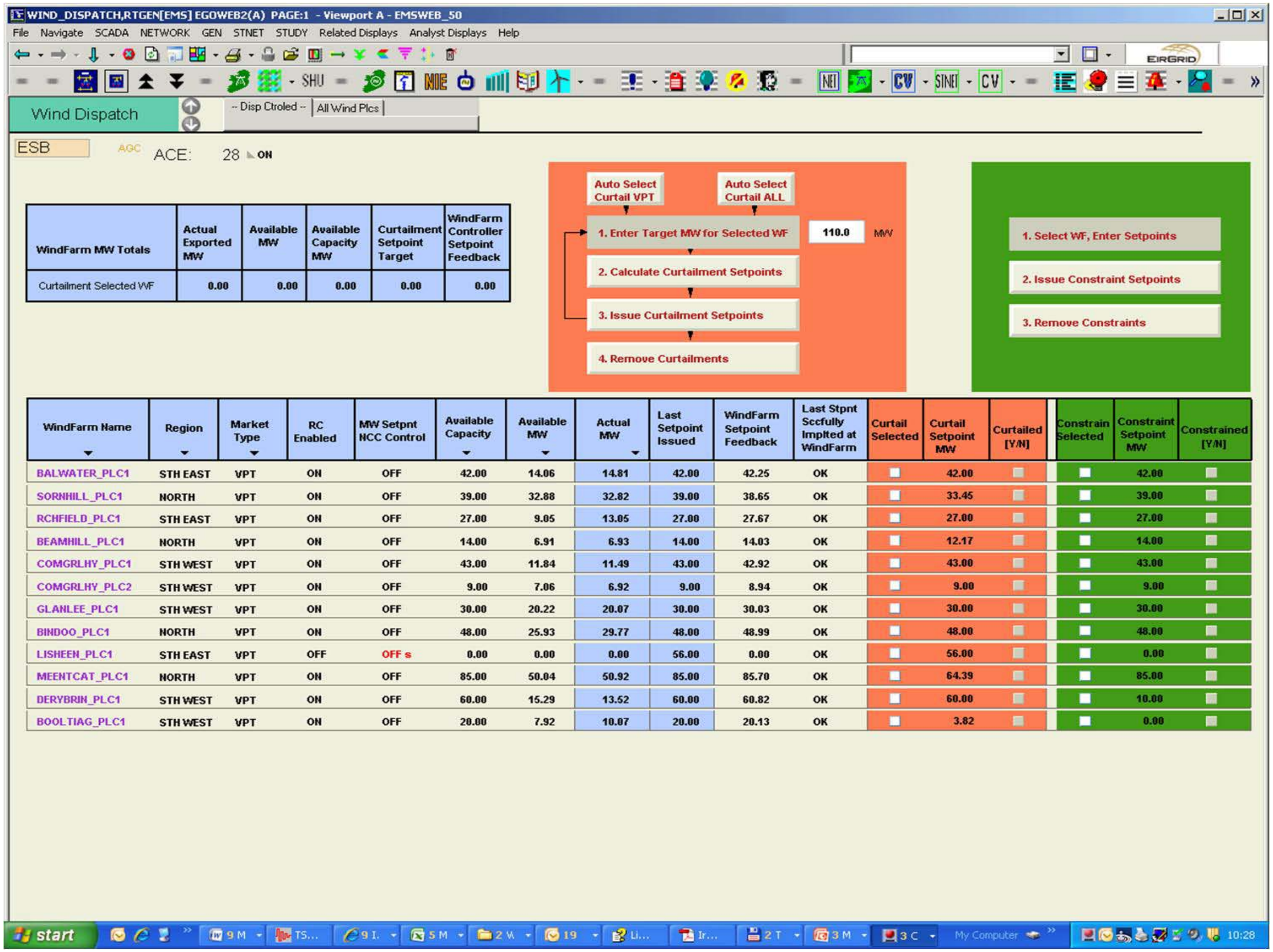


Figure 64. Eirgrid Wind Dispatch Tool Display (Provided by Jon O'Sullivan, Eirgrid)

A.4.6 Assessment of Wind Power Impacts on System Security

As previously mentioned, the Eirgrid transmission system is facing increasing wind penetration today and more is expected in the next decade. For example, in April 2010, wind generation supplied 50% of the load. This level is expected to grow as a result of pursuing the 37% wind generation target in Ireland. (At present, it is 12%). System operators are also very concerned about the highest amount of wind generation that the system can accommodate at any given time, and how this affects system stability.

To address these issues, Eirgrid developed its Wind Security Assessment Tool (WSAT) together with an industrial partner. WSAT was installed and officially launched at the National Control Center (NCC) in October 2010.

Figure 65 shows the functional flow chart of the WSAT. It interfaces with other tools in the control center including the EMS, and on-line Voltage Stability Assessment Tool (VSAT) and on-line Transient Stability Tool (TSAT). Input to the WSAT includes a real-time snap shot of the system and wind power forecast.

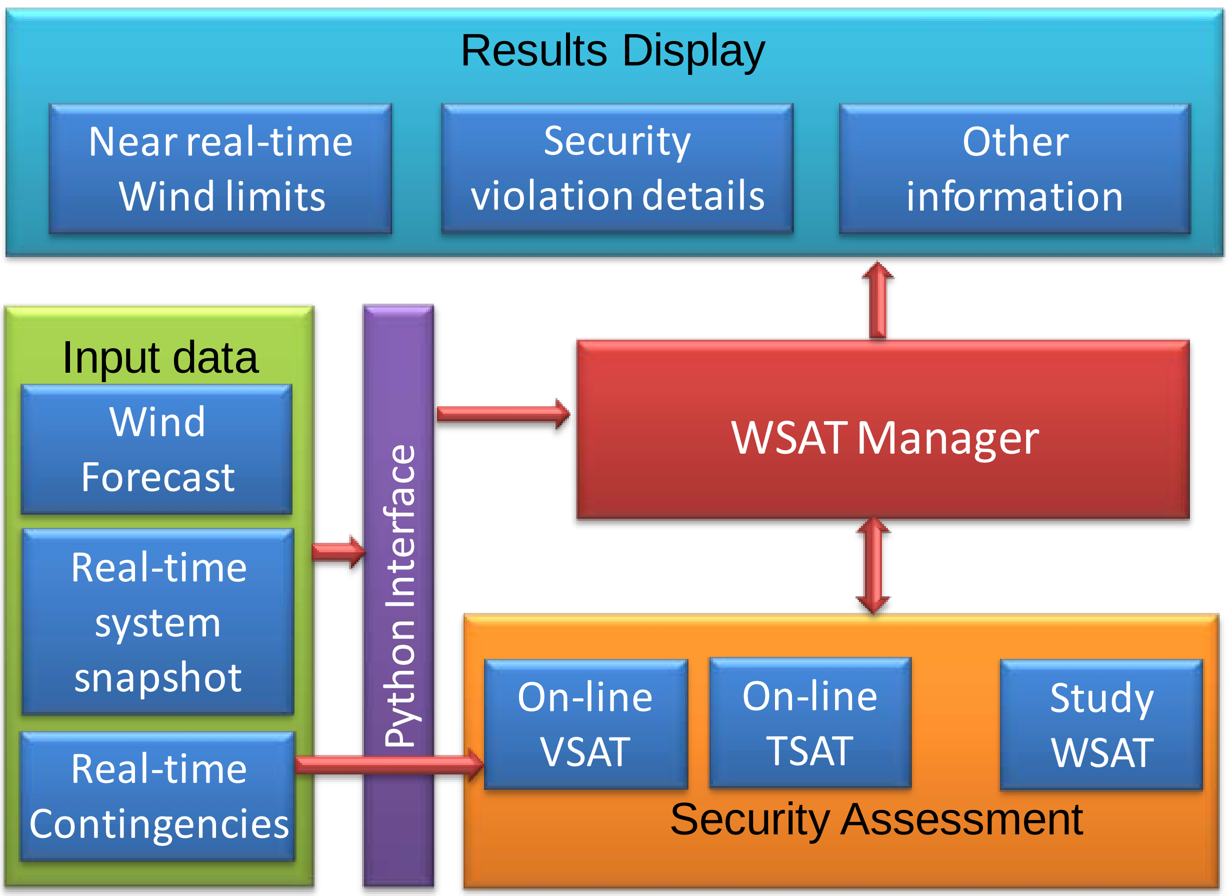


Figure 65. WSAT Functional Flow Chart (Provided by Ivan Dudurych and Jon O'Sullivan, Eirgrid)

In Figure 66, the main WSAT display screen used by the NCC operators and dispatchers is presented. For ease of use, the operators can navigate to the VSAT and TSAT applications from a single display.

VSAT's security assessment is further extended to include power transfers caused by increases in wind power and decreases in conventional generation based on specified merit orders. Power transfers due to changes in load flows are also considered. WSAT performs the system security analysis using the VSAT and TSAT tools every 15 minutes. Security violations and other information such as Remedial Action Schemes (RAS) are also available to operators to aid their decision making.

Figure 67 shows a WSAT display, which summarizes some of its results. Specifically, operators can see and compare the wind power forecast, the actual wind power production and the limit of the wind power generation that a system can absorb without compromising the system's security.

EirGrid will continue to make enhancements to WSAT. Some of the potential improvements include:

- Ability to perform frequency stability analysis as part of security assessment.
- Ability to forecast system stability, e.g., performing stability assessment of the system within a time frame of 12 to 48 hours.

In terms of wind integration from an all-island perspective, EirGrid also plans to launch the WSAT in SONI's control center.

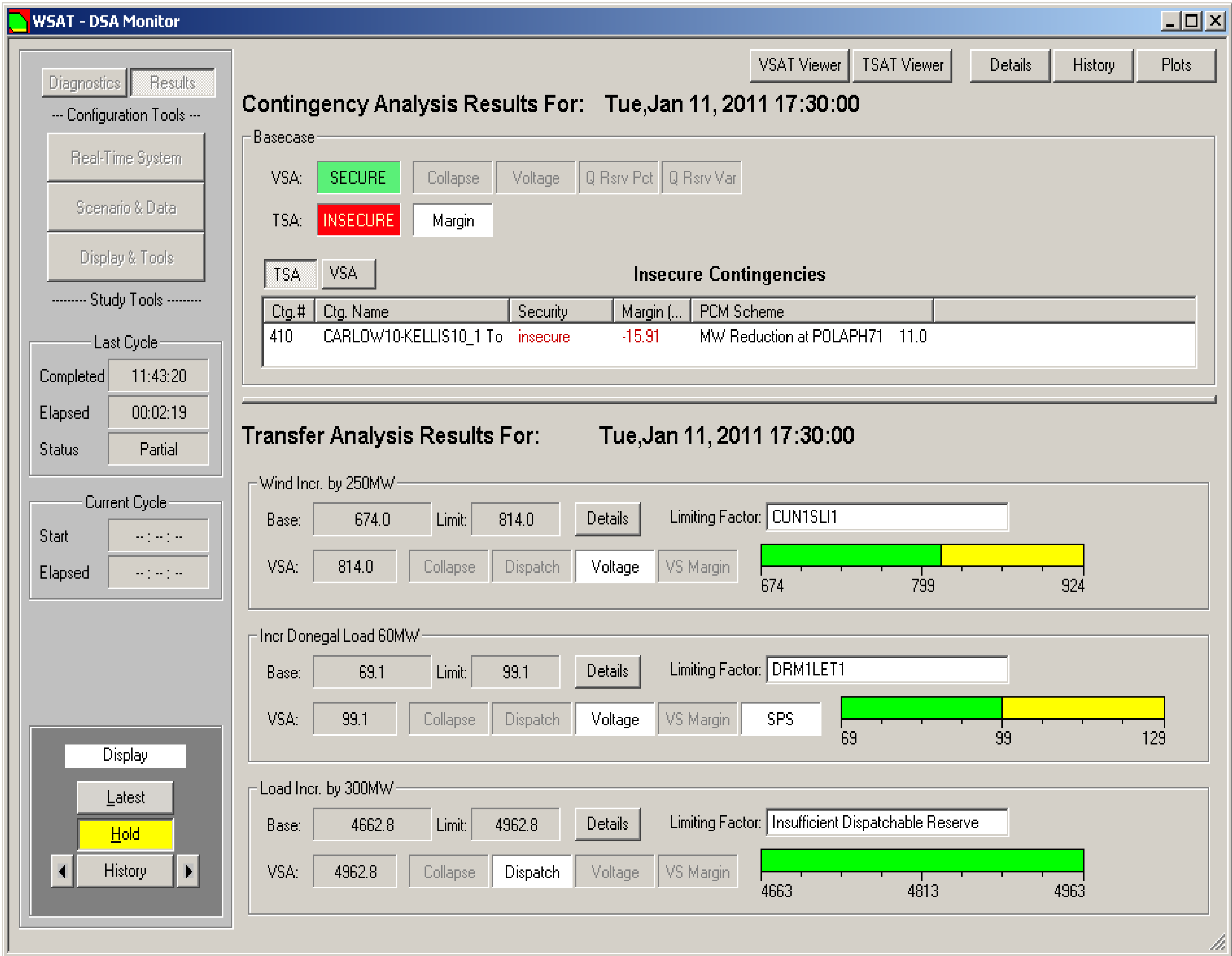


Figure 66. Main WSAT Display or NCC Operators and Dispatchers (Provided by Alan Rogers and Jon O'Sullivan, Eirgrid)

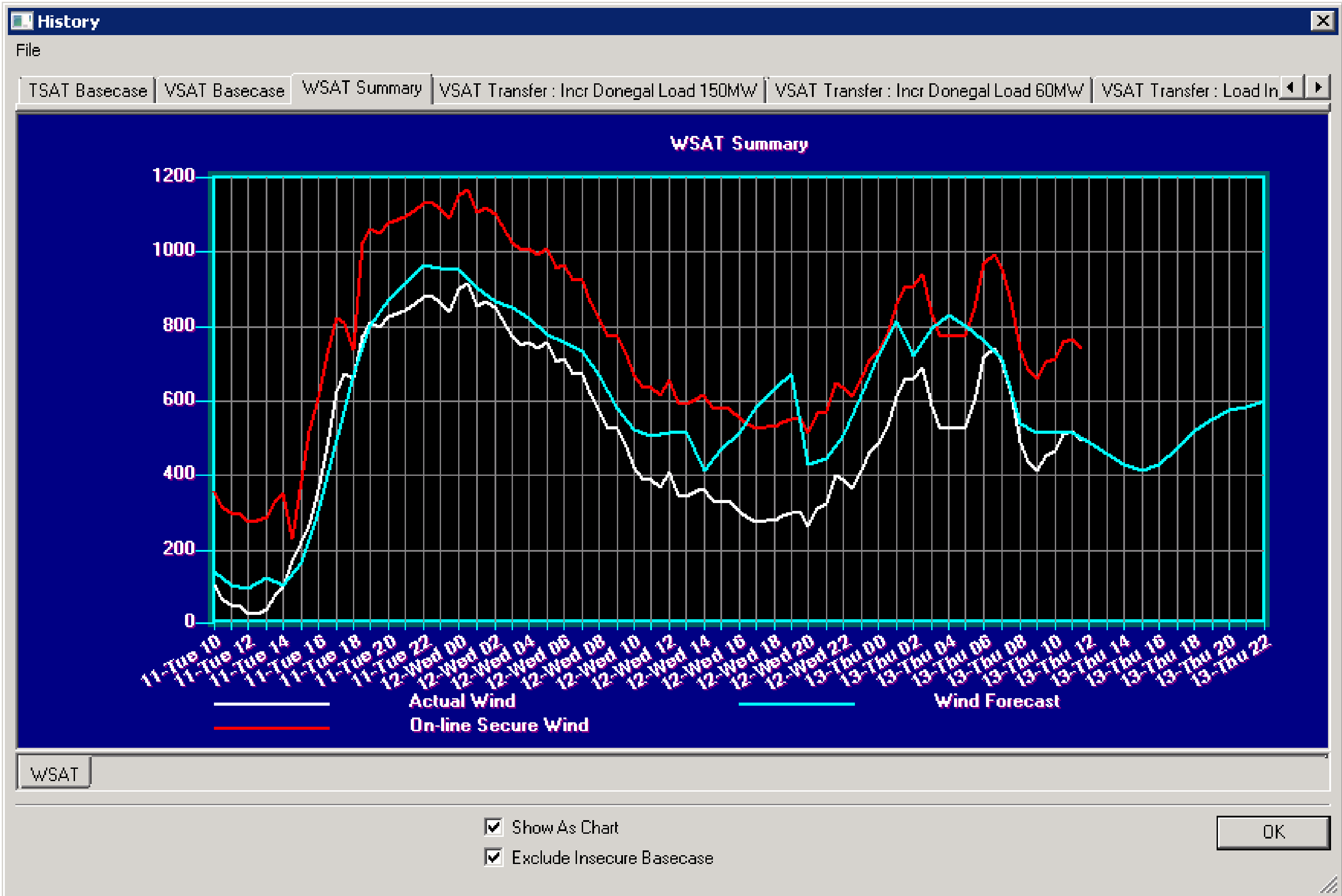


Figure 67. WSAT History Display (Provided by Ivan Dudurych and Jon O'Sullivan, Eirgrid)

A.5 Energinet (Denmark)

Energinet is the TSO of Denmark. It was formed in 2005 as a result of the merger and consolidation of ELTRA and ELKRAFT, two earlier, smaller Danish TSOs. Energinet is responsible for grids at the 400kV, 150kV and 132kV levels. The power grid of Energinet is divided into two different synchronous power grids: the Nordic power grid and the grid of Continental Europe. The generation fleet of the former is predominately hydro and the latter is thermal. It is also connected to different electricity markets in these regions.

A.5.1 Impact of Long-Term Energy Policy

Denmark was a pioneer in wind energy. A key driver that led to this unique position in the world, given the size and population of the country, was the long-term energy policies that the Danish government put in place in the 1980s. Those policies spurred the growth of wind power in the country. Figure 69 illustrates the proliferation of wind turbines across Denmark today, compared to 1980.

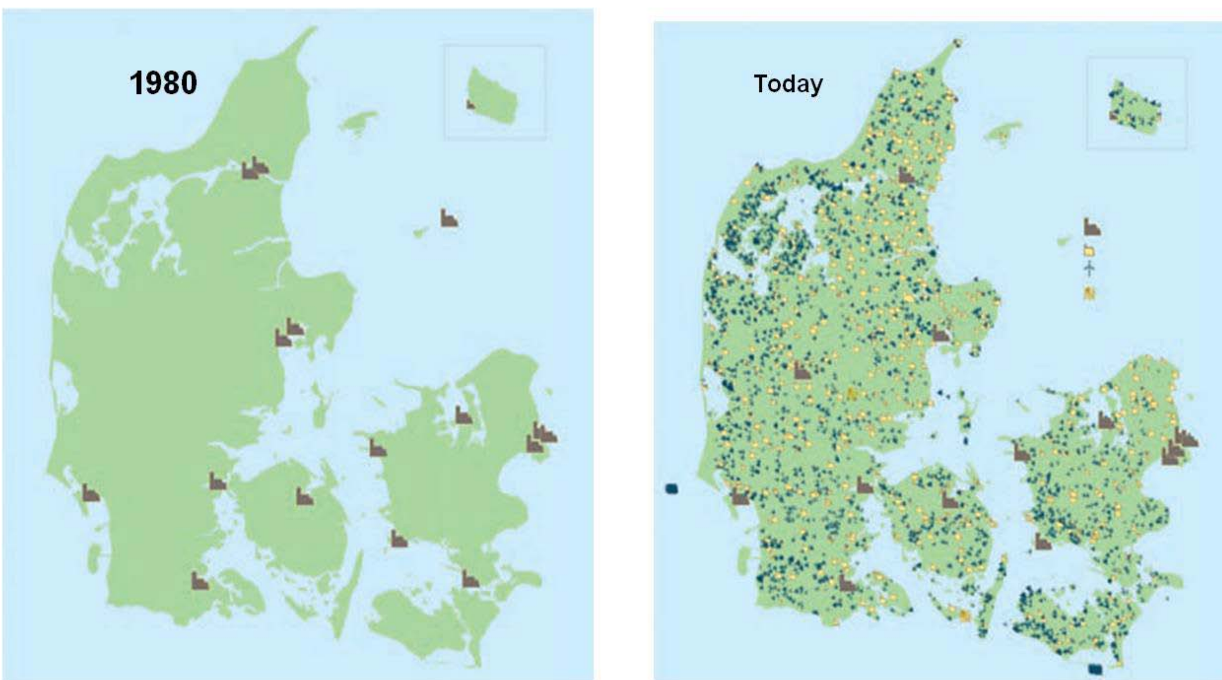


Figure 68. Wind Energy Penetration in Denmark from 1980 to Today (Source: Energinet)

This is quantified in Figure 69 which illustrates the cumulative installed capacity over two decades. At the end of 2010, total installed wind capacity in the Danish power grid was 3,752 MW, peak load was 6,400 MW and total generation including wind was about 13.1 GW.

Wind power provides a substantial amount of energy to Denmark. Today, wind share of total electricity consumption in is 24% – the highest in Europe as seen in Figure 12. Wind energy growth in Denmark is expected to grow unabated over the next decade. This growth is due to the fact that, in order to meet its share of the European 20-20-20 goal, 30% of Denmark's energy consumption must come from renewable sources, namely wind. As shown in Figure 69, most onshore wind potential has been built out, and the majority of the future wind energy will come from offshore resources. (See projections for 2011 and 2012 in Figure 69). About 4.6 GW of available potential offshore wind power sites have already been identified.

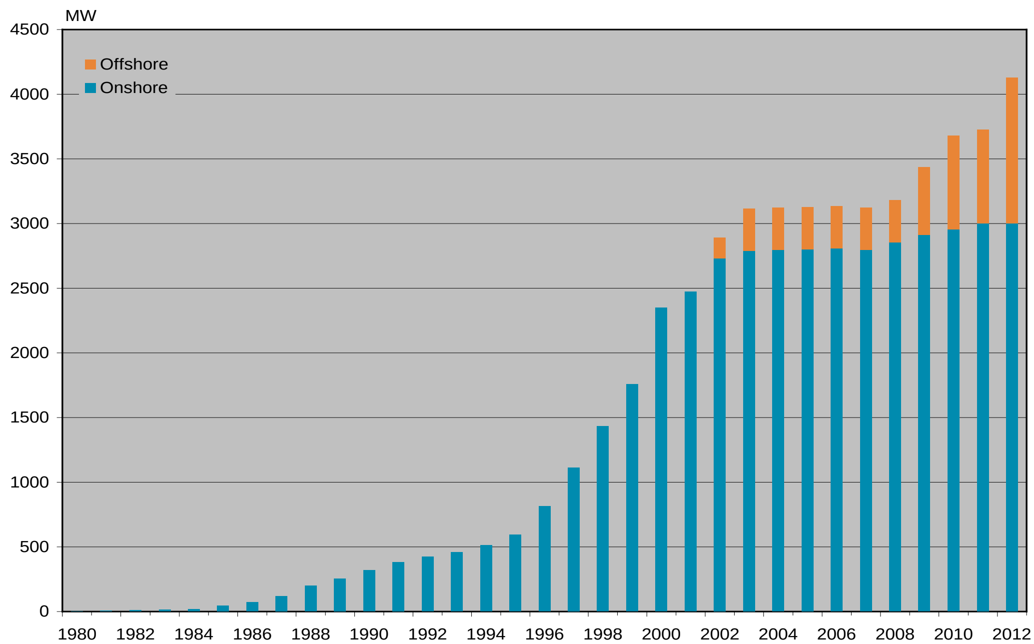


Figure 69. Cumulative Installed and Projected Wind Capacity in Denmark (Provided by Thomas Krogh, Energinet)

Energinet's system is comprised of two synchronous systems in the western and eastern regions of the country. The generation mix consists of primarily thermal power plants, local Combined Heat and Power (CHP) plants, and more than 5,000 wind turbines. Most of the turbines are connected to the distribution grid. Energinet enjoys an excellent source of system flexibility through its connection to its neighboring countries of Sweden and Norway, via HVDC cables, and Germany, via AC transmissions. Another HVDC Interconnection is planned for the Netherlands, which will provide additional flexibility. These interconnections are crucial to Energinet's ability to integrate wind generation.

A.5.2 Interaction of Energinet with DSOs and other Market Participants

The total installed capacity of wind in Denmark consists of generating plants of small to medium capacity connected at the distribution levels. Power from these distributed generating units is injected into the grid at many points in the low voltage grid, for which Energinet has limited or no visibility. To effectively balance the Danish power system, which must operate in deregulated markets, entities, known as Power Balance Responsible Parties (PBR), manage the distributed wind generators (DWG). The PBR makes power and energy bids into the markets, which include a contribution from conventional generators as well as the DWGs.

The important task of system balancing and scheduling of resources must be achieved through consideration of the different rules of de-regulated electricity markets in the Nordic countries and Germany. Taking this into account also affects the integration of wind power.

The electrical interconnections, mostly High Voltage Direct Current (HVDC) to the TSOs in Sweden, Norway, Germany and soon the Netherlands require that operators at Energinet have the adequate tools to coordinate the power flows between these systems. This coordination between the TSOs around Denmark is critically important for the successful integration of wind power.

To address the challenges related to wind energy, Energinet enhanced its EMS and other existing decision support tools as well as developed new ones. All of these tools extensively use wind power forecast and the forecast of other distributed generation resources, which can affect system balancing.

A.5.3 Integrating Distributed Wind Generation in Transmission Operations

Figure 70 illustrates the situation of DWGs with power capacity from tens of kW up to several MWs, connected at the distribution voltage levels in Denmark. To address the related issues with large numbers of DWGs, Energinet implemented a tool that provides real-time estimates of the amount of injections from these resources. A key function of the solution is its ability to aggregate the total injections at multiple levels. Operators use this information to balance the system. Aggregation is completed per PBR, per high voltage substation injection point, per areas and per generator. Another challenge which Energinet faces is the DWG resources located in a single park may be owned by different PBR. The aggregation of wind plant output up to the TSO level has been a key to successfully integrating wind. The estimates of wind power production at the injection points include both telemetered and un-telemetered units, and thus improve situation awareness of grid operators. This tool for managing distributed wind generation is integrated with the EMS.

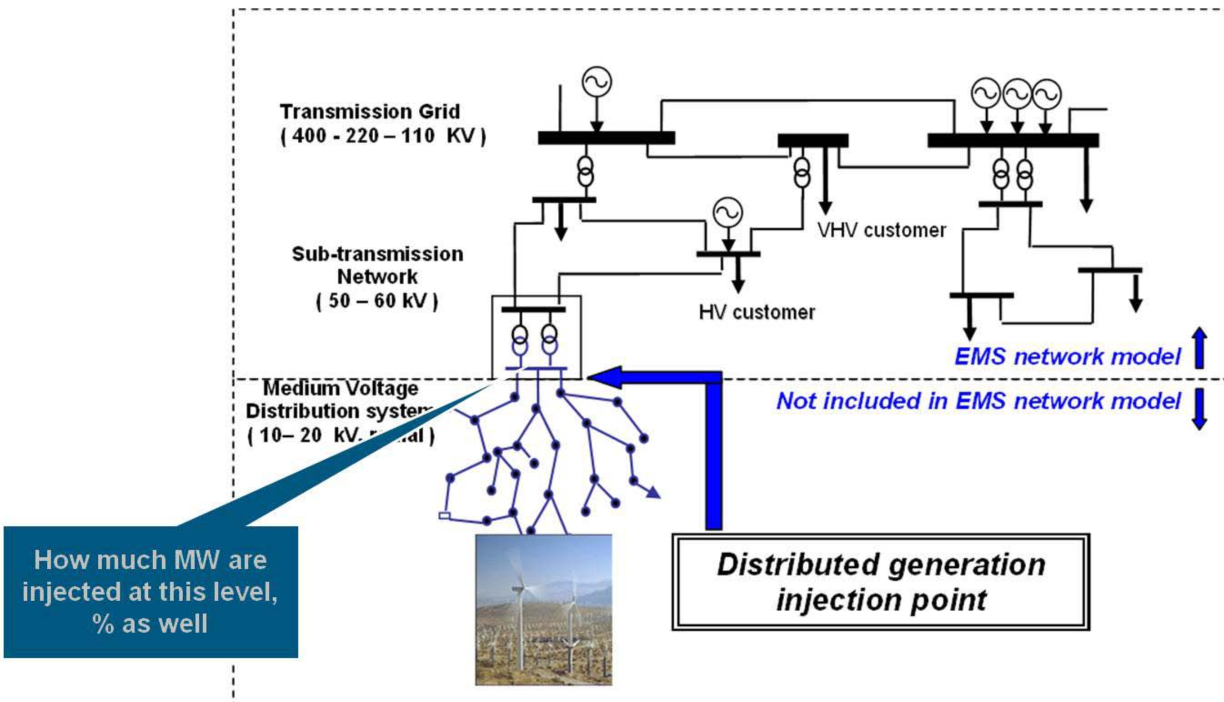


Figure 70. Distributed Wind Generation at the Distribution System Level

A.5.4 Centralized Wind Forecasting at Energinet

As the first country in the world to obtain significant amount wind power, it should come as no surprise that short-term wind power forecasting has its roots in Denmark, dating back to the early 1990s (Giebel & Kariniotakis, 2007). Over the years with advances in wind power forecasting, utilities in Denmark developed more than 15 years of experience using wind power forecast and how to integrate it into the operations of power systems and electricity markets. Today, because of how Energinet was established, i.e., the merger of two smaller TSOs, it has broad expertise in wind forecasting and how to use forecast information, along with other decision support tools in the control room. Some of these will be discussed here. Energinet is continuously working to improve the forecast using different combination of forecast tools and methods.

A.5.5 Operational Planning with Look-Ahead Capability

Energinet has developed a special system for real-time operational planning, looking 2 to 3 hours ahead. This "Drift Planlægnings System" (DPS)[60] tool allows operators to integrate a wind power forecast when making decisions. However, to successfully accommodate more wind, efforts are underway to shorten the planning time horizon to 5 minutes. From this tool, the operator has access to a number of different forecasts including wind, CHP, etc., as shown in Figure 71.

SCADA measurements can be viewed directly in the DPS. See Figure 72. Online forecasts are frequently updated to improve short term planning. Control room operators access results from different wind power forecast tools used for medium and long term planning. Wind power forecast from the previous day is also used as the basis for day-ahead planning. System imbalance due to wind power can be seen as the difference between the forecast and actual production.

Real-time monitoring of the power flows on the transmission lines between Energinet and the power grids in Germany, Sweden and Norway is essential for managing wind generation. This monitoring is completed in the DPS as shown in Figure 73. In addition, the operators at Energinet must always know the total power production that is injected into the grid. For this, generation schedules from the large power plant operators are provided every 5 minutes. Each generator in the western part of Denmark (DK1) with capacity greater than 10 MW must also provide 5-minute schedules. As discussed earlier in this section, a lion share of the wind generation in Denmark is connected at the distribution level. With the help of the aforementioned tool for estimating injections from DWGs, operators can track the real time aggregated productions for all units with less than 10 MW.

A key system-wide operational quantity used by Energinet to monitor the performance of the system, and to some extent the balancing markets, is the expected power imbalance. This quantity, as shown in Figure 72, combines the total load, generation and power exchanged with neighboring systems. The more accurate the schedules and forecast, the more an operator can rely on the expected imbalance curve as a basis for system balancing.

A.5.6 Wide-Area Situation Awareness with the Nordic Operational Information System

For decades, the four Nordic countries (Denmark, Finland, Norway and Sweden) have developed strong co-operation in electricity markets and the power grid. The regular communication between staff at the National Control Centers (NCC) of these countries is the reason for its success. However, a few years ago, it became clear that the NCC operators did not always have a common view and understanding of the health and status of the Nordic power grids. In addition, the level of information exchange was not adequate to support the kind of team SA required for coordinated decisions during normal and emergency operating conditions.

In recent years, three developments occurred at a very fast pace in the region: 1) increased expansion of the Nordic electricity markets and coupling to other regional markets in Europe, 2) more transmission interconnections, mostly HVDC, are being built between the Nordic countries and even to TSOs in other

[60] Drift Planlægnings System is Danish for Operational Planning System.

neighboring regions; and 3) increased penetration of wind energy in the Nordic countries. Together these drivers accentuate and exacerbate the need for NCC operators to have common mental models about the grid and the interaction with the electricity markets. To address this challenge, the TSOs for the four countries agreed to develop the Nordic Operational Information System (NOIS)[61] in 2004. Today, the system is in operation at the four NCCs and NOIS computer hardware is hosted at Energinet.

The primary objective of NOIS is to enable the seamless exchange of relevant system overview data among the four TSOs. The main areas covered in the NOIS are capacity, balance, reserve and outage management functions. The NOIS is expected to continue to evolve as the three drivers of the initial system continue to influence the development of the Nordic Power Systems and Electricity Market.[62]

In the future, additional functions for NOIS could include:[63]

- "What-if" analysis for different scenarios due to a rapid increased amount of wind power.
- A Common Nordic market for the frequency-controlled reserves.
- Increased operational transparency via a web portal to publish relevant information from TSOs for market participants and the general public.
- Commercial operation of interconnections to Europe. With the expansion of the Nordic electricity market, NOIS could be used for the capacity management of the interconnections to other markets.

A.5.7 Multi-TSO Monitoring and Coordination of Operating Reserves

This report has discussed the impacts of wind generation on system reserves. It is important to gather an accurate share of knowledge of the usable reserves and other aspects so that an adequate amount of reserves are available to operate the power grid. More specifically, NOIS allows operators at Energinet and their counterparts at the three other TSOs to have a closer co-operation and coordination of operating reserves necessary to maintaining the balance of supply and demand in the regional power grid. Figure 75 shows a display with the reserve management function in NOIS. Various operating reserves can be monitored both at the regional and country-specific basis.

A.5.8 Planning for Future Power Grids and Markets

Energinet is constantly investing in R&D activities to enhance its tools to cope with more wind generation, which will become critical as large conventional central plants are decommissioned and not replaced. In view of the expected increased penetration of wind generation in the Nordic Power Grids,[64] changes in market rules and potential coupling of the different electricity markets in the EU,[65] Energinet plans to continuously adapt new business processes in the control room. New tools under consideration include early warning systems to

[61] For more details, see "NOIS (Nordic Operational Information System) - A successful joint Nordic project in close co-operation". Cigre Technical Paper, CS_206_2010 by C. Norlander, D. Auguy, F. Nilsson, A-K Nystad, J. Siltala, and S-R Hansen, September 2010. Paris.

[62] Based on discussions about NOIS with C. Norlander of the Swedish Grid Company and also Chairman of the NOIS System Group.

[63] Id.

[64] The report "Impact of Increase Amounts of Renewable Energy on Nordic Power System Operation" published by ENTSOE, August 31, 2010, provides an excellent account of the role of Energinet in the integration of wind energy in the Nordic countries and the future plans for the region as it relates to wind energy.

[65] The article "EU sees Single Power Market by 2015" in Platts EU Energy, Issue 239. August 27, 2010 offers a good overview of the EU plans and ongoing efforts toward a single electricity market and some of the related market coupling issues.

alert operators about extreme weather events, applications of data mining techniques to identify new power flow patterns in the system due to wind generation, and advanced applications based on synchrophasor data that will help to improve situational awareness.

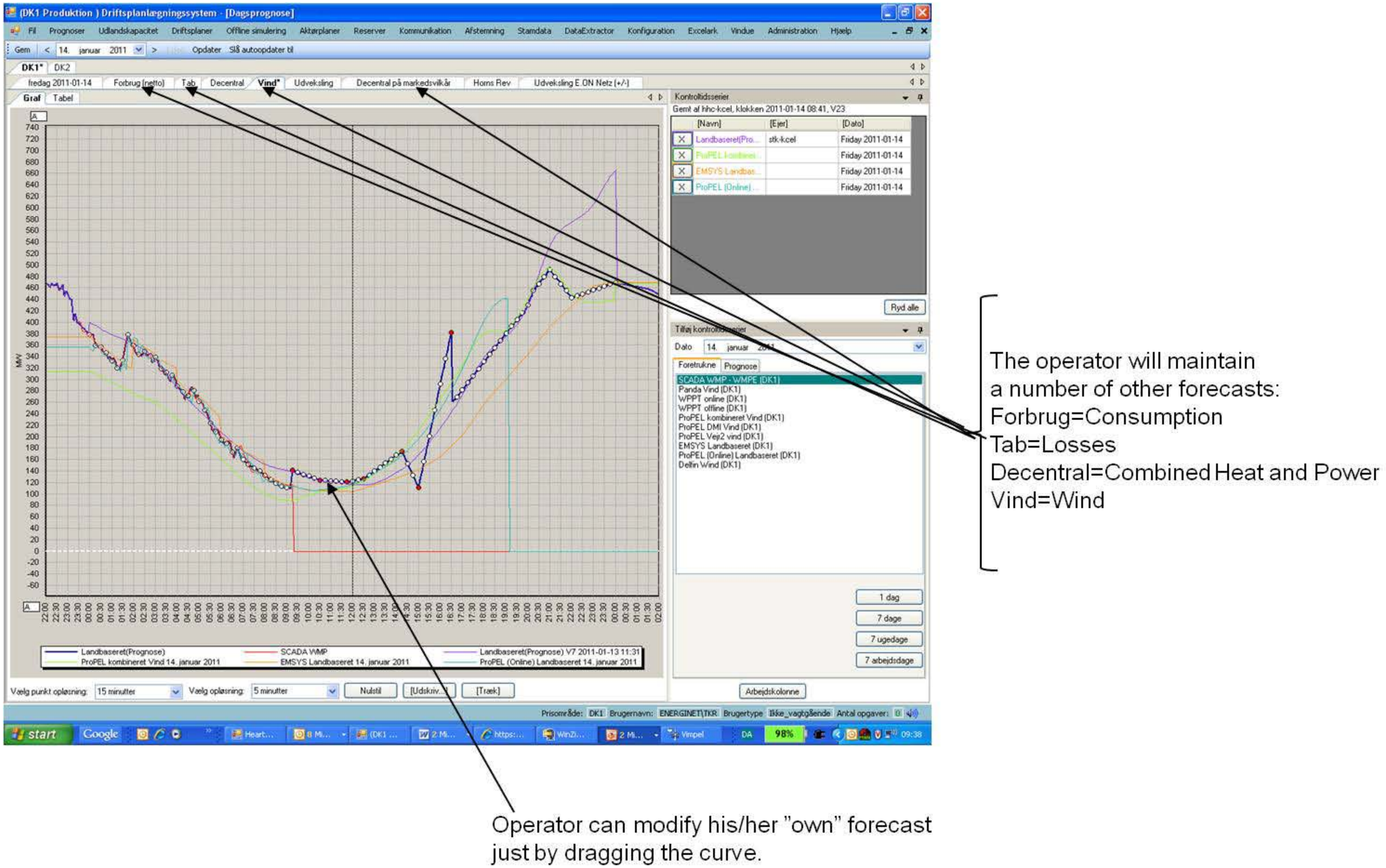


Figure 71. DPS User Interface shows Operators Multiple Forecast Information (Provided by Thomas Krogh, Energinet)

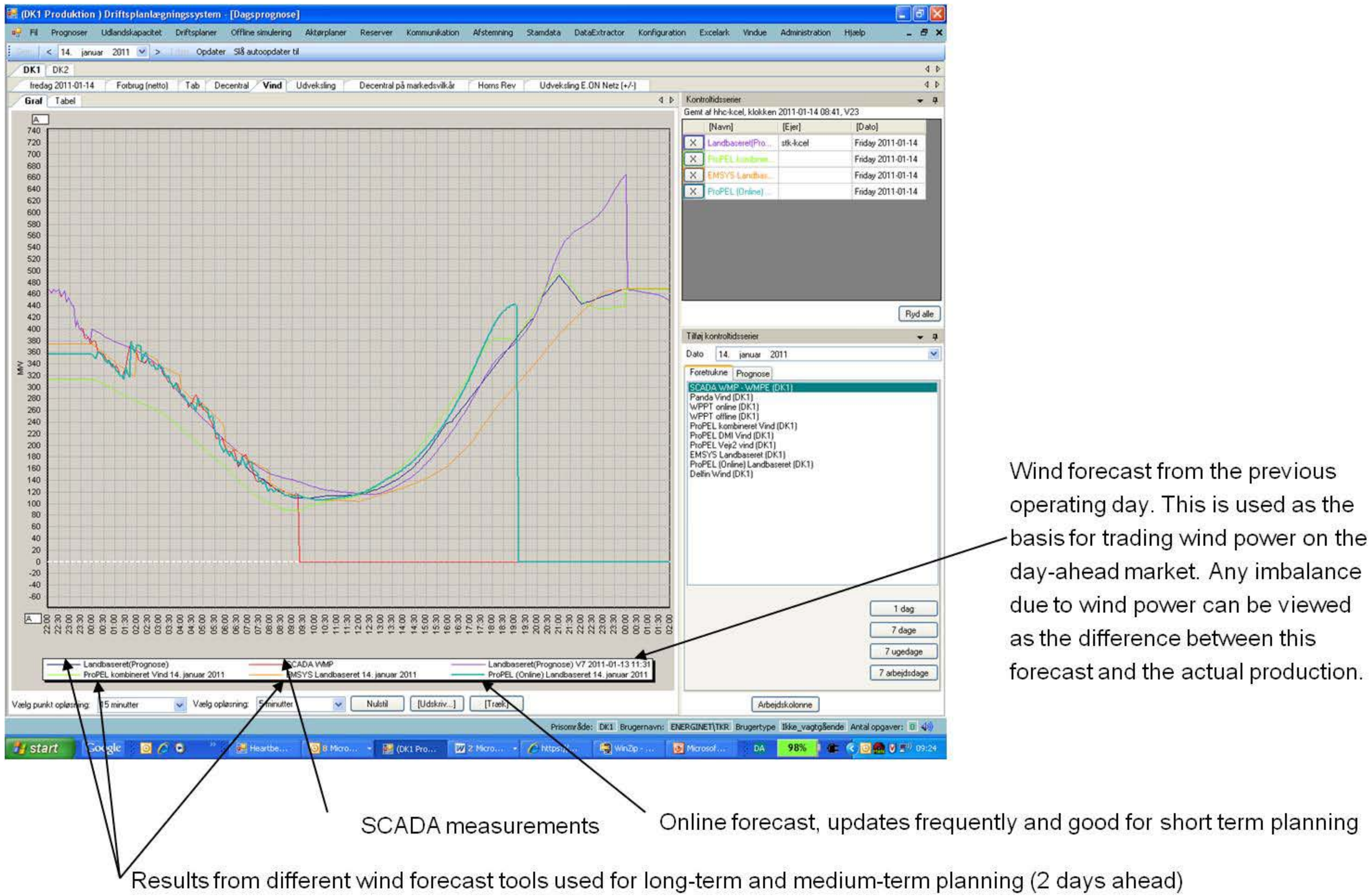


Figure 72. Viewing Results from Different Wind Forecast Tools in DPS (Provided by Thomas Krogh, Energinet)

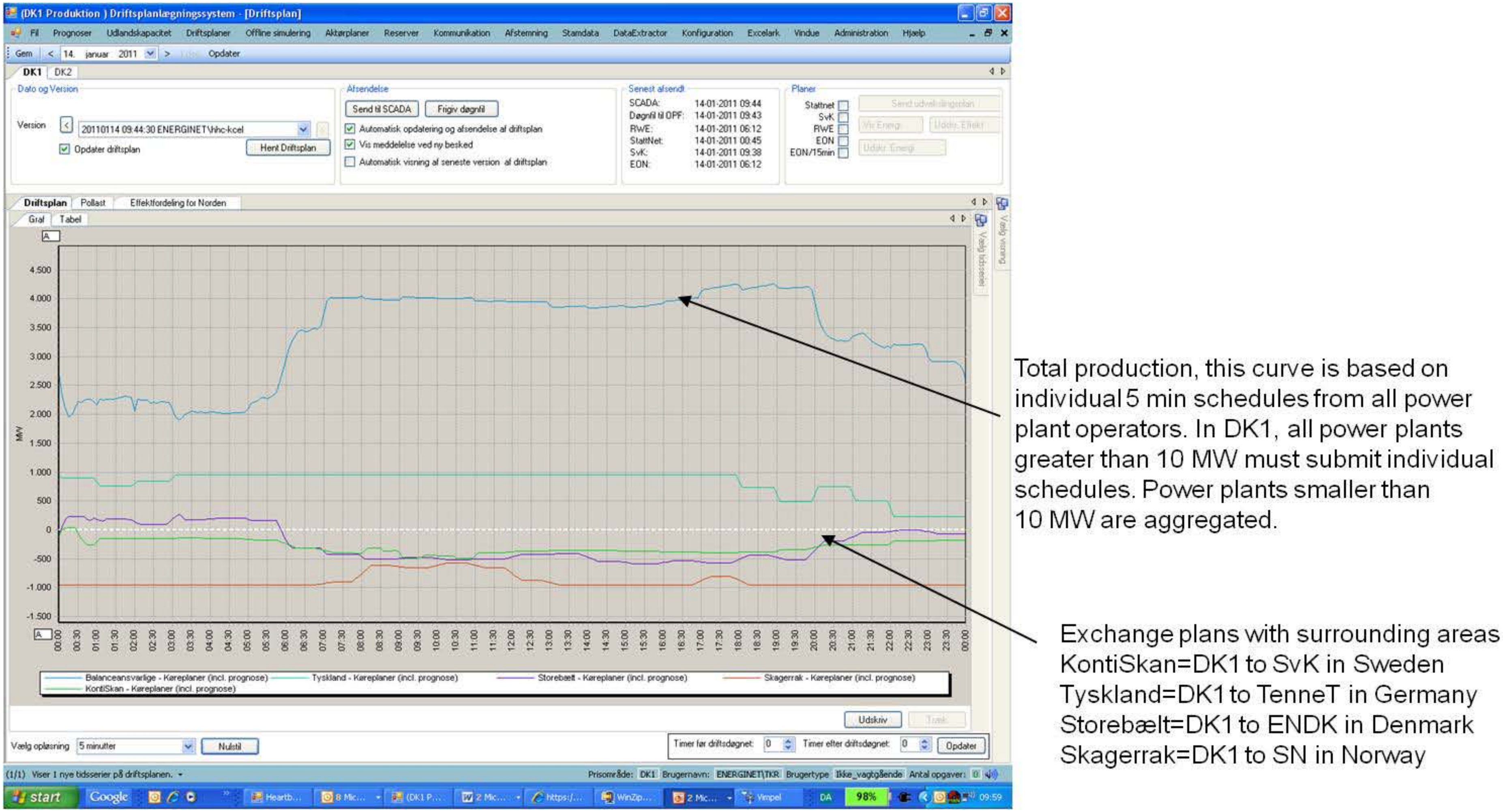


Figure 73. Monitoring Power Generation and Power Exchange with Neighboring Power Grids (Provided by Thomas Krogh, Energinet)

Note: If you add all the curves, you get the resultant curve shown in Figure 74. If all inputs, both schedules and forecasts, are of good quality this curve can be used as reference when the grid operator tries to keep the system in balance.

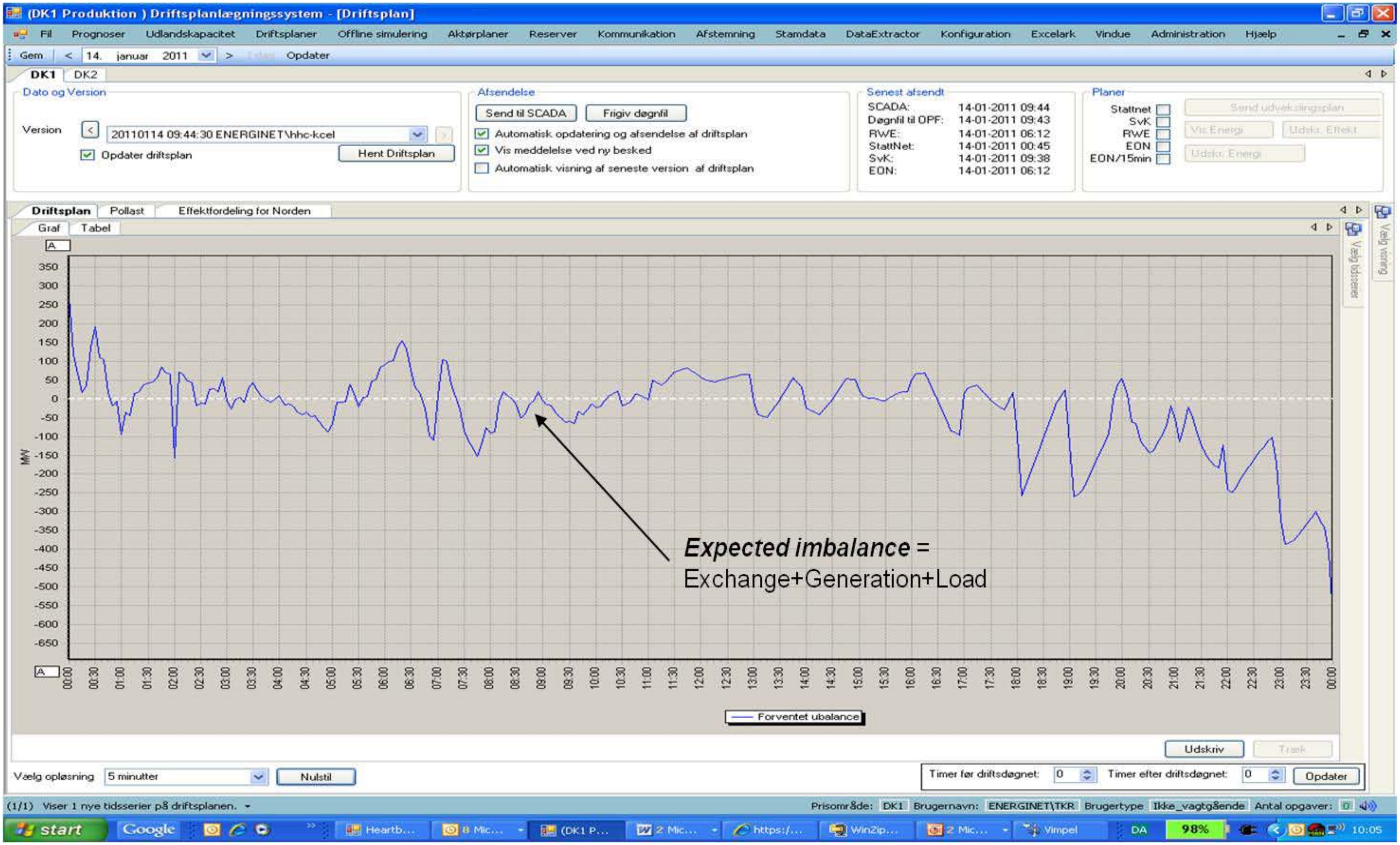


Figure 74. Monitoring of Expected Power Imbalance (Provided by Thomas Krogh, Energinet)

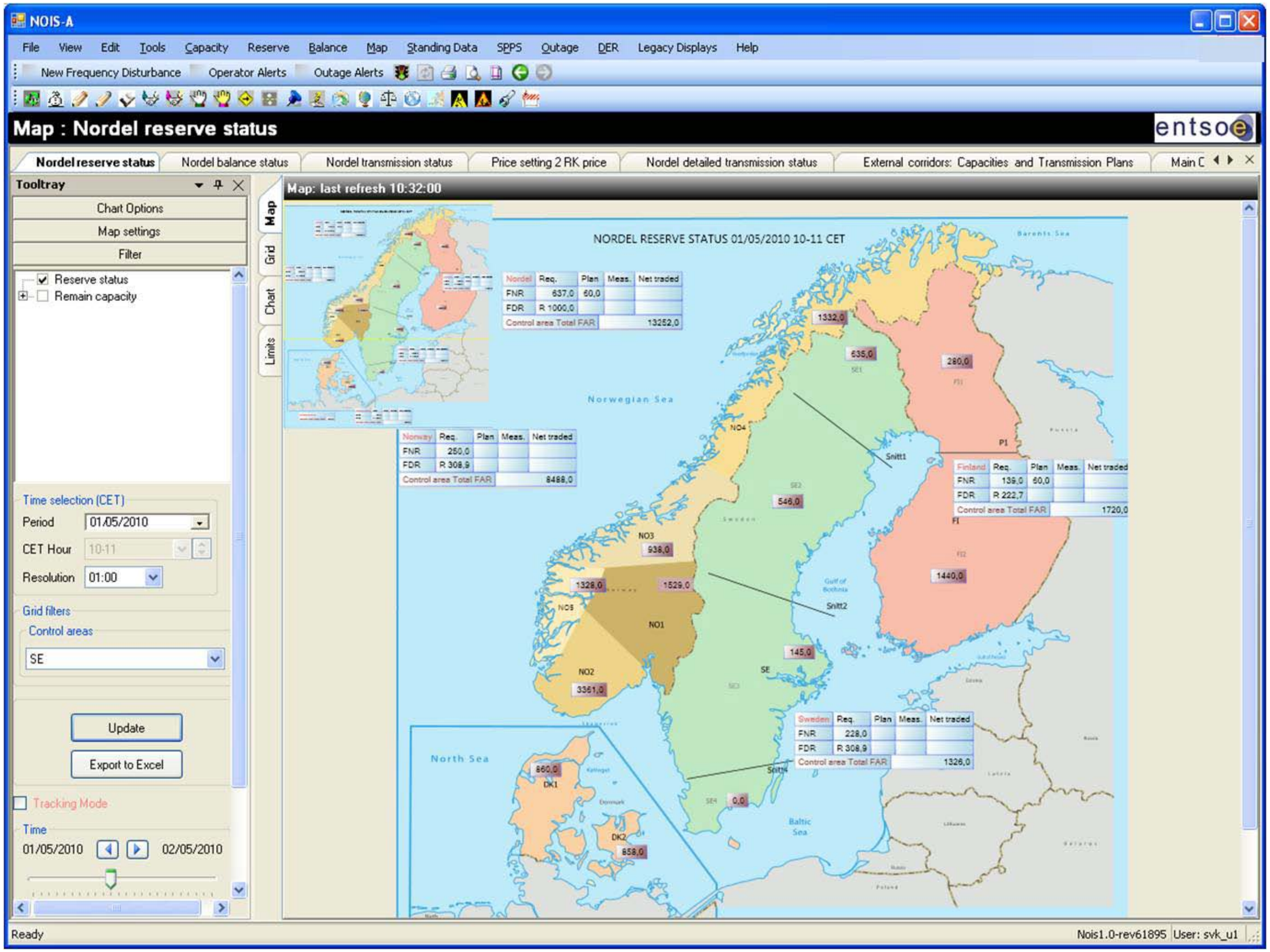


Figure 75. NOIS Display of Reserves Status in the Nordic Power System (Provided by Christer Norlander, Svenska Kraftnät)

A.6 Electric Reliability Council of Texas (USA)

ERCOT is the operator of the electricity market and the interconnected power grid in most of the state of Texas. ERCOT leads the U.S. as the ISO with the most installed wind capacity. At the end of 2010, it had 9,400 MW. Figure 76 shows the projected cumulative installed capacity up to 2013. ERCOT is asynchronously connected to the rest of the U.S. with a number of High Voltage Direct Current (HVDC) ties. As such, the system is subject to an array of challenges in coping with the ever increasing amounts of wind generation being connected to the ERCOT grid. The majority of Texas wind plants are in the western parts of the state, while the major load centers are in the east, southeast and central parts. This geography highlights the need to build sufficient transmission capacity and deal with some of the wind related operational issues. To facilitate the future wind penetration, Texas is building significant amounts of transmission through its Competitive Renewable Energy Zones (CREZ) process that the Public Utility Commission of Texas (PUCT)[66] established.

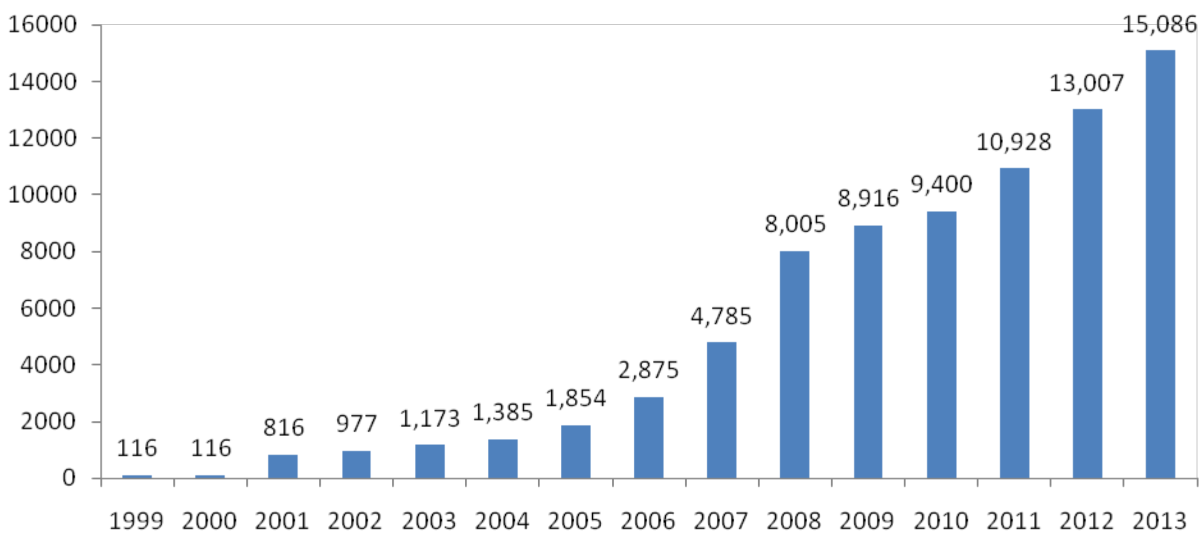


Figure 76. Cumulative Installed Wind Capacity (MW) in ERCOT (Source: Presentation by John Dumas, ERCOT)

More than a decade ago, clear energy policy goals in Texas began to spur the growth of wind energy in ERCOT. In reaction to the future level of wind generation developed, ERCOT began to invest in resources to develop the appropriate operational policies to integrate wind. ERCOT has since played a leading role in the U.S. wind energy industry. As the growth has accelerated and wind generation began to make up a higher percentage of the installed generation mix, ERCOT increased its efforts to develop and implement the necessary tools and market designs to facilitate the integration of wind generation. ERCOT's noteworthy activities related to managing wind energy in the control room have received the industry attention, and will be discussed here.

[66] A CREZ is an area where wind generation facilities will be installed and from which transmission lines will be built in the State of Texas. It will extend to various other areas of the state and deliver renewable power to end-user consumers in the most cost-effective manner. The CREZ was established by order of the PUCT in 2008 as a direct response to the legislation passed by the Texas Senate to increase renewable energy generation in the state. Ultimately, the CREZ effort would allow Texas to build up to 18,456 MW. Available at http://www.texascrezprojects.com.

A.6.1 Centralized Wind Forecasting at ERCOT

ERCOT uses a centralized Wind Power Forecasting (WPF) system incorporating the services of its wind forecasting provider. The WPF is comprised of the complete system used to provide the Short Term Wind Power Forecast (STWPF). In the ERCOT's view and its forecast vendor, the key to a successful centralized forecast is the efficient collection and use of wind generation data. This data must be provided for all the Wind Generation Resource (WGR), a group of wind generators that inject wind power onto the transmission system at a given point. With the WPF, ERCOT provides STWPF for the next 48 hours to its market participants. The quality of the wind generation data (including wind speed and wind direction data from the individual wind plants) provided to ERCOT affects the performance and accuracy of the forecast. It is interesting to note that centralized forecasts from some grid operators in Germany and Denmark are completed without such detailed information from the wind generators. This is likely due to the approach of ERCOT's forecast vendor, as contrasted with the approach of most other forecast vendors.

Wind forecast is also used along with the EMS, MMS and other decision support tools to operate the markets and the grid. Several new tools are under development that incorporates the wind power forecast, including tools for ramp event forecasting.

A.6.2 Wind Generation Integrated in the Market Management System

In 2010, ERCOT began operating its new electricity market based on nodal pricing design. This market was originally designed for conventional resources but has been redesigned to accommodate wind generation. Specifically, WGR are treated just like any other generator in the market. Wind generators can bid offers into the market that are cleared every 5 minutes, thus reducing the potential impact of variability and uncertainty due to wind. This regular assessment results in minimizing the quantity of wind that is curtailed and the length that it is curtailed. ERCOT uses the short-term wind power forecast for each of the next 48 hours to determine the limits on resources in the Day-Ahead Market and the Reliability Unit Commitment process.

The process for dispatching wind resources has since improved. The Security Constrained Economic Dispatch software directly generates the dispatch signals. An important benefit of this process is that operators will, to a lesser extent, have to manually intervene in the dispatch process when dealing with reliability issues.

A.6.3 ERCOT Large Ramp Alert System (ELRAS)

Unpredicted large ramp events can have serious impacts on the operations of power systems and the cost of additional ancillary services that must be procured to maintain supply-demand balance. Prediction of ramp events is a difficult task and is receiving much attention in the industry. However, it would be useful if information on the likelihood that a ramp will occur is provided to the operators in some cases.

Due to the geography and diverse weather phenomena in Texas, wind plants or Wind Generating Resources (WGR) in ERCOT have shown to be susceptible to frequent wind ramp events, and especially those that create inverse load-wind relationship during the morning and evening periods of the day. Instantaneous wind ramps of a shorter duration can also occur as shown in Figure 77 below.

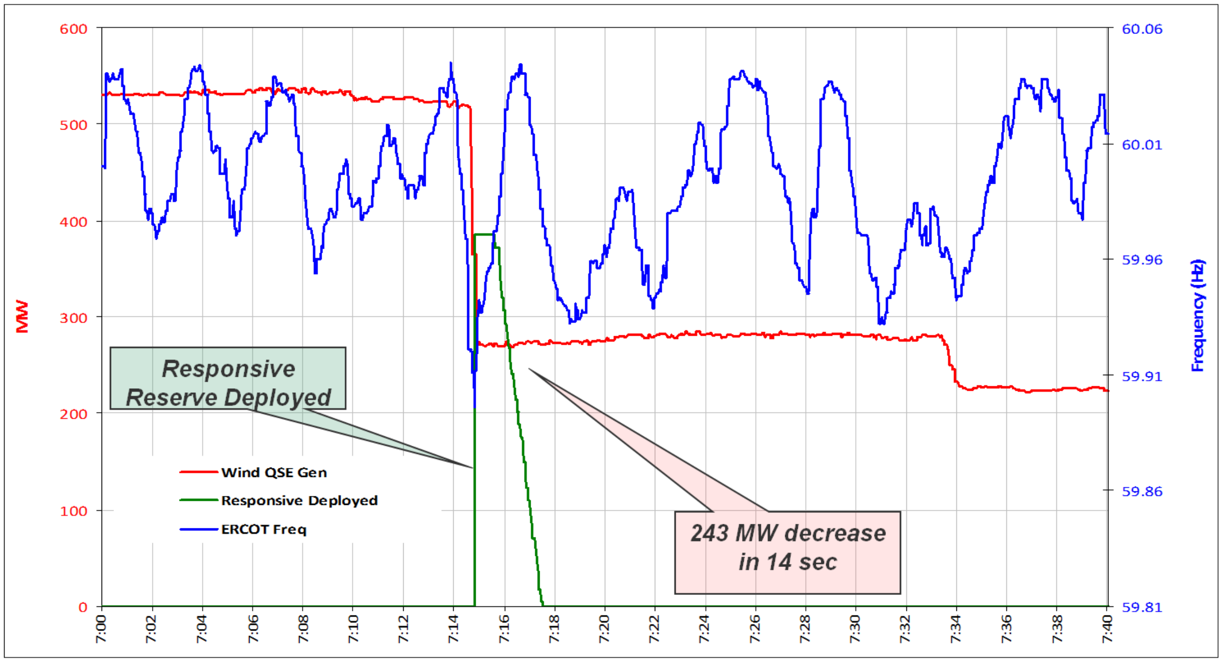


Figure 77. Instantaneous Wind Ramp in ERCOT on February 28, 2008 (Source: Presentation by John Dumas, ERCOT)

To address the problems related to wind ramp events, ERCOT has developed ELRAS. The ELRAS provides probabilistic wind power forecast information to operators in graphical form on 15-minute intervals for the next 6 hours. The displays also include information about the weather conditions, which allows operators to correlate system conditions and ramp events. As shown in Figure 78, the animated graphics are provided for the operators to track wind speed, the wind speed gradient, and radar over time. Weather observations for historical hours and forecasted weather for the next 6 hours can be seen.

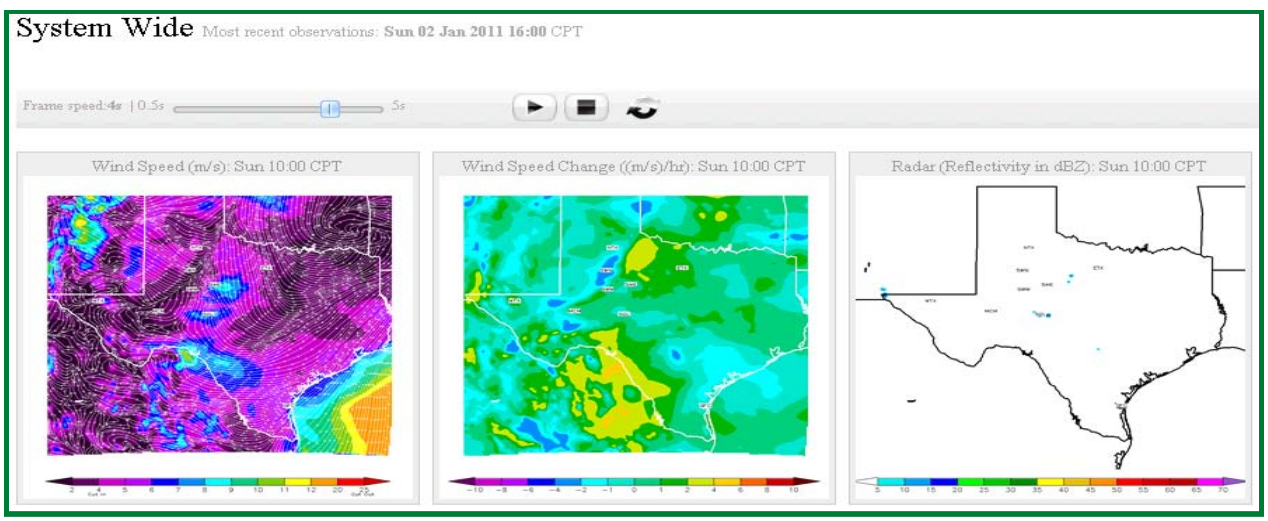


Figure 78. ERCOT Large Ramp Alert System (Provided by David Maggio, ERCOT)

ELRAS provides operators with the probability of wind power output ramp events of various MW changes occurring over several different time frames as shown in Figure 79 below. In this case, the graph to the far right indicates that there is a 30% chance that the wind power output will change by 2,000 MW or more between 6 p.m. and 9 p.m. on that day. With this, operators can anticipate potential impacts of this event and plan necessary actions.

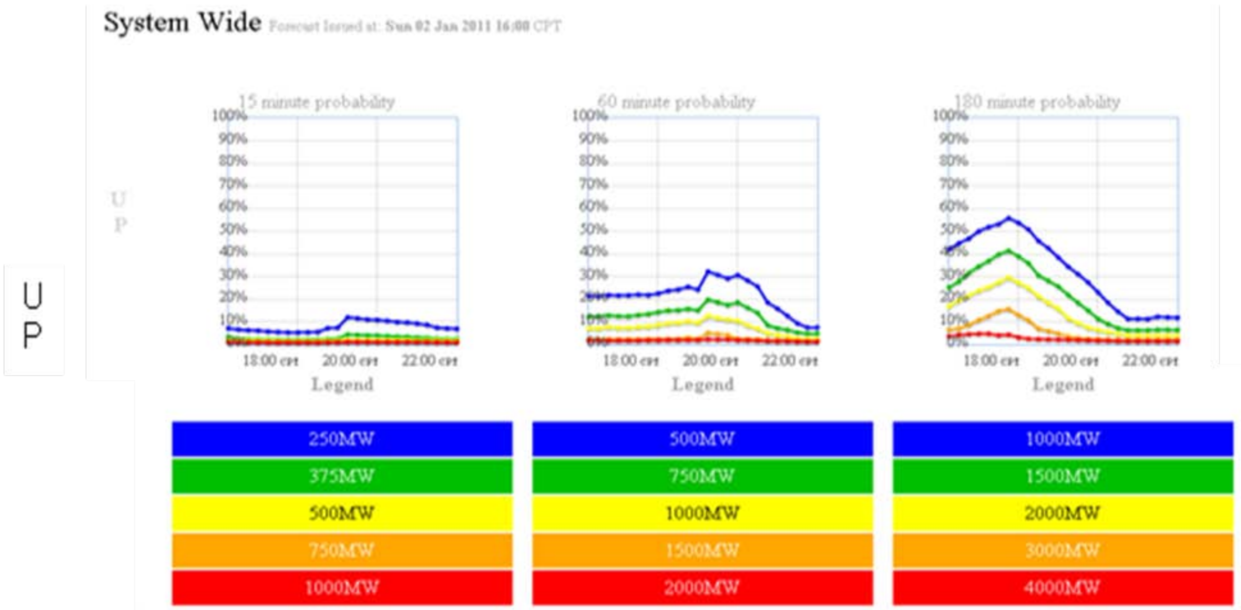


Figure 79. ERCOT Large Ramp Alert System (Provided by David Maggio, ERCOT)

The ELRAS tool can also display the expected STWPF along with the 10% and 90% Probability of Exceedance (POE) forecasts as shown in Figure 80. Here, historical hourly wind power output can be observed. Forecast displays that the operators have seen can be recreated from any historical point in time.

The ELRAS displays illustrate different ways that operators can use probabilistic information (EPRI, 2010), (Maggio, 2011). As wind generation becomes a greater share of the generation connected to power grids, better utilization of probabilistic data will be extremely important.[67]

[67] Based on separate communications with David Maggio, Claudine D'Annunzio and John Dumas of ERCOT; Pablo Muñoz Martin of Red Eléctrica de España; Jon O'Sullivan of Eirgrid; and Michael Milligan of NREL.

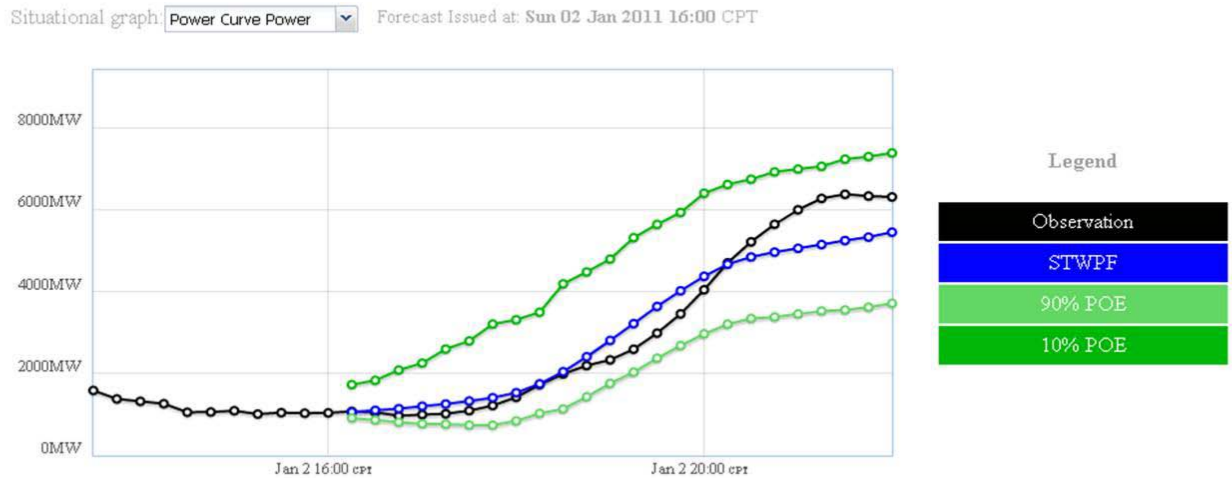


Figure 80. ELRAS Display of Probabilities of Exceedance (Provided by David Maggio, ERCOT)

A.6.4 ERCOT Risk Assessment Tool (ERAT)

Grid operators continuously analyze to assess the risk of events that could impact the reliability of the system. ERCOT is developing a tool that will be complete a risk analysis of loss-of-load events, considering several scenarios including: the planned online generation; the same generation with demand response; and the generation with both demand response and non-spinning services. Connecting more wind generation increases the variability, uncertainty and as a consequence, the system could be exposed to additional risk. Therefore, the ERAT will also take the wind power forecast and how the wind power forecast error is distributed in ERCOT into consideration. When deployed, ERAT will display information such as the target probability of the event occurring on a graph, thereby improving operator situation awareness. ERCOT is still developing the criteria for this target. Figure 81 shows a prototype display from the ERAT tool.

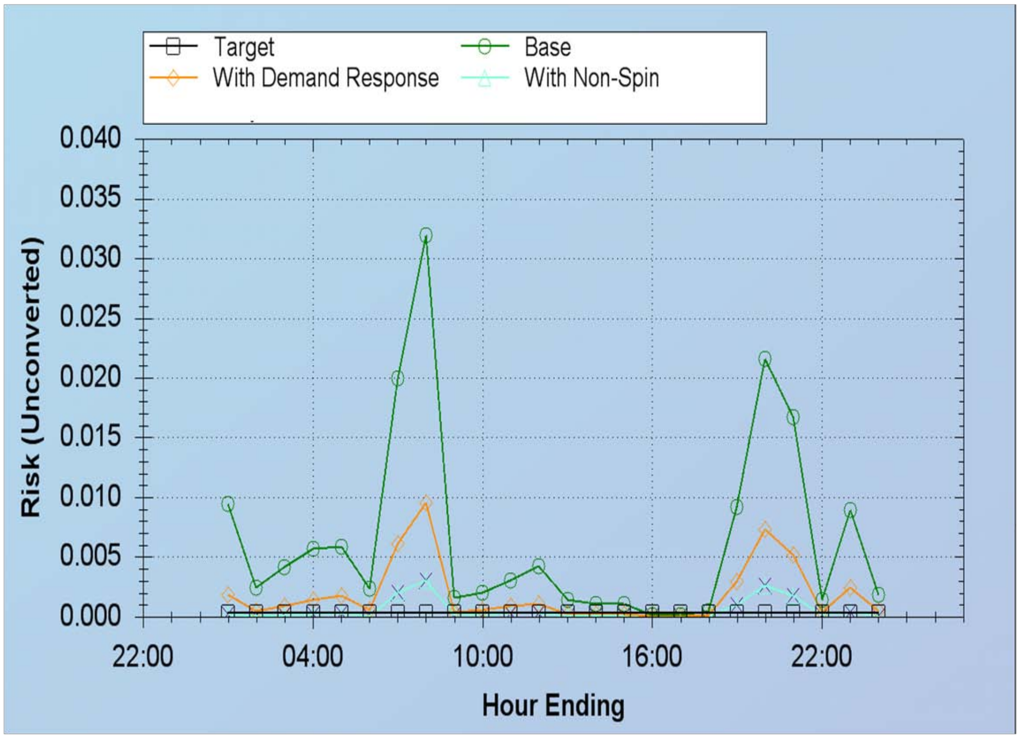


Figure 81. ERCOT Risk Assessment Tool (Provided by David Maggio, ERCOT)

ERAT information may also be useful when performing Reliability Unit Commitment (RUC) studies during the operating day as well as in the day-ahead time frame. It might also be an additional tool to help grid and market operators determine requirements for ancillary services.

A.6.5 Correlating Ramp Events with Meteorological Phenomena and Weather Regimes

Different meteorological phenomena cause ramp events. Therefore, the best parameters for accurately tracking and predicting them vary. As more wind plants are connected to the power grid and impacts of wind ramp events become more common, operators and dispatchers will need to develop a better understanding of how different meteorological phenomena and weather regimes affect wind ramps. One approach which is primarily part of the ELRAS tool is to create a chart that can correlate wind up-ramps and down-ramps to different phenomena such as a cold front, a low level jet, a pressure gradient or a nocturnal stabilization.

Operators understand the relationship between ambient temperature and different system operational conditions. Similarly, a ramp-weather-climate phenomena diagram will improve operators' projection level situational awareness. Developing such charts will require close collaboration between the utilities' forecast providers, meteorologists and the grid operators. Historical information with all of the relevant about the ramp events must be archived to perform this kind of correlation analysis. Several TSOs in Europe are also exploring how to develop such a tracking tool and can be used as part of the operator training course.

A.7 New York Independent System Operator (USA)

NYISO operates a wholesale electricity market and the transmission grid in the state of New York. The grid is electrically connected to four other large power systems in the northeastern U.S. and Canada namely, PJM, New England ISO, Hydro Quebec and Ontario ISO. The proximity to neighboring ISOs affects how NYISO deals with issues of reserve sharing to accommodate a higher penetration of wind power on the system.

The cumulative installed capacity of wind in NYISO is shown in Figure 82. At the end of 2010, there was 1,349 MW of commercial wind generation in NYISO system, or approximately 3.6% of the total generation capacity.

Many of these are located in northern and western parts of New York, while the demand centers are in the southeastern part of the state. Thus, the wind plants and other conventional generation can become locationally constrained under certain operating conditions due to inadequate transmission capacity, which in turn creates congestion in the system. Based on proposed wind plants currently in NYISO's generation queue, there is a potential that another 7,946 MW wind capacity will be developed in the system.[68]

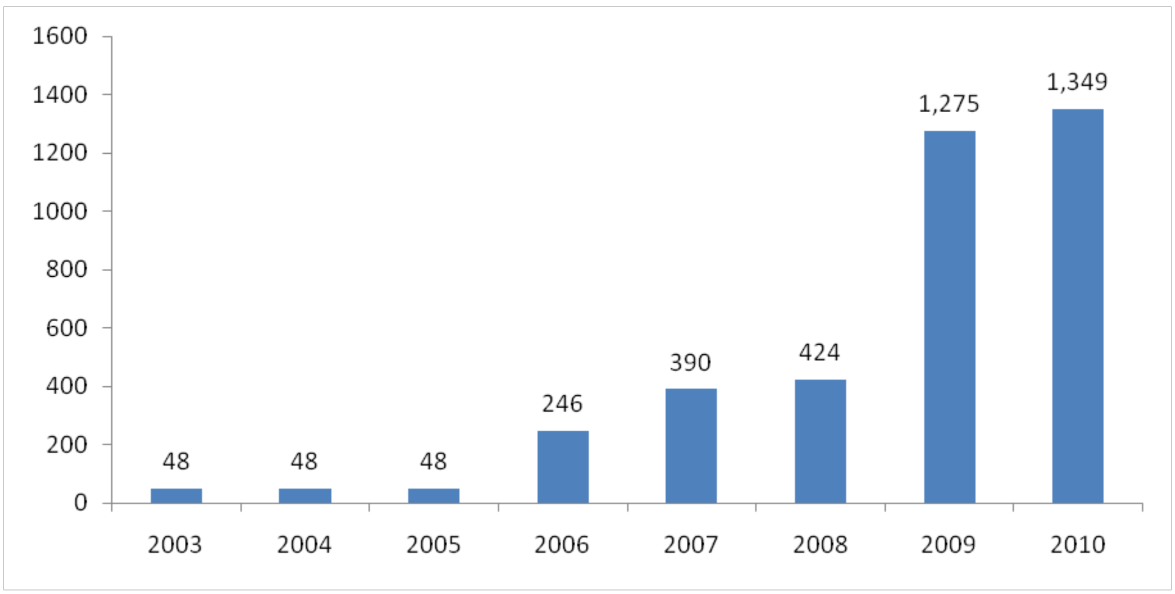


Figure 82. Cumulative Installed Wind Capacity (MW) in New York (Source: NYISO)

In spite of the current low penetration level compared with other grid operators in the U.S. and around the world, NYISO has been proactively planning for future conditions of high wind penetration expected during the next 5 to 10 years. NYISO has demonstrated its leadership in wind energy integration through its implementation of groundbreaking policies and programs that have accelerated the growth in wind energy. In 2008, NYISO was one of the first ISO in the U.S. to establish a centralized wind forecasting system. As a result, wind generation has been integrated into NYISO Market Management System, specifically the day-

[68] For more information on the future for wind energy in NYISO, see "Growing Wind - Final report of the NYISO 2010 Wind Generation Study" available for download at www.nyiso.com.

ahead and real-time software. In 2009, it became the first U.S. grid operator to dispatch wind power while balancing the system and simultaneously meeting reliability requirements of the system.[69]

A.7.1 Centralized Wind Forecasting at NYISO

NYISO began operating a centralized wind forecasting program in June 2008. At that time, the installed wind capacity was only 424 MW, a relatively small amount in comparison with the total generation. A third-party wind forecasting company for both real-time and day-ahead energy market operations provides these forecasts to the NYISO. The forward-looking decision to invest in decision support tools for operating its system with higher penetration of wind has put NYISO in a unique position. Operators of the NYISO grid and markets will begin to understand the impact of wind variability and uncertainty as the penetration level increases. Figure 83 is an example of a display in the NYISO Control Center which shows the actual wind production versus forecasts of wind production that were made 30, 60, and 90 minutes ago. This allows operators the easily track the forecast accuracy.

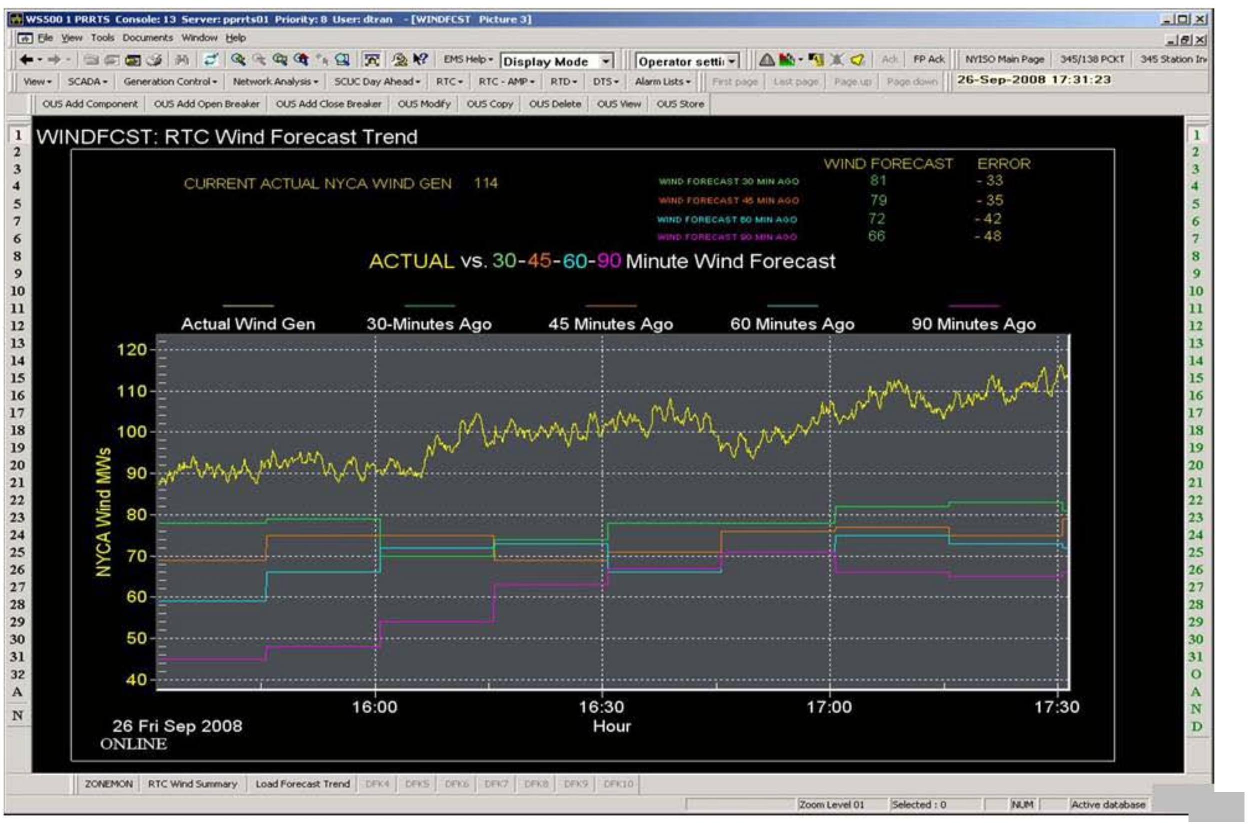


Figure 83. Display with Wind Forecast in NYISO Control Center (Provided by NYISO)

Centralized forecasting for NYISO requires meteorological data from the wind plants. New York ISO requests meteorological data is sent directly its control center every 30 seconds. NYISO has developed an integration guide that focuses on data reporting that is required of the wind plant operators to support the integration of wind power into the New York Control Area. This was one of the first detailed data requirement guide for

[69] More information on renewable energy integration in NYISO can be found in the report "Power Trends 2010 – New York's Emerging Energy Crossroads", published by New York independent System Operator.

wind plants in the U.S.[70] The NYISO is also currently investigating the ability to manage significant wind plant output ramp events.

A.7.2 Wind Generation Integration in the Market Management System

NYISO uses real-time and day-ahead wind power forecast information in its control center applications for security constrained dispatch and next day unit commitment. During real-time operations, for an eight hour forecast period, the forecasted production from wind plants is updated every 15 minutes, with 15-minute forecast intervals. For day-ahead operations, forecasted production from wind plants are updated two times a day on an hourly forecast interval basis.

As in the case of other generators, the output from wind generation in NYISO can be better optimized by performing an assessment of each wind plant's participation using the real-time Security Constrained Economic Dispatch (SCED) software with is part of the MMS. Wind plants bid into the Real-time market, allowing SCED to optimize resources and ensure system reliability. In May 2009, the NYISO implemented changes in its market rules allowing wind plants to receive and follow instructions to dispatch-down directly via the Security Constrained Dispatch software.

Frequently clearing electricity markets and dispatching resources improves integration of wind energy in grid operations. NYISO performs a re-dispatch of it entire power system every five minutes when it clears the market. This has been shown to reduce variability which would be much greater if the system was re-dispatched less frequently.

A.7.3 Visualization and Situation Awareness

NYISO has developed several visualization tools that are integrated in its control room to enhance operators' situation awareness about the impacts of wind generation on system operations. The visualization tools allow grid and market operators to monitor various aspects of the wind generation in the system. This includes but is not limited to: wind plant output, wind speed, wind direction, wind curtailment and wind power forecast. An example of a system display of wind power information and other operational data is shown in Figure 84. These tools will continue to be enhanced as dispatchers become more experienced with operating the system with high penetration levels of wind power capacity.

[70] The NYISO Wind Operator Data Guide can be downloaded from http://www.nyiso.com/public/webdocs/documents/guides/Wind_Plant_Operator_Data_Guide_2010.pdf.

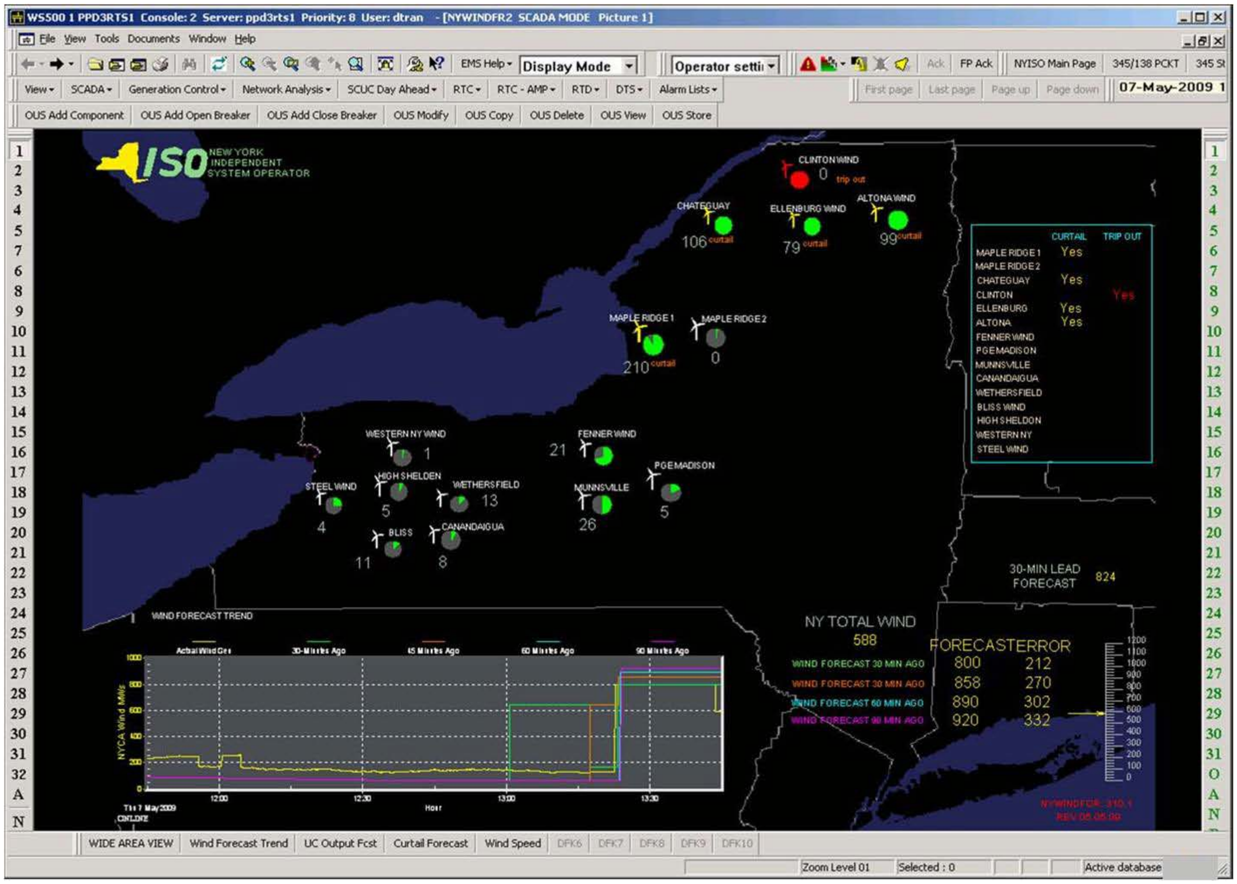


Figure 84. Display of System-Wide Information about Wind Plants (Provided by NYISO)

A.8 Red Eléctrica de España (Spain)

Red Eléctrica de España (REE) is the Spanish TSO, both for the peninsular system in Spain and for various Spanish Islands. Figure 85 shows that Spain has experienced unprecedented growth in wind generation over the years, and wind is an increasing portion of the generation mix.

At the end of 2010, the total installed capacity of wind in the REE system was 20,676 MW, which placed Spain as 4th in the world and 2nd in Europe after Germany. In order to meet its share of the EU 20-20-20 renewable energy targets,[71] wind generation will provide 21% of Spain's total electricity demand. Another driver for this growth in Spanish wind energy was several other government policies.[72] REE anticipates that the installed wind capacity in the system could reach about 29,000 MW (18% of the total electricity production) by the year 2016.

[71] See "Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources." European Parliament and Council Proposal, January 23, 2008.

[72] See "Plan de Energías Renovables para España, 2005-2010" IDEA, June 2005.

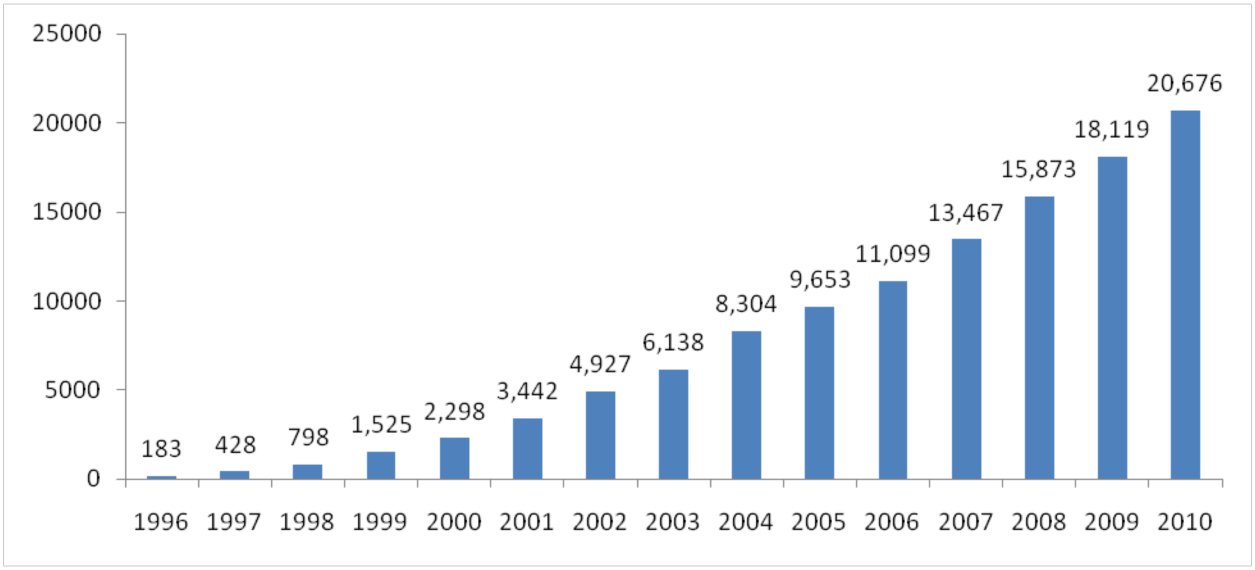


Figure 85. Cumulative Installed Wind Capacity (MW) in Spain (Source: REE)

The Spanish power grid is connected to the rest of the European grid via high voltage transmission lines to France and to Portugal. REE continuously faces a number of operational challenges including voltage control stability, transmission congestions, and system balancing especially under certain operating conditions. Nearly 40% of the wind generation in Spain is connected at the distribution system level.

Integration of wind generation in Spain is achieved through communications, exchange of information and coordination between three different control centers: the national electrical control center, CECOEL; the control center for renewable energy (CECRE)[73] and 28 or more control centers for renewable energy sources (RESCC). From the CECOEL, REE coordinates real-time operations and supervision of generation and transmission.

A.8.1 Unique Pioneering Control Center for Renewable Energy

In June 2006, REE commissioned the CECRE.[74] See Figure 86. It is physically collocated with the CECOEL as shown in Figure 87 and both centers are functionally and operationally integrated. The CECRE was created to facilitate the integration of those renewable energy resources in Spain that were subject to the special regime regulation. The goal was to maximize the production of electricity from renewable resources while always ensuring reliable operations of the grid. This unique accomplishment by CECRE made Spain the first country in the world to have a unique and dedicated control center for wind, solar and other variable renewable generating plants. Grid operators and regulators from many countries are constantly visiting CECRE. It was visited as part of this project.

[73] CECRE is the abbreviation for "Centro de Control de Régimen Especial".
[74] In order to control, supervise and integrate the large amounts of renewable energy (especially wind and solar) in Spain, REE launched the Control Center for Special Regime in June 2006. The Special Regime generation in the Spanish legislation refers to all renewable energy sources except for large hydropower plants.

Figure 86. General View of the Control Center for Renewable Energy, CECRE (Provided by Miguel de la Torre, REE)

CECRE CECOEL

Figure 87. Red Eléctrica Collocated Control Centers (Provided by Miguel de la Torre, REE)

With more than 700 wind parks in Spain today, and more expected, close coordination and an exchange of information between REE and the wind plant operators is crucial. This fact, and the increasing amount of data that must be exchanged between REE and the generator as more wind power is connected, were the reasons for the energy regulation of June 30, 2007.[75] It stipulates that a control center must direct all renewable energy plants with a total installed capacity greater than 10 MW. This regulation resulted in the creation of RESCCs.

[75] According to "Real Decreto RD661//2007, de 25 de mayo, por el que se regula la actividad do producción de energía eléctrica en régimen especial" Ministerio de Industria, Turismo y Comercio, BoE num. 126 26 mayo 2007, Spain. All special regimes Facilities with power capacity greater than 10 MW must be connected to a RESCC. Those that do not comply with this requirement lose their Special Regime status.

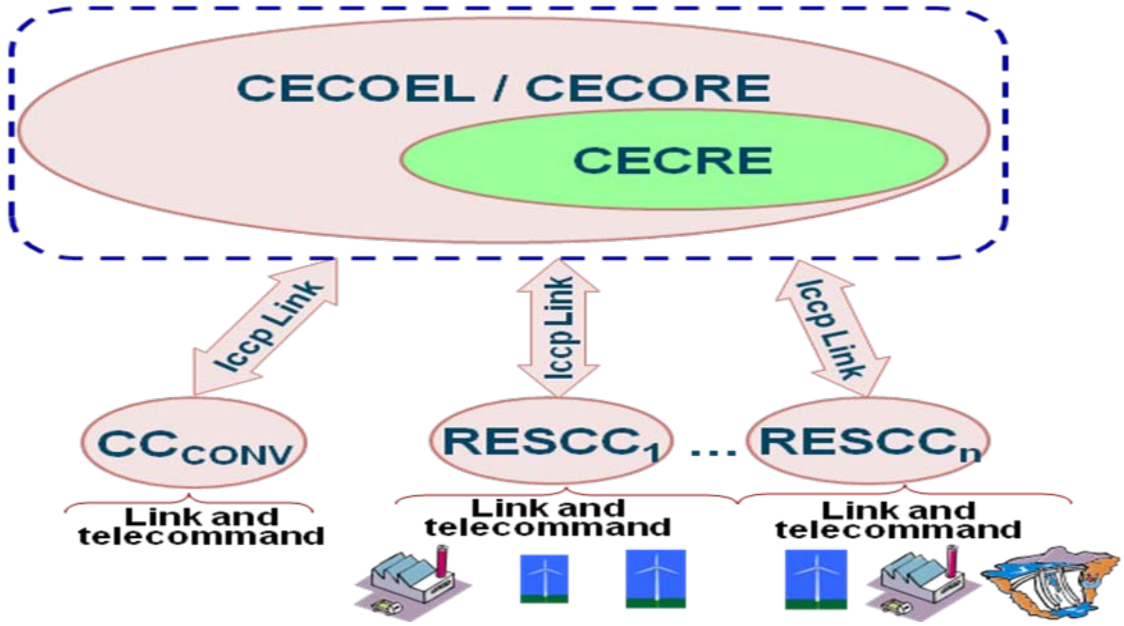


Figure 88. Functional Scheme of CECRE and RESCCs (Source: REE)

Currently, Spain holds 28 RESCCs, all of which are owned and operated by companies other than REE. These RESCCs must be directly connected to the CECRE as shown in Figure 88. Bi-directional communication and exchange of real-time data between RESCCs and the CECRE is via the Inter-Control Center Communications Protocol (ICCP). The CECRE sends set-points for controlling the wind power output to RESCCs, who in turn, send these signals to the wind energy producers. The CECRE also coordinates, controls, and supervises all generation units by grouping them in the RESCCs.

Relevant real-time wind production information that goes to CECRE is also sent to the CECOEL, where it is integrated into the EMS and other decision-making tools. In order to anticipate possible incidents which may arise as a result of integrating renewable energy resources, CECRE continuously analyzes the current scenario. With the help of wind power forecast and other tools, it also predicts the amount of wind power injected into the grid. The analysis is performed either for each individual wind farm or as an aggregation for each node in the transmission grid. Given that the REE grid has limited electrical interconnections to the power grid in France, the CECRE and its interfaces to RESCCs play a crucial role in wind integration and maintaining supply-demand balance.

A.8.2 Improving Wide-Area Situational Awareness

To enhance situational awareness of operators in CECRE, in addition to real-time and forecast wind power, other information about the impact that wind generation may have on grid operation is provided using various displays. For example, Figure 89 shows operators that the amount of wind power actually generated is based on data from the generators at different locations in the country.

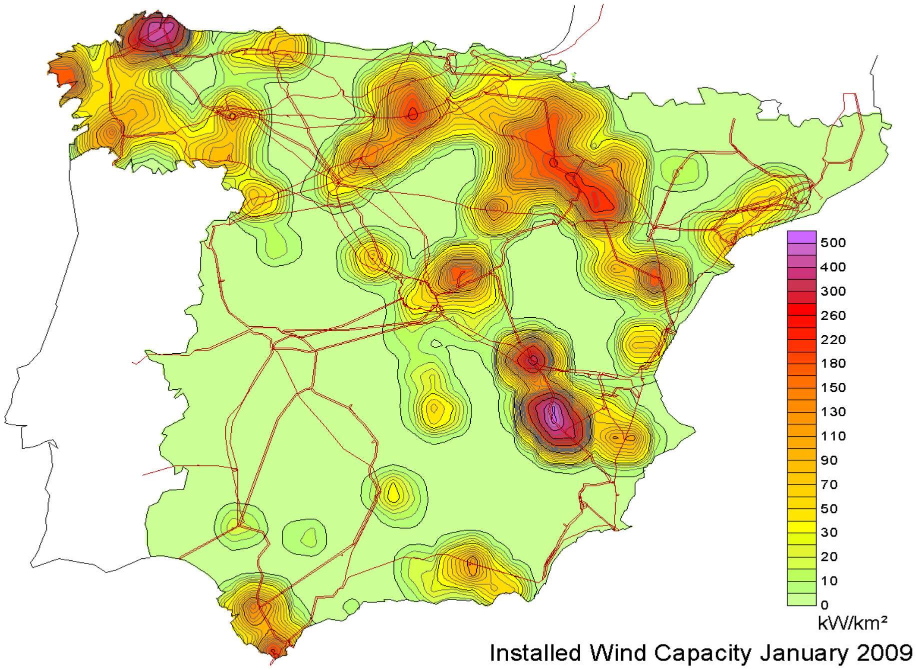


Figure 89. Wind Power Distribution across Spain (Source: REE)

One of the real-time operational challenges that operators at Red Eléctrica must cope with is the potential loss of wind generation due to voltage dips caused by transmission network faults. Voltage profiles throughout the network are used to perform real-time assessment of the risk and location of wind generation. As wind farms are spread across the country, contour maps like Figure 90 show real-time voltages in different parts of the system. Use of such displays allows operators to develop more efficient local- and wide-area situation awareness about the correlations between different system data (e.g., wind generation and system voltage).

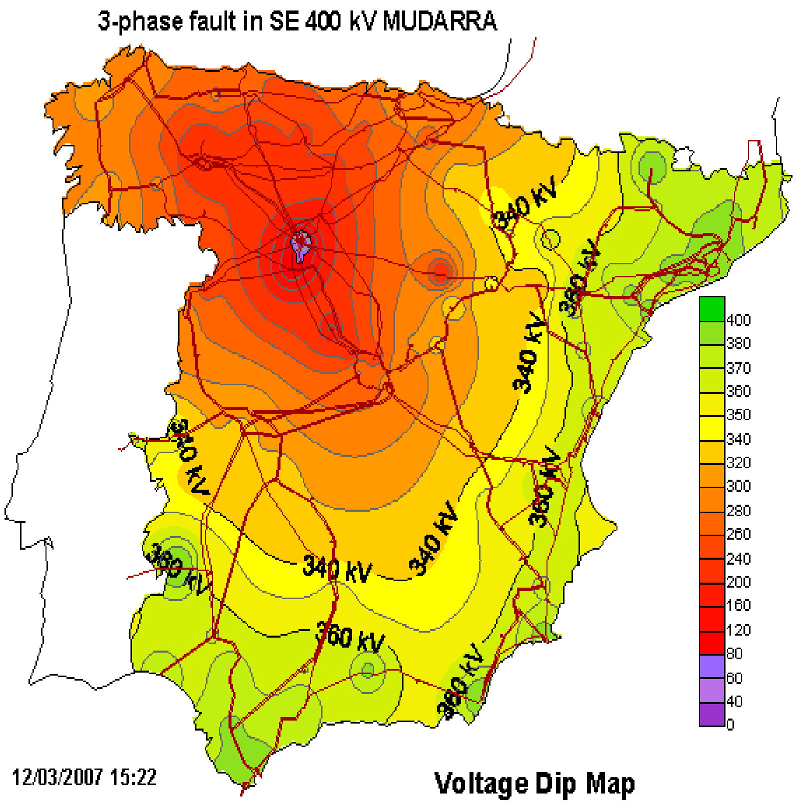


Figure 90. Voltage Contours after a 3-Phase Fault (Source: REE)

CECRE also provides real-time information about operating reserves and the amount of carbon dioxide (CO_2) that other conventional generators do not have to produce due to power from wind generation. Although not critical for grid operators, system planners and policy makers use their knowledge about CO_2 reduction relative to wind energy to inform energy policy decisions.

A.8.3 Centralized Wind Power Forecasting at Red Eléctrica

An accurate prediction of wind power is a prerequisite to the successful integration of wind energy in power systems. Increasing amounts of wind energy in Spain prompted REE to develop a tool for wind forecasting nearly a decade ago. SIPREOLICO is a wind power prediction tool to support the operation of the Spanish peninsular power system. In 2002, with nearly 5,000 MW of installed wind providing 3% of the country electricity, REE deployed a prototype of its own short-term prediction software, known as SIPREOLICO. REE was one of the first TSOs in the world to have a wind power forecasting system integrated with other tools in real-time system operations. Since then, the tool is fully operational and continued to evolve. It is an indispensable tool providing wind power forecast and other related information to the operators at CECRE and CECOEL. Operators today, compared to 2002, must control a system which has more than 20,000 MW of installed wind capacity.

SIPREOLICO makes a forecast for all wind parks on the system. Hourly forecasts for the next 48 hours are computed by region or the node at the transmission system. This information is updated every 20 minutes.

Hourly forecast is also computed and updated every hour. In addition hourly stochastic forecast of the total production is made for 15, 50 and 85 percent probability.

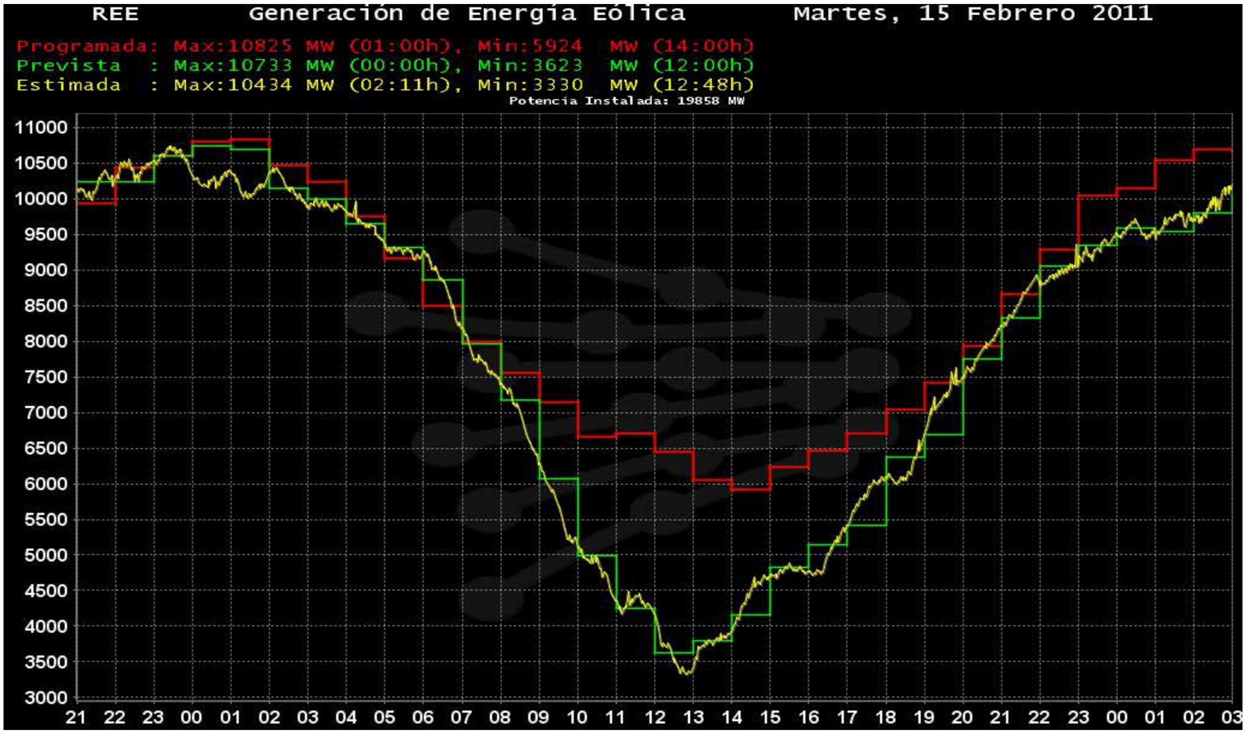


Figure 91. Wind Power Forecast from SIPREOLICO on February 11, 2011 (Provided by Pablo Martin, REE)

Figure 81 shows an example of the wind power information presented to operators. The RED graph is the wind power schedules or forecast from the generators; the GREEN is the forecast from SIPREOLICO that was made in the last hour; and the YELLOW is the estimation of the total wind power production made from real time measurements. In this case, the forecast in SIPREOLICO is updated every 20 minutes but the graph is updated every 60 minutes.

A.8.4 Use of Multiple Forecast Providers

REE, like many other TSOs in Europe, uses wind forecast from multiple providers. Wind power forecast is computed using both single and combined versions of the forecasts received from the different providers. As a common practice, REE constantly performs a comparison of the forecasting errors to track the forecasts with the least error and better performance. In general, it is believed that the combined forecast is better. Figure 92 shows the Mean Absolute Error (MAE) for wind power forecast from SIPREOLICO, using four individual wind forecast, and one for a combined forecast, for 48 hours. The combined forecast has the lowest MAE for all time horizons.

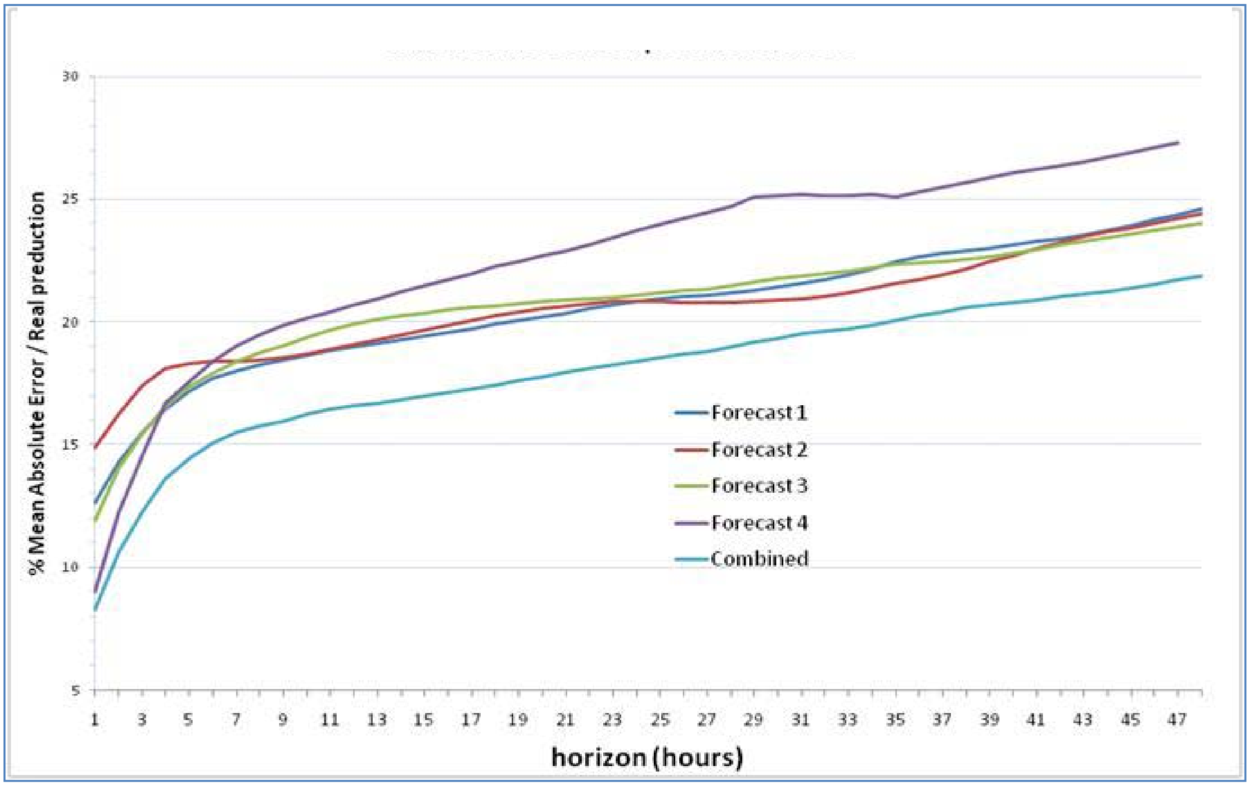


Figure 92. Forecast Error Using Single or Combination of Forecasting Models (Provided by Pablo Martin, REE)

A.8.5 Wind Forecast Management Process

Given the importance for wind power forecast in wind integration and grid operations, REE makes a continuous investment to improve the wind power forecast accuracy. It has implemented a wind forecast management process which involves: a) a generation of weekly and monthly reports of forecast errors; b) an update of the wind farm data database; and c) data cleansing to identify bad or erroneous data. Over the past 5 years the MAE of the wind power forecast from SIPREOLICO has reduced consistently in the critical time periods, e.g., (5 hours, 24–32 hours), shown in Figure 93, for 2005 to 2008. This improvement reduced the amount of reserves that have been needed to account for forecast errors in the day-ahead operations.[76]

[76] Source: Interviews with the staff at REE on October 7, 2010, and the internal document *Renewable Energy Development in Spain.*

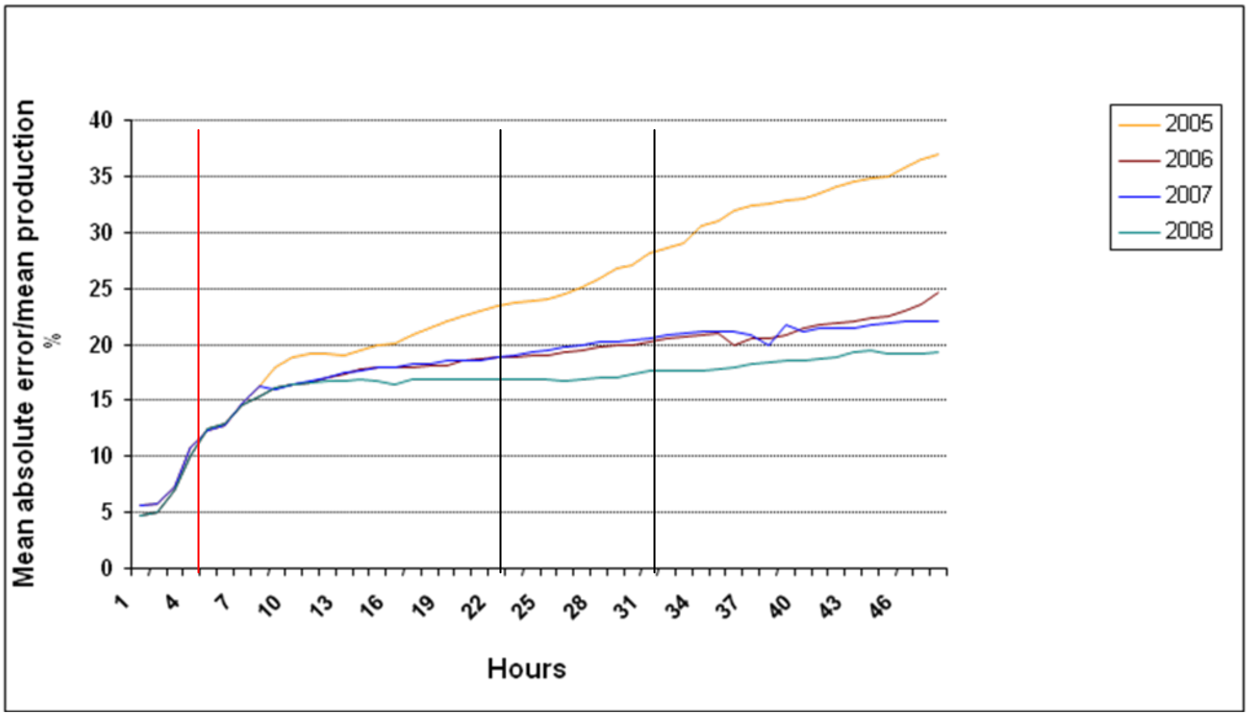


Figure 93. Improvement in Accuracy of the Forecast from SIPREÓLICO (Provided by Pablo Martin, REE)

REE developed an Error Calculation to compute and track different error metrics for different time horizons. An internal full-time team dedicated to maintaining SIPREOLICO and other related software tools regularly use this metric. As another approach to continuous improvement in the forecast performance, REE defines specific goals to reducing forecast errors from SIPREOLICO as part of the annual objectives of the team in charge of maintaining the tool.

A.8.6 Advanced Decision Support Tools for Maximum Wind Power Integration

Successful integration of the maximum admissible wind power generation in the system must be achieved with minimal impact on the grid security. Important tasks such as the management of potential network congestion, control and supervision of wind plants to mitigate the impacts of voltage dips, and wind plant curtailment must be carried out in a coordinated manner. To achieve this, REE developed an advanced decision support tool, known as GEMAS.[77] Operators in the CECRE regularly use this tool.[78]

GEMAS continuously, i.e., every 20 minutes, checks which wind generators will trip due to voltage dips. In addition, the tool calculates the wind generation curtailment set-points to be issued to the RESCCs due to voltage dips, system faults, congestions or potential problems with system balancing. See Figure 94. The input to GEMAS includes real-time wind power production, snapshots from the EMS state estimator and other applications, and wind farm data.

[77] Acronym GEMAS is Spanish Generación Eólica Máxima Admisible en el Sistema.
[78] The brief description of GEMAS in this report is based on emails from, and notes taken, during discussions Miguel de la Toro of REE at the CECRE on October 7, 2010. Another source was the internal document Renewable Energy Development in Spain.

To determine the worst fault condition in the grid in terms of voltage dips, GEMAS uses a state estimator case from the EMS. Three-phase fault conditions are studied at a significant number of substations in the transmission system. The faults are simulated using so-called pseudo-dynamic studies (e.g., switching studies). After the simulation of every fault, the program analyzes the voltage in all of the nodes where wind plants are connected, in order to know the sensitivity of every wind plant to that fault. In this way, given the actual power production of every wind farm, it is possible to determine the generation loss that is associated with every fault simulated. This process is repeated for all the nodes included in the list of significant nodes. If it is detected that the simulated loss is larger than the generation loss that the system can handle without affecting operations, some wind farms will need to be curtailed to lower the maximum possible generation loss. In GEMAS, this calculation is done using a two-step linear optimization process, in order to integrate the maximum energy ensuring the security of the system.

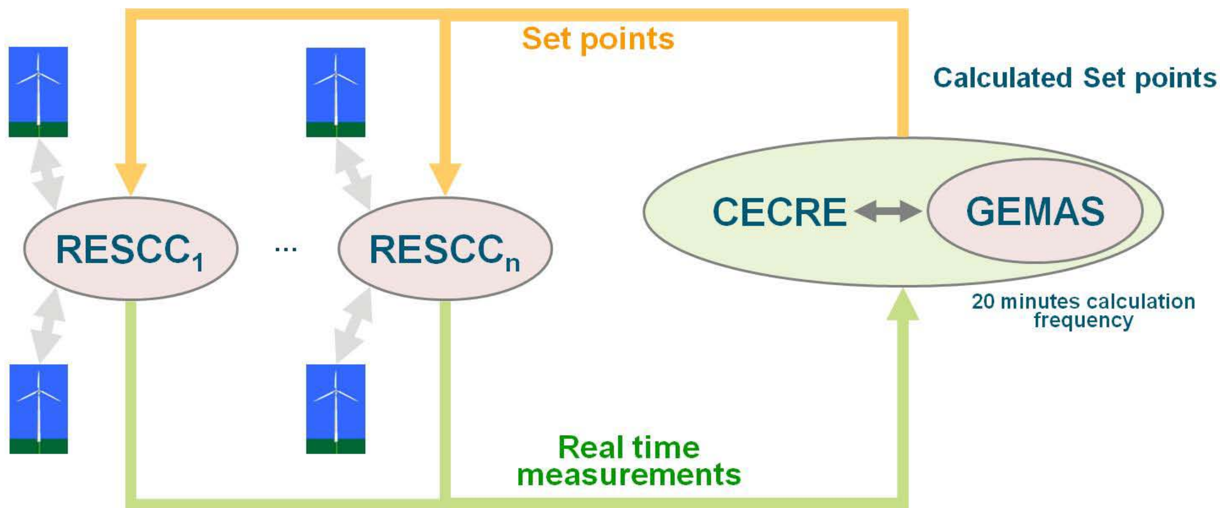


Figure 94. GEMAS – Wind Plants Curtailments (Source: REE)

Apart from the voltage dip wind generation tripping estimator, two modules for managing congestion in GEMAS exist. With the first module, the CECRE operator defines a group of wind plants that have been identified with the same sensitivity with respect to given constraint. The operator may enter a maximum production value for that group and GEMAS automatically distributes the curtailment levels according to the predefined legal requirements. Another module manages curtailments due to balancing constraints where all wind parks installed in the system have the same sensitivity to the constraint.

GEMAS does not explicitly use wind forecast as an input data. However, the operator, who has knowledge of the wind forecast prior to making his/her decision, always decides what the final instructions to curtail wind generation, derived from GEMAS and sent to the RESCCs will be. This is especially important when there is curtailment due to balancing constraints. This balancing-constraint restriction affects all wind farms connected to the system. At that point, the only the wind power information that is available is the wind forecast. For this reason, it is very important that the wind forecast model has the wind power output limits published by GEMAS as an input, in order to inform the SIPROELICO that, for the wind farms that are curtailed, the actual power is not related with the wind speed.

A.9 RTE (France)

RTE is the TSO of France. The installed wind power capacity in France at the end of 2009 was 4,574 MW. During 2010, another 1,086 MW was added, making the total installed capacity 5,660 MW. Figure 95 shows how wind power in France has evolved since 2002. Today, France ranks 6th in the world in terms of total installed capacity. Wind power plants in France are located in different areas around the country. Wind plants are also in several different landscapes and experience different kinds of winds and load duration curves.

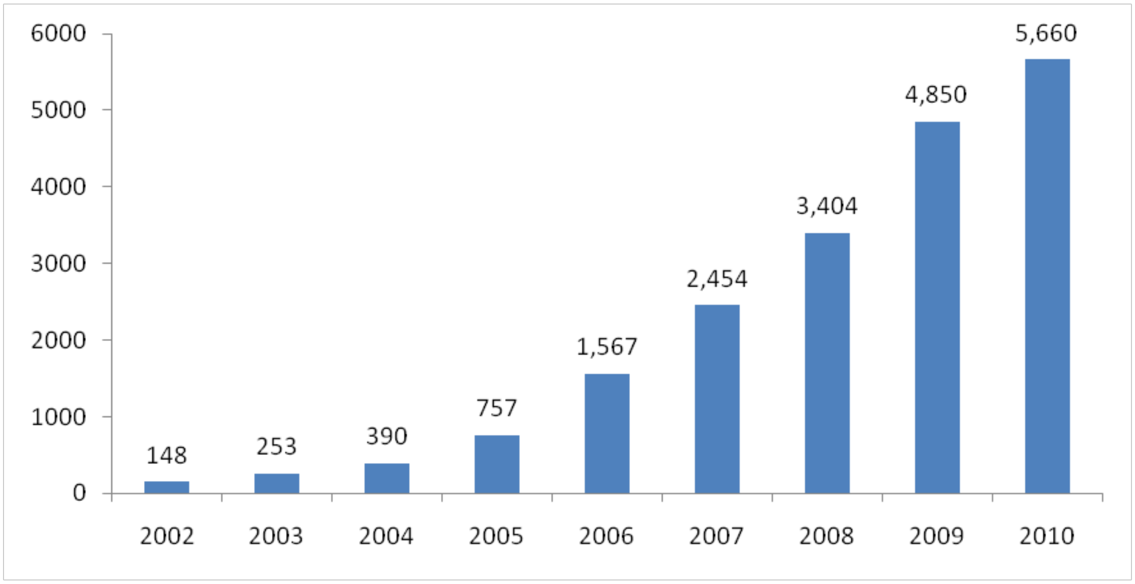


Figure 95. Cumulative Installed Wind Power (MW) in France (Sources: GWEC and RTE)

The growth of wind power in the RTE system is expected to continue in order for France to meet its EU '20-20-20' renewable energy target. The share of electricity demand in France met by renewable generation must reach 23% by 2020.[79] The French government set a target in December 2009 of achieving 11,500 MW of installed wind energy capacity by 2012 and 25,000 MW by 2020. While existing wind plants in France are on-shore, future wind farms are planned to be built offshore. An official goal of building between 1,500 MW and 6,000 MW of offshore wind from 2012 to 2020 is also in place. In February 2010, the French government announced that it would launch an international tender to build 3,000 MW wind offshore in France.[80]

More than 95% of the wind power injections are at the distribution network, although the impact is felt at the transmission network, where RTE is responsible for maintaining supply-demand balance. Therefore, integrating wind power in France required RTE to use wind power forecasting to improve the operators' ability to observe wind power production and to determine reserve requirements that ensure reliable grid operation. A key activity at RTE has been to provide its operators with forecast information in the control centers.

[79] The Global Wind Energy Council is a valuable source of information on wind energy world. The data about the cumulative installed wind power in France was accessed online on February 26, 2011 from http://www.gwec.net.

[80] The offshore wind farms are expected to be developed in the western regions of the Loire, Brittany and Normandy. Accessed on February 28, 2011 from http://www.offshorewind.biz.

A.9.1 Integrating Wind Forecast in Real-Time Operations

In 2009, RTE deployed a system called "IPES"[81] to help operators cope with increasing wind generation on the grid. Operators use the data from IPES, along with the short-term wind production forecasts, to perform network studies tools. The dispatchers benefit from real-time observations of wind power injection on the network, which enables them to better anticipate the power flows on the transmission system during real-time operations. See also (Houot).

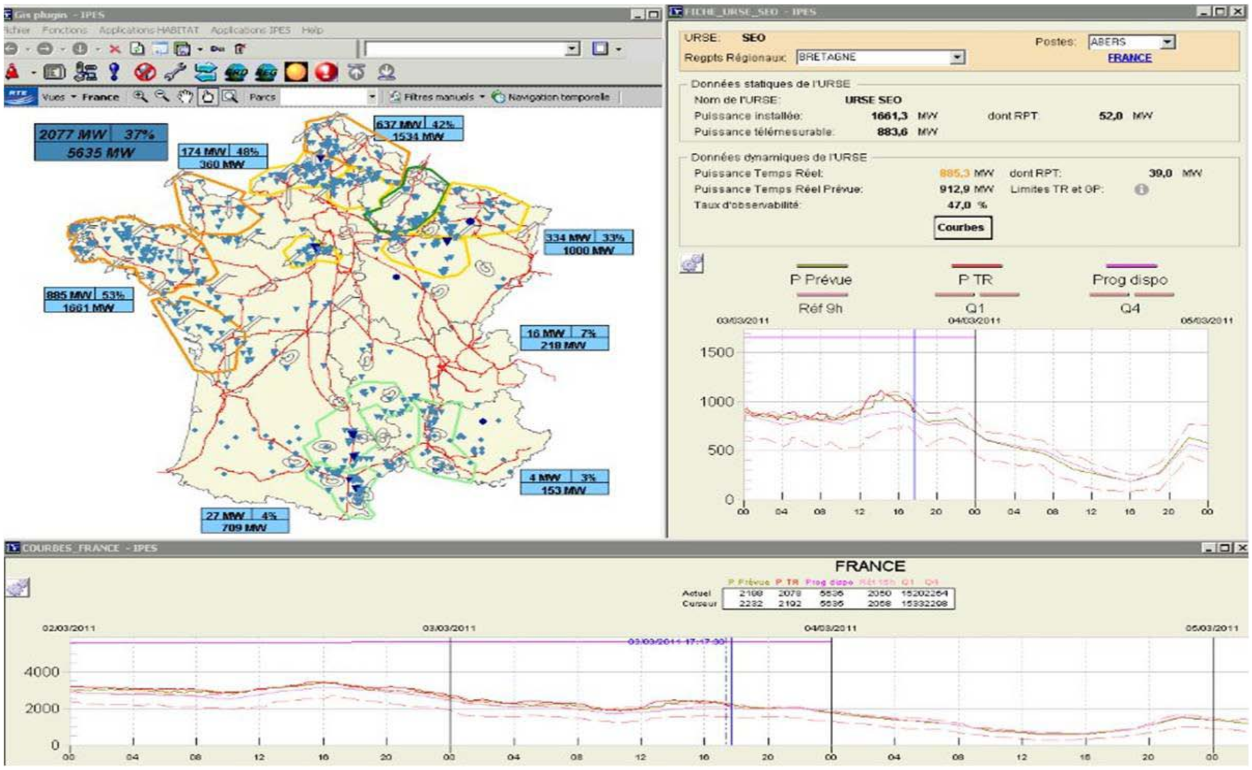


Figure 96. IPES Main Operator Display (Provided by Emmanuel Neau, RTE)

Figure 96 shows the main view of IPES. It provides the location of wind farms and the definition of main wind areas, different information such as the installed and the measured wind power capacity, and curves of production (forecast and estimation) for different wind farm, regional areas or for the country.

By consolidating information and knowledge about wind power production, the IPES system allows RTE to take preventative measures that would change the system topology or issue a request to generators participating in the system balancing to adjust their output so as to alleviate congestion and solve other operational issues.

[81] IPES is the abbreviation for Insertion de la Production Éolienne dans le Système. The English translation is Integration of Wind Production into the System (Grid).

A.9.2 Collaboration between TSO and DSO

Most of the wind generation is connected at the distribution level. Therefore, in order to anticipate and mitigate certain risks related to network operation as a result of high penetration of wind, RTE worked with ERDF, the French distribution system operator (DSO) in 2010 and installed local automation in the network power stations that control the wind production. This automation can curtail wind plant outputs during a period of operation when there are constraints on the transmission system.

The IPES solution deployed in the RTE control room platform is based on a SCADA and includes a module that manages wind generation. As shown in Figure 96, it enables power system dispatchers and day-ahead operators of the grid to access technical data about all wind farms and to get real-time power measures sent by distribution or production control centers for 74% of the total wind power installed capacity in France. The application includes an estimate of missing telemetry data that is produced for each wind farm. This is based on the load factors of other remotely metered wind farms, usually located close to the wind farm being estimated.

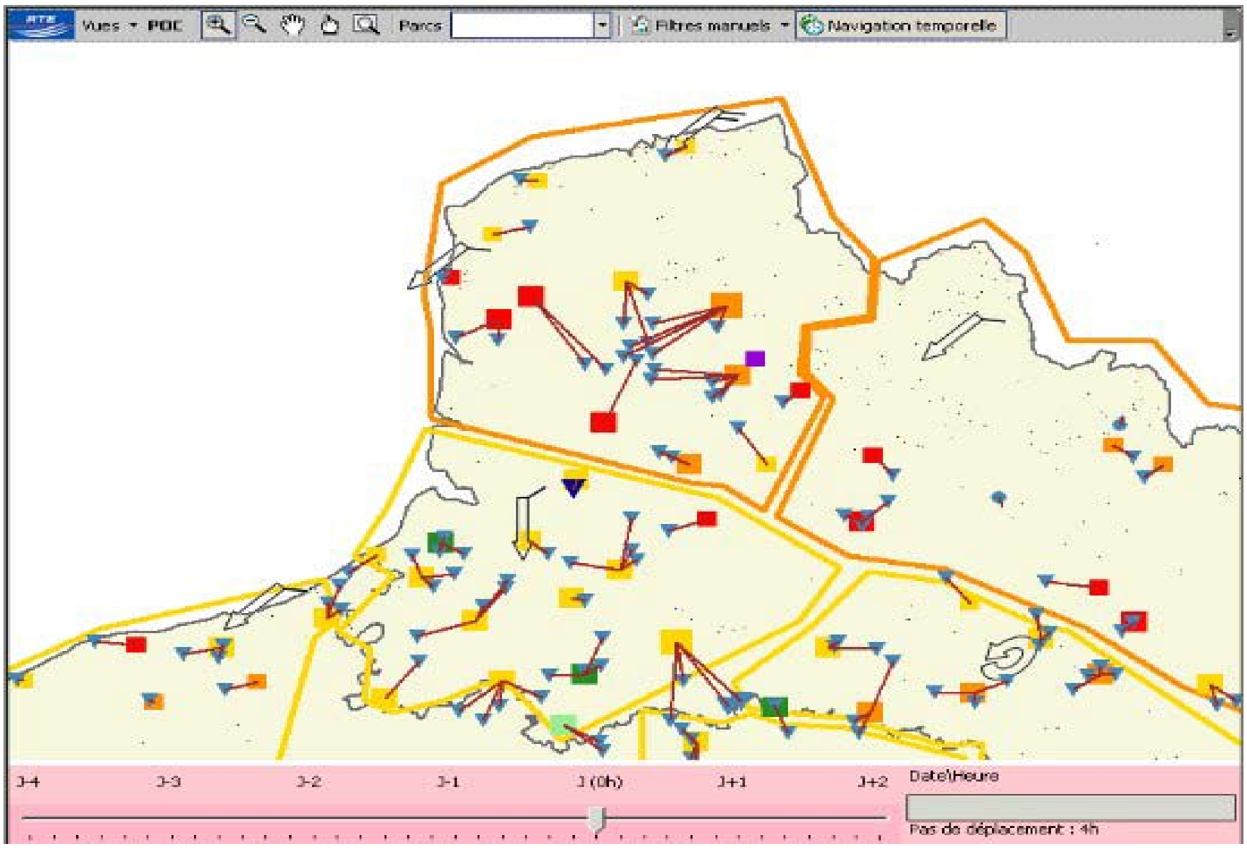


Figure 97. Temporal Information about Wind Farm and Power Substations (Provided by Emmanuel Neau, RTE)

A.9.3 Wide-Area Situational Awareness with Look-Ahead Capability

For real-time situational awareness, the IPES system has a dynamic Human Machine Interface (HMI) with layered access to information based on geographical and chronological criteria. The system also has the possibility of configuring alarm thresholds depending on wind generation levels or wind speeds. As discussed in the previous sections, projection is an important aspect of situation awareness, especially when operating under a high level of variability and uncertainty due to wind. Therefore, the IPES system has a look-ahead capability, which enables operators to view every hour updated forecasts for wind generation for a three day period at different geographical, aggregated levels: country, regional, electrical substations and wind farms. For example, as illustrated in Figure 97. IPES could also provide temporal information about wind farm and the power substation. With the unique alarming technique, the operators at RTE can monitor and be easily alerted about areas where grid constraints could occur due to a certain level of wind production. This ability to do projections will help operators maintain higher levels of wide area situational awareness.

APPENDIX B.

LIST OF RESPONDENTS

This appendix includes a list with the names of organizations who responded to the survey, the installed wind capacity, total generation, peak demand and the penetration as a percentage of the total installed capacity. The data is the current situation as of January 31, 2011.

Table 1. List of Respondents and Relevant System Data

Organization	Country	Type of Organization	Installed Wind Capacity (MW)	Total Generation (MW)	Peak Demand (MW)	Penetration (%)[82]
50Hertz Transmission GmbH www.50hertz-tranmission.net	Germany	TSO	11,513	37,570	18,101	30.6
Alberta Electric System Operator www.aeso.com	Canada	ISO	777	13,510	10,236	5.7
Amprion GmBH www.amprion.net	Germany	TSO	4,565	70,201	30,533	6.5
Australian Energy Market Operator www.aemo.com.au	Australia	TSO	1,650	42,000	35,000	3.9
Bonneville Power Administration www.bpa.gov	USA	BA	3,372	32,700	10,700	10.3
CORESO www.coreso.eu	Belgium	RC	36,000	220,000	170,000	16.4
EirGrid www.eirgrid.com	Ireland	TSO	1,425	8,360	5,090	17.6
ELERING www.elering.ee	Estonia	TSO	147	2,222	1,600	6.6
ELIA www.elia.be	Belgium	TSO	911	15,700	13,700	5.8
Electricity Reliability Coordinator of Texas www.ercot.com	USA	ISO	9,317	84,237	63,830	11
EnBW www.enbw.com	Germany	TSO	620	18,065	11,603	3.4

[82] Penetration is defined here as the ratio of installed wind capacity to total installed generation capacity.

Organization	Country	Type of Organization	Installed Wind Capacity (MW)	Total Generation (MW)	Peak Demand (MW)	Penetration (%)[82]
Energinet www.energinet.dk	Denmark	TSO	3,752	13,100	6,400	28.6
ESKOM www.eskom.za	South Africa	TSO	20	44,000	35,000	0.05
Hawaii Electric Company www.helco.com	USA	BA	31	321	200	9.6
Hydro Quebec www.hydroquebec.com	Canada		600	40,000	38,000	1.5
Idaho Power www.idahapower.com	USA		200	3,410	3,200	5.8
ISO New England www.iso-ne.com	USA	ISO	204	31,518	28,000	0.65
Korean Power Exchange www.kpx.or.kr	Korea	TSO	377	76,131	71,423	0.5
Manitoba Hydro www.hydro.mb.ca	Canada	BA	238	5,580	4,273	4.3
MAVIR www.mavir.hu	Hungary	TSO	250	9,322	6,232	2.7
Midwest ISO www.midwestmarket.org	USA	RTO	8,200	144,132	116,030	5.7
New Brunswick System Operator www.nbso.ca	Canada	ISO	455	4,550	3,300	10
New York Independent System Operator www.nyiso.com	USA	ISO	1,349	37,416	33,939	3.6
PJM www.pjm.com	USA	RTO	3,800	167,320	144,644	2.3
Power System Operating Company Ltd.[83] www.powergridindia.com	India	TSO	13,065	103,670	103,007	12.6
Puget Sound Energy www.pse.com	USA		430	4,600	5,100	9.3

[83] As of 2010, Power System Operating Company (POSOCO) Ltd. is fully owned by Power Grid Corporation of India.

Organization	Country	Type of Organization	Installed Wind Capacity (MW)	Total Generation (MW)	Peak Demand (MW)	Penetration (%)[82]
Red Eléctrica de España www.ree.es	Spain	TSO	20,676	93,700	44,876	22.1
REN - Rede Eléctrica Nacional, S.A. www.ren.pt	Portugal	TSO	3,702	17,915	9,403	20.6
RTE www.rte-france.com	France	TSO	5,660	110,000	96,300	5.1
Southwest Power Pool www.spp.org	USA	ISO	3,469	78,473	53,146	4.4
State Grid Corporation of China www.sgcc.com.cn	China	TSO	28,260	855,950	497,970	3.3
TERNA www.terna.it	Italy	TSO	5,797	105,200	51,900	5.5
Transend www.transend.com.au	Australia	TSO	139.75	2,802	2,366	5.9
Transpower www.transpower.co.nz	New Zealand	TSO	453	8,668	6,550	5.2

APPENDIX C.

SURVEY QUESTIONNAIRE

Q1: Which of the following best describes your organization?

Q2: How has increased penetration of wind power affected the reserve requirements in your system?

Q3: What are the reserve requirements on your system with and without wind for each of the following function?

Q4: In what time frame does wind variability and uncertainty have the most significant impact on CURRENT operation of your system or business?

Q5: In what time frame do you expect wind variability and uncertainty to have the most significant impact on FUTURE operation of your system or business?

Q6: Which aspects of maintaining grid reliability will become most difficult with high levels of wind power integration?

Q7: What do you see as the biggest and/or most urgent change needed in your system or business to support integration of additional wind energy?

Q8: Have you integrated wind forecasts in real-time or planning processes or solutions to manage the following:

a) Voltage Stability

b) Unit Commitment

c) Transmission Switching

d) Transient Stability

e) State Estimation

f) Regulation

g) New Transmission

h) New Generation

i) New FACTS Devices

j) Load Following

k) Economic Dispatch

l) Contingency

m) Contingency Analysis

n) Congestion Management

Q9: How would you rank the following wind forecasting products on the basis of their IMPORTANCE in control room operations?

a) Ramp forecasting

b) Short-term forecast (e.g., 10 min.)

c) Probabilistic forecast

d) Ensemble forecast (use of multiple wind forecast)

e) Weather Situational Awareness

f) Ramp Risk forecast

g) Next-hour forecast

h) Wind plant high-resolution forecast

Q10: What are the limitations of wind forecasts that are currently available to support your system or business?

S11: The ability to integrate a significant amount of wind will largely depend on the accuracy of forecasts.

Q12: Have the frequency of curtailment and the quantity of wind power curtailed reduced with better integration of wind forecast?

Q13: Do you have automated tools and solutions that are used to manage wind curtailment?

Q14: What tools have you deployed (to support your operators, if applicable) to manage the integration of wind power? Please also identify where they used in the organization (e.g., operations, planning, scheduling, etc.) and how they are used (e.g., operation decision-support, situational awareness, reliability analysis, corporate oversight, etc.).

Q15: North American Electric Reliability Corporation (NERC) has identified that new “advanced decision support tools” are important to manage grids with large amounts of wind energy. Please rank the value of the following tools to support integration of wind power.

a) Dynamic security assessment with stochastic model

b) Optimal power flow with wind forecast

c) Optimization-based transmission planning

d) Price responsive demand forecast

e) Probabilistic reserve allocation

f) Stochastic unit commitment

g) Stochastic power flow

h) Stochastic unit commitment

i) Voltage stability analysis

j) Transient stability analysis

Q16: Which of these are currently implemented or are there plans to implement them in support of integrating wind power in your system?

Q17: Rank how each of these smart grid applications, when integrated with wind forecast, will have the most impact on integrating wind power in real-time grid operations?

a) Dynamic Line Rating

b) Demand Response

c) Energy Storage

d) Plug-in Hybrid Electric Vehicles

e) Transformer Load Management

f) Volt/VAr Optimization

Q18: Which of these are currently implemented or there are plans to implement in your system?

Q19: What other tools may be needed for the reliable and efficient integration of wind power?

Q20: How is the ability to integrate significant amount of wind will largely depend on the decision support tools deployed to support control room operators.

Q21: Has wind generation affected the process for scheduling transmission in your organization?

Q22: Has wind generation affected the process for scheduling conventional generation in your organization?

Q23: Describe the inter-BA or inter-TSO scheduling process in your organization?

Q24: Do you currently consider wind ramping events when determining regulating reserves?

Q25: Do you currently consider wind ramping events when determining contingency reserves?

Q26: Do you currently consider wind ramping events when determining other reserves or conventional unit commitment?

Q27: What policies have you established with balancing authorities, wind plant owners/operators, other utilities, or other entities to manage the integration of wind power?

Q28: What internal operating procedures have you established in your control room to manage the integration of wind power?

Q29: What new business processes and procedures is your organization considering in support of wind integration, and what processes and procedures do you think may be important for higher penetration of wind energy?

Q30: What national policies, state policies, or grid codes need to be changed to support large-scale wind power integration for your organization?

Q31: Various changes to grid operations have been proposed to allow large scale integration of wind power. Considering the costs and benefits, please rate the value of each of the following approaches or others that you see.

a) Building more transmission

b) Dynamic interchange scheduling

c) Dynamic Line Rating

d) Larger balancing areas

e) More accurate wind forecasting

f) More flexible conventional generation

g) Lower minimum loads

h) Faster/more accurate ramping

i) Visualization of system conditions

j) Automated decision support tools

k) Surgical load shedding

l) Controllability of load resources

Q32: The ability to integrate a significant amount of wind will largely depend on the operating policies deployed to support control room operators.

Q33: Grid codes and reliability standards must be substantially changed to support the integration of high levels of wind power.

Q34: Is the standardization of data communications protocols and system interoperability are not sufficiently developed to support integration of high levels of wind power?

Q35: Where do you get information about current wind integration issues, tools and methodologies?

Q36: What are new systems needed to gather and/or develop information to support wind power integration?

Q37: How would you rate the current level of training in your control center compared with what is necessary to effectively manage high levels of wind energy?

Q38: What skills have you identified as important for effective integration of wind power? For example, have you modified training or qualifications required in your organization?

Q39: Where should emphasis be placed in education and training to develop new skills needed to manage wind-power integration?

Q40: Which of the following new skill sets do you expect to be required in your control room to cope with higher penetration of wind power?

APPENDIX D.

LETTER INVITING UTILITIES TO PARTICIPATE IN THE SURVEY

Dear XXXXXXX

My colleagues and I are conducting a research project supported by the U. S. Department of Energy to identify the best path forward to guiding the development of the operational strategies, business processes, solutions and tools that may support the scenario of achieving 20% wind energy in the United States of America by 2030. Details about this scenario can be found in the report *"20% Wind Energy by 2030: Increasing Wind Energy's Contribution to the US Electricity Supply,"* published by the U.S. Department of Energy in 2008.

I am inviting you and/or a contact in your company to participate in this research project. Your participation is voluntary and will involve completing the attached questionnaire that asks a variety of questions based on both the current operating conditions and practices in utilities as it relates to wind integration, and also anticipated operating conditions that will emerge as a result of higher penetration of wind generation, e.g., 20% in the U.S. by 2030.

In addition to the questionnaire, please let me know if you or the person responding would be available for a follow-up telephone conversation in case we have any questions based on your feedback.

The results of this study will provide utilities with recommendations on how to best improve existing and develop new policies, business practices, decision support tools and solutions for integrating wind energy in the U.S. By identifying best practices from a broad collection of utilities, the findings will serve as a field guide for grid operators and dispatchers, and could also be a fast-track for training grid operators. They could also aid in the establishment of operating procedures and practice in the control room environment for managing wind integration.

I hope you will take the time to complete the questionnaire and return it to me by August 27, 2010. My email address is Lawrence.Jones@alstom.com.

We anticipate that the report from this research project will be publicly released during the second quarter of 2011. You will of course be forwarded a copy of it.

Please note that neither your name, nor that of the utility you represent, will be personally identified with any specific responses you provide in this questionnaire. This also applies to all answers provided to questions in any form, as part of this research project. In the final report, however, with their written consent, the name of a utility represented in the questionnaire shall be listed for reference purposes.

To provide diverse industry perspectives in the development of this questionnaire, we sought the feedback of a voluntary Industry Advisory Committee. Members of the committee included:

Mark Ahlstrom, CEO, WindLogics, USA
Pierre Bernard, Secretary General, ELIA Group, Belgium
John Dumas, Manager, Electric Reliability Council of Texas (ERCOT), USA
Brendan Kirby, Energy Consultant, USA
J. Charles Smith, Executive Director, Utility Wind Integration Group (UWIG), USA

Thanks in advance for taking the time to complete and submit this questionnaire. Your insight and information are important for the success of this project.

Regards

Dr. Lawrence E. Jones
Principal Investigator

APPENDIX E.

RESPONDENTS' ANSWERS TO SURVEY QUESTIONS

This appendix contains the answers to some of the survey questions that require explanation or a description of process and procedures. As a pre-condition for responding to the survey, the name of the utility and/or its representative responding must remain anonymous. See Appendix D. As a result, the responses have been slightly edited to mask the exact identity of the utility or representative who provided a response to a given question in some cases. In addition, some of the answers have also been corrected for spelling and other grammatical errors. These responses to the survey should not be used alone to determine the path towards 2030. Instead, they offer important guidance when identifying best practices, formulating policies and developing future solutions for wind integration.

Table 2. List of survey questions and the corresponding tables with responses

Question #	**Table #**
6	Table 3. Aspects of maintaining grid reliability which will become most difficult with higher penetration levels of wind power (Q6)
7	Table 4. Biggest and/or most urgent change needed in your system or business to support integrating more wind energy (Q7)
10	Table 5. Limitations of wind forecast currently available to support your system operations and business (Q10)
13	Table 6. Automated tools and solutions used to manage wind curtailment (Q13)
19	Table 7. Additional tools that may be needed for reliable and efficient integration of wind power (Q19)
23	Table 8. Description of inter- BA or inter-TSO scheduling process in your organization (Q23)
27	Table 9. Policies established with other BAs, wind generators, utilities, or other entities to manage wind power integration (Q27)
28	Table 10. Internal operating procedure established in your control room to manage wind integration (Q28)
29	Table 11. New business processes and processes in support of wind integration (Q29)
30	Table 12. National or State policies, or grid codes that need to be changed to support large-scale wind integration (Q30)
36	Table 13. Systems needed to gather and/or develop information to support wind integration (Q36)
38	Table 14. Skills important for effective wind integration, e.g., modified training or required qualifications (Q38)
39	Table 15. Emphasis in education and training to manage wind integration (Q39)

Table 3. Aspects of maintaining grid reliability which will become most difficult with higher penetration levels of wind power (Q6)

Issues related to Unit commitments and out-of-order dispatches.
Power transfer flows through our grid coming from wind in-feed of neighboring systems.
Handling significant wind ramp events.
• Management of power flows across the interties during large and rapid wind power changes. • Frequency control on the Island system when intertie is out of service. • Different market outcomes in the form of negative prices are already being experienced during periods of high wind generation and light load.
System Inertia; System fault levels; Frequency Control Ancillary Services requirements.
Congestion due to insufficient transmission capacity linking wind power to the load centers.
Managing localized transmission constraint and near-term economic commitment of generation.
• Congestion management and N-1 constraints due to geographical concentration of wind farms in certain regions • Market price volatility and extreme market behavior in some cases due to forecasted high wind ramps and erroneous forecasts.
• Management of congestion as more wind continues to be integrated is the most pressing concern. • Another concern is wind variability over the 20 minutes to 1 hour timeframe. Specifically, maintaining the ability to manage very large changes in wind conditions over this timeframe.
A high level of wind power integration will impact congestion management in some parts of our grid. Also, balancing of the system during minimum load conditions, especially for island systems.
Ensuring enough regulation reserves are dispersed and delivered. In addition having the necessary intra-hour ramping capabilities.
• Ensuring that enough conventional and dispatchable generation and demand is available to meet the fluctuations in the variable resource. • Having an effective dispatch algorithm that considers the availability of the transmission on the system.
Voltage control. Also, it will become increasingly difficult to calculate transmission capacity since infeeds can vary quite a lot.
The ability to plan for and maintain adequate reserves.
• Frequency stability would be a problem in the next two years. • In the long run, wind variability would lead to congestion in the transmission system. • Moreover, there are negligible reserves for capturing the variability of the wind generation.
• Congestion on the system.

Our market design is based on discrete half hour trading periods leaving generators, through offers to generate, to manage inter-temporal issues such as thermal unit commitment and river flows through multiple stations. The level of expected wind generation from one to day to the next is expected to continue to compound generator thermal unit commitment decisions.
The key limits to wind integration resolve around the lack of holistic mix of generation and ancillary services. The issue of transmission adequacy should be transitory as the network gets built.
Unless wind forecast improves dramatically, meeting the difference between the scheduled wind and the actual output of wind will be the most significant impact to grid reliability. The dynamic movement of wind may also begin causing problems with voltage and the settings on remedial action schemes as the amount of wind increases in our system.
Frequency regulation and system balancing.
Voltage stability.
In general, operating reserve and ramp rate would be the most difficult issues with large wind penetration.
Real power balancing during wind power ramping.
There will be a need to use wind for voltage control. There might be transient stability problems. Additional primary and secondary (spinning) reserve will be needed, so wind farms will be required to provide it.
• Load Following - the most significant problem. • Electricity Quality - frequency and voltage problem.
Wind variability and uncertainty in one day.

Table 4. Biggest and/or most urgent change needed in your system or business to support integrating more wind energy (Q7)

Operational forecasting is required and is being implemented. Curtailment rules have already been established.
We need a more accurate and precise wind power prediction system which we can use for intraday scheduling.
Continuing to enhance our wind situational awareness tools to support the grid operators.
Forecasting of large rapid changes in wind generation and the development of rules and procedures to manage the impacts.
Market mechanism to bring on additional generating plant to alleviate the inertia and fault level issues.
• Addition of new transmission lines to handle delivery of wind power during periods of high wind output. • Increased flexibility of resources could also increase the levels of wind generation. This flexibility could be provided from resources such as: new energy storage technologies which could curb the need to deliver the energy at the instant of generation; quick start generators; and demand response.
Transmission expansion to reduce off-peak wind curtailment and development of energy storage devices to off-set the variable nature of wind.

Necessity of coordination and information sharing by means of an international (i.e., shared between national TSOs with connected grids) knowledge and data platform for TSOs. This should contain real time market data, wind power forecasts with uncertainty range, and relevant grid information.
The most important change is a full integration of wind into the real-time dispatch, including the ability to provide economic offers, the ability to be dispatched, and to set prices. Doing this will provide automated congestion management through the Security Constrained Unit Commitment (SCUC) and Security Constrained Economic Dispatch (SCED) algorithms we already use.
• Enhancement in our Energy Management System (EMS). • Development of Special Protection Systems (SPS) to enlarge operational limits of the grid. • Introduction of dynamic rating of the grid and security assessment of the system. • Enhancement of wind power regulation (e.g., storage).
• There needs to be increased of public acceptance of new transmission and acceleration of permitting procedures. • Large scale and decentralized storage applications. • Online data exchange between transmission and distribution level. • Controllability options for generations and loads for TSO also in distribution level.
Unit commitment coupled with a consolidation of the market Balancing Authorities is critical to increased wind penetration.
We have limited issues with the current penetration levels. However, one problem that we are having is with self scheduled wind resources that do not respond to price signals. We are considering placing the wind resource on economic dispatch to allow those resources to reflect their willingness to pay to access transmission.
Better voltage control and perhaps more frequent market settling. Instead of one price calculation for the coming day you could have more and reduce the uncertainty of wind.
Good forecasting of wind ramp periods, both up and down.
Efficient markets for ancillary services will improve wind integration.
• Better primary response from generating units and need for demand response programs at the state utility level would be urgently required to support integration of additional wind energy. • At the current level of wind penetration in our system, congestion of the transmission network is not a critical issue. However, the future transmission planning at the supergrid level must consider the increased wind penetration and its variability.
Demand side management and the quality of system balancing services.
More transmission capacity.
Improvement in wind generation forecasts over the next 24 hours.
Currently, the examination of loss of mains protection on wind farms connected to the distribution networks is important in our system. Long term however, issue is the appropriate incentives for ancillary services.

Being able to modify schedules every 20 minutes would allow us to integrate a lot more wind without the adverse impacts to balancing that we are seeing with the hourly scheduling. Also, more accurate forecasts are always needed and will help to reduce impacts on the grid.
• Market for regulation reserves. • Wind forecasting.
More accurate short and long term wind MW forecast and increased operating reserve.
Wind power management, wind power forecasting.
In the next years, it is expected that there will be wind spillages during off-peak periods. In order to avoid it, it is necessary more transmission interconnections and more storage capacity be built for use by system operator.
Good forecasting of wind ramp periods, both up and down.
• Make criteria for reserves such as frequency control, spinning and operating reserve. • Develop tools for forecasting.
Increase the amount of flexible generation.
• Being able to monitor the availability and be able to predict the potential wind generation. • To ensure we have pump storage capacity to balance the sudden loss of wind generation.

Table 5. Limitations of wind forecast currently available to support your system operations and business (Q10)

Forecasts are currently provided by marketers as hourly production schedules and the timing and tuning of the forecasts is not within our control. We are in the process of procuring a commercial forecasting service thereby gaining control, greater resolution, and more appropriate timing.
We only have day-ahead forecasting.
Current forecasts are not tuned towards forecasting ramp events.
• Currently we cannot identify large short duration wind power changes. • We rely highly on good quality SCADA for the 5minute/30 minute forecasts. • Difficulty in getting wind farm operators to supply accurate availability information.
Difficulty obtaining good quality meteorological data from wind plants. Limited resolution of the NOAA numerical weather prediction model used by our forecaster.
Currently ramp forecasts are still in the development stage.

• Our forecast is fragmented amongst various data sources (wind speeds vs. wind farm locations vs. where they are connected to the grid). • Different forecasting methods & formats used by each country. • Uncertainty range is not delivered together with the forecasts; it has to be considered based on experience.
In addition to the need for improved accuracy in wind forecasting, wind forecasts must be developed that are independent of any downward dispatching that the wind resource may be receiving from the Market.
Limited historical data series and, the resolution of the forecast can be enhanced.
We receive forecast only twice a day available at 8 am and 8 pm.
We are not currently using a wind forecast vendor due to the low penetration levels. We do have plans to develop a forecast and are in the midst of completing a wind integration study that will help us determine the requirements of that forecast.
Wind forecast accuracy is usually measured on the mean absolute error (MEA) and on an average basis, it may be fairly accurate. However, that is not an indication of forecast ramp accuracy. Forecasting ramps will be more important as wind penetration increases.
There has been little incentive for wind power producers to forecast their generation and send these forecasts to the control centre. This is due to the fact that historically wind power producers operated through the FIT (feed-in tariff) mechanism and they were insulated from the imbalance pricing mechanism.
Short-term forecasts are limited to persistence forecasts. Longer term forecasts available.
The forecast at times can have significant error. The solution to this is likely to lie in managing this uncertainty through appropriate deterministic policies or develop new stochastic solutions. Basing the solution around never having a significant error could lead to increased risk of security issues.
The forecasts are inherently inaccurate, some accuracy at times on a fleet-wide level but not at the individual plant level.
No good forecast for intra-hour variability and lack of ramp forecasting in near-term.
We don't have an applicable wind forecasting system, currently approximate methods are being used.
No ability to forecast extreme events.
Short-term forecast is only about 4 to 6 hours.

Table 6. Automated tools and solutions used to manage wind curtailment (Q13)

We have deterministic rules for curtailment conditions and curtailment allocations. Our generation dispatch tool uses the deterministic curtailment rules.
Wind is integrated into our Security Constrained Economic Dispatch algorithms and is dispatched down during times they are not economic, just like conventional generators. If there are system constraints that indicate a wind generator should produce at a lower level, this is typically reflected in our market clearing prices. These prices are compared with the wind generator's economic offers, and if not fully economic, are dispatched down to their economic operating point.
We have developed runback schemes with hourly based ratings build in the scheme to maximize transmission capacity.
State Estimator application determines when congestion becomes binding on resource output. Out of Merit Energy instructions are issued to curtail wind.
Wind is treated the same as any other generating resource. All resources are curtailed based on pure economics during minimum generation conditions or cost-effectively ($/MW effect) under transmission constraint conditions. Our automated dispatch system considers unit bid parameters and sends economic basepoints to generators.
We are currently automating the wind curtailment process. The tools will track/log the curtailments as well as assist the operator determine when, what, and how much to cut. The manual curtailments will be replaced with dispatch via our SCED.
Working towards implementing a design in 2011.
If the wind resources bid economically into the markets then we have an effective method for curtailment. However, when resources self scheduled their energy as a price taker, the market formulas do not develop sensitivities to constraints and a manual process is used to conduct the wind curtailment based upon several economic and reliability criteria.
We have a tool that can within 10 seconds send a MW or MVAr set point to wind farms who are obliged to respond. This functionality is used daily in our system and is a key requirement to managing high penetrations of wind.
We have developed the ability to measure regulating reserve deployed on a real-time basis. We will curtail wind if they under-generating and we have deployed our incremental reserve up to given threshold. We will curtail wind output if they are over-generating and we have deployed our "decremental" up to a given threshold.
Curtailment is performed by the system operator primarily for excess energy conditions. It is currently not fully automated due to complex priority order for excess energy curtailments of multiple resources, some of which have no EMS controls interface. The system operator must also wind on occasion due to transmission issues (i.e., to reclose certain line and for line overload).
Our real time contingency analysis tools would indicate a potential problem requiring wind curtailment. We then curtail wind by telephone instruction to the wind operators to give them a maximum output limit. They enter this limit into their plant SCADA to control the wind plant to not exceed the output via either switching off units or via pitch control.
We have developed its own tool to deal with wind curtailment. The tool computes the worst possible contingency, determines wind curtailment needs and sends orders to wind farms through delegated control centers.
We can send set-point to limit the production of the large wind producers connected to the high voltage grid. We can also send set-points to two renewable energy control centers. Finally, we can also trip the lines connected to the wind farm.
We do not have a tool in operations at this time. However a tool is under development with plans to put it into operation in 2011. The tool has two functions: 1) to calculate the total system wind power limit level 2) to allocate the limit to individual wind power facility.

Table 7. Additional tools that may be needed for reliable and efficient integration of wind power (Q19)

Improved situational awareness tools.
Ability to forecast large rapid changes in wind farm output.
System Protection Scheme with fast tripping of generators or loads.
Flexible AC Transmission Systems (FACTS), such as phase shifter transformers, on the condition that coordination exists between the involved TSOs.
Wind Resource Operating Reserve capabilities have been considered, and will be considered more completely in the future.
Intelligent decision support tool for daily system operation. For example a quick tool which assesses large loads and storages but also all types of generation available in real-time and in the next hours.
Situational awareness tools based on real-time and forecast information, including rate of change for wind resources, wind forecasting near term and looking out a day or two including ramp forecasting.
Reserve forecasting.
Stochastic unit commitment and management of forecasting is being actively examined but no decision has been made to implement.
Methods for increasing the amount of dynamic capacity available in the power systems in our region. Along with this, methods for taking advantage of the diversity of the interconnection by using tools that make it easier for corporation between balancing areas.
• Improved control capabilities on wind plants. • Visibility and control of distributed resources (competing for same demand as wind).
Sufficient amounts of controllable power plants.
Dynamic line rating

Table 8. Description of inter- BA or inter-TSO scheduling process in your organization (Q23)

Outage scheduling together with other TSOs of the region on a yearly, monthly, weekly, and daily basis. This includes weekly operational teleconference.
Currently we schedule inter-BA interchange once per hour. We are currently engaged in a project to increase the scheduling frequency options to 5, 15, and 60 minutes.
Power flows on interties between regions are a function of the 5 minute dispatch process and are dependent on generation availability, pricing and transmission limitations in each region.
We are the BA, TSO and RC. We utilize wind power forecast as part of the day-ahead analysis. We also consider the impact of the neighboring systems wind forecast on our transmission constraints.
Transmission maintenance on interconnection, exchange scheduling.

We are the scheduling entity and as such each BA in our market footprint schedules directly with us as the scheduling entity. External BAs that are directly connected to BAs in our footprint also schedule directly with us. Interchange schedules are submitted through the tagging process no later than 30 minutes prior to the start of the schedule. The BAs verify the schedules to ensure they have sufficient ramping capability. We verify that appropriate transmission service has been arranged and that the market has sufficient ramping capability to support those schedules into or out of our market footprint.
Hourly scheduling under ISO/RTO tariff. We are looking moving to a more granular schedule in the future.
Schedules are based on 5 min breakpoint power values.
Coordinated multilateral trading arrangements are in place. Under this each state in our national grid is treated as a control area. All the distribution companies within the state are responsible for balancing their portfolio. While balancing the portfolio all contracts to buy/sell power from outside the state are communicated to the regional control centre in advance. The regional control centre has a limited role in checking whether such contracts do not lead to network congestion. If no congestion is foreseen, the regional control centre incorporates it in the net withdrawal schedule of the state. On the actual day of operation, the regional control centre monitors the actual withdrawal by the state vis-à-vis the schedule. Deviations are allowed provided that they do not lead to off-normal frequency operation below or above certain threshold, voltages level and line loadings are within limits. At the national level, co-ordination between the five regional TSOs/ISOs is done by the National Control Centre.
Hourly scheduling is the norm as a standard business practices. We currently allow wind generators to schedule excess energy at the half hour.
We post the Available Transfer Capability (ATC) for the interties and import/export market participants will submit their offers in to the energy market.

Table 9. Policies established with other BAs, wind generators, utilities, or other entities to manage wind power integration (Q27)

We have direct control to curtail wind farms if and when necessary (all in accordance with market rules). We are seeking ability for intra-hourly schedule updates with neighboring Balancing Authorities.
• Interconnection rules for wind plants in our grid code. • Establishment of 'virtual power plants' (VPP) in order to enhance dispatchability and the flexibility of the generation mix.
We have established a guide which specifies the data wind plants must provide.
Our market protocols and operating guides provide specific requirements for wind plants. For examples wind plants must provide a resource plan that reflects the wind forecast; they must provide voltage support; they must provide governor like response to frequency deviations; they have a wind ramp limitation when ramping down or up due to congestion instructions.
We are currently working on a modeling solution to allow wind plant operators to take full advantage of market dispatch.
Grid code requirements for wind plant owners/operators.
Policies are currently under development.

Penetration levels are too low for wind to cause issues at this time. We are completing a wind integration study to assess changes necessary under higher penetration levels.
Wind can be managed as part of the balancing market.
All the entities are expected to follow the national electricity Grid Code ordered by the federal regulator. Violation of any of the provisions is punishable by law.
Curtailment of offshore wind production under predefined seasonal limits.
Grid code policies.
Have established many policies including wind farm commissioning, TSO-DSO interaction, Priority dispatch management.
We calculate and hold a specific amount of balancing reserve. When we have reached a limit on the amount of reserve deployment, we take action on the wind resources, either having them reduce output or result to curtailment.
• When wind approaches speeds that may result in high-wind-speed shutdown, the wind plant operator reduces the output or goes offline. This is to avoid the high wind speed shutdown at fast ramp. • Wind is routinely curtailed for excess energy and also certain switching. This is necessary to reduce output of wind to allow reclosing of a certain transmission line.
We are currently formulating market rules for wind power owners/operators for wind power forecasting and wind power management. We also have technical requirement which establishes the minimum connection requirements for wind power facilities.
We publish the maximum amount of wind power installable every year for the next five years. For the power system security we already restrict the wind power integration on a small (weak) island network connected to the main land through the HVDC.

Table 10. Internal operating procedure established in your control room to manage wind integration (Q28)

Rules for when curtailment can be performed and how to allocate the curtailment. Use of forecasting tools will be incorporated.
Displays of real-time measurements of wind information.
Apart from the wind forecasting process we treat wind generation the same as any other form of generation.
Outage procedures; contingency plans for loss of communications to wind farms; procedures for limiting wind farm output with the loss of voltage support at wind farm.
Wind generation receives unit specific dispatch instruction in the same manner conventional generation receives these instructions. The variability is managed through forecasting and ancillary services.
Two manual curtailment procedures are in effect; one procedure for location curtailments in the event of congestion; another procedure for system wide reduction in wind output, in (relatively rare) instances of low-load.
According to national energy regulator, in case of security violation wind power production can be curtailed.

Manual operator intervention is currently required to curtail wind when appropriate.
We are currently allocating extra amount of reserves in relation to the output of the wind plants. We are doing this in both during wind ramp up and ramp down.
Visual and audible alarms provide guidance when reaching reserve limits.
Application of the seasonal limits for real time and D-1 needs
• We utilize forecasting using marine weather forecast of wind near the facilities and consider this in the timing of unit startups and scheduling peaking units in the near-term. • We monitor wind outputs and variability in real-time for consideration of inter-hour regulation requirements due to wind. • Larger reserves will be maintained during variable wind conditions.
Monitoring of forecast data available in control room to make decision about balancing and to determination of reserves.
Day-ahead schedule and intraday adjustment of schedules.

Table 11. New business processes and processes in support of wind integration (Q29)

May need to establish two-way (iterative) communications between the forecasting tools and the dispatch tools to find the optimum operating point taking operational risk and costs into account.
Forecasting of large rapid changes in wind power. This may in the future lead to the requirement to reclassify some multiple contingencies as single contingencies under certain conditions. However wind penetration will need to increase significantly before this becomes an issue.
To be determined depending on level of wind and where in the network it will be commissioned. However, one of the key ones would be system black start.
We are implementing a new nodal market which will have new processes and protocols that define requirements for wind resources.
• Changes to regional transmission planning processes to consider state mandates for renewable energy and energy efficiency. • Changes to transmission planning processes to include low load performance criteria. • Changes to grid interconnection standards for wind.
Increased granularity of information regarding wind sites. Much of this is to manage the added complexity of projects having multiple owners/offtakers.
• Improving of transmission planning process in order to support higher wind penetration. • Introduction of smart grid concepts.
• Grid reinforcement, promotion and use of storage facilities. • Development of new and effective congestion management measures.

Wind forecast component to regulate reserve requirements.
We are currently completing a wind integration study. Some of the items for the future implementation include development of a wind forecast including ramping forecast. In addition, we are considering whether to place the wind resources under economic dispatch similar to what has been done other wholesale markets.
We are pursuing a better forecasting method for the load schedulers.
Intra-hourly scheduling, balancing reserve forecasting, ensemble wind forecasting, ramp forecasting, expanding dynamic transfer capabilities, expanding plant capabilities.
• Pilot projects to get wind generation forecast from large wind farms and integrating it with the present scheduling mechanism. • Demand response programs, particularly in states with large wind penetration, are important.
There are many new processes from scheduling of transmission maintenance, to priority dispatch, use of forecasts, special protection schemes, remote control and operational policies. Some of these have already been changed, others are planned to be reviewed.
Better forecast.
Integration of wind forecast in reserve planning.
We are pursuing a better forecasting method.

Table 12. National or State policies, or grid codes that need to be changed to support large-scale wind integration (Q30)

Universal requirement for economic dispatch combined with greater inter-market scheduling flexibility.
National initiatives to improve the weather service models such that they target support for wind generation would have a beneficial impact on day-ahead forecasting quality. Additionally, any initiatives which spur off-shore wind development would benefit the system because it would geographically diversify the wind resources connecting to the system. Large geographic diversity is proven to be a beneficial factor in reducing the impact of individual wind plant variability.
Government incentives for wind farm investments, and establishing of a carbon price.
Policies that encourage resources that are flexible and can respond to wind variability.
Cost allocation for new transmission.
Equal and fair procedures in power market for wind power plants as for conventional power plants, in order to develop experience and maturity amongst market participants.
• Massive reinforcement and extension of transmission grid which requires a sustainable political consensus and a stable framework for investments. • Additional storages must be implemented in the electricity system. • Cooperation between all stakeholders of electricity system must be increased significantly.

First and foremost, standard interconnection requirements should be developed at a national level to ensure that the grid is proactively built to be operated reliably. With standard interconnection requirements in place, the industry will be better equipped to identify operating standards needed to integrate large-scale wind power.
National and regional synchronized electricity markets.
Integrate wind power in market mechanism, and participation of wind generation to ancillary services.
Policies, standards and grid codes should be created that would positively impact Balancing Authorities working toward greater cooperation.
Significant frequency variations may occur with large wind generation in the system. NERC CPS standards may need to be reviewed for large wind integration.

Table 13. Systems needed to gather and/or develop information to support wind integration (Q36)

Improved situational awareness tools.
Higher resolution NOAA numerical weather prediction model and more meteorological instrumentation in the field.
Necessity of coordination and information sharing by means of an international (i.e., shared between national TSOs with connected grids) knowledge and data platform for TSOs. This platform should containing real time market data, wind power forecasts with uncertainty range, and relevant grid information such as important line outages.
Weather Forecasts tuned to wind at wind turbine hub heights.
Fast online data processing of large amounts of data; and high quality of forecast for short and medium term analysis.
We are currently in the process of selecting a vendor for a wind forecasting service, and are also working on requirements to integrate wind forecasting service into our market system.
• Met tower data sharing. • Secure communications networks to share data with the Balancing Areas and forecasters from the wind farms • Situational Awareness Systems to show operators approaching weather systems, rate of change of wind speed for wind farms, and as a region within the BA or for the entire BA.
More focused interactions between engineers from different countries through partnership programs.
Clear view on real time wind power infeed.
It's not new systems we need; it's more real-time information from wind plants.
Intra-hour forecasting improvements.
Wind forecasting system.
A system that can assess the uncertainty of the wind power forecasts with the ramping and maneuverability of the convention generation resources or controllable load resources.

Table 14. Skills important for effective wind integration, e.g., modified training or required qualifications (Q38)

New tools for training (forecasting and decision support tools) and specific meteorology.
Ability to adapt to new technologies.
As we essentially treat wind the same as other generation little additional training is required.
We have modified training and operator procedures for effectively dealing with wind. Examples are situational awareness for large ramp rates and incorporating the wind forecast into our operator tools to identify potential capacity shortages.
No skills have been identified to specifically address effective integration of wind power. The same set of skills that operators need in general, e.g., operational awareness, focus, and critical decision making skills, are all important.
Knowledge of special rules for fulfilling the legal requirements related to wind integration. Knowledge about characteristics in and influences from/to neighboring power systems.
Because the penetration levels are so low we have not been required to modify training at this time. Once we complete our ongoing Wind Integration Study and prior to higher wind penetration levels beginning requisite training will be developed and delivered to update the system operators and forecasters on the new tools.
It is important to have a high quality of forecasting, and adequate levels of measurements so one can distinguish between what is wind and what is load changes. As a consequence it is important to have people that can use and understand these new tools and the results that are produced.
Knowledge of probability and statistics.
There is a new requirement to train control center staff on new tools including wind forecast. There is also a broader need to educate the operators and engineers about the results from latest studies on issues related to wind.
The largest training effort has been in the administration of excess energy curtailments and documentation of these curtailments The present methodology is administratively burdensome and not recommended as best practice. This is to curtail for excess energy on the basis of the date the contracts were approved to purchase the energy, rather than on other factors such as cost or reliability impact; since there are numerous facilities in the curtailment priority list and some are not controllable remotely, and the curtailed resources desire reports and logging of curtailments, this has become a burden and required a lot of instruction to the operators.
Ability to understand and effectively control multiple large wind plants based on real time monitoring and contingency analysis.
Understand the system capability to handle uncertainty.
Operators are trained in system restoration skills with high penetration wind.
Forecasting, training, etc.

Table 15. Emphasis in education and training to manage wind integration (Q39)

System operator training should be supplemented with non-deterministic planning concepts, wind farm operations, and relevant topics in meteorology.
Understanding and forecasting of weather patterns.
I believe it has more to do with having the proper tools for the operators and having procedures surrounding the use of those tools for managing the wind.
Emphasis should be placed on dispatcher tools and visualization.
• Operators should be stimulated to - or should have the tools and support to - perform (day-ahead) security analysis for a wide range of possible scenarios (e.g., with regard to wind power production), each with a given probability. • They should learn to anticipate and have remedial actions ready for possible events, not only for the classical outlined scenario but also for scenarios with different load/generation pattern etc. • Operators should not be surprised by critical situations in real time; remedial actions should be discussed in advance with all involved parties. For this, operators of various countries must have sufficient oral and written language skills to be able to communicate with other TSOs (bilaterally or in conference call).
It is important to have a basic understanding of how wind plants work. Current staff has good familiarity with traditional generation, but does not have the same understanding of wind facilities. Education about wind plants will be very important as more wind is integrated in the system.
Keep control room operator updated about the new issues of system operation especially related to wind power penetration.
Wind forecasting and translation to power output and situational awareness training.
Wind forecasts, flexibility in conventional generation, demand response, Wide Area Monitoring Systems, Situational Awareness, energy storage systems.
The operators need to clearly understand the tools available as well as the rules and priorities of the control room. Operators are under a lot of pressure to conform to various NERC compliance measures, maintain reliability, keep costs down; sometimes it is not clear what is of highest priority - accepting purchases of RE such wind, maintaining balancing area criteria, avoiding overloads of transmission lines, or maintaining service to customers. Operators get a lot of instruction and have many new conditions to deal with and unless they are confident and encouraged to act, there can be confusion and a delay in action ultimately risking reliability.
Characteristic of wind generation versus conventional generation and its impact on the interconnected grid.
Handling wind power uncertainty and developing operational experience (learning by doing).
Control theory, operation experience, etc.
Planning and Dispatch.

APPENDIX F.

GLOSSARY

F.1 Forecasting Products[84]

Ramp forecasting – A "wind ramp" is a relatively rapid and sustained change in wind power output within a specified time period. The exact definition may vary based on the size, situation and flexibility of the system. A "wind ramp forecasting system" is one that is tuned to identify the risk and potential ramp rate from such an event. This tuning for ramp events could be done as part of improved general purpose wind power forecasting systems, separate ramp forecasts that are distinct from the "normal" wind power forecasting system, or various combinations thereof.

Short-term forecast – While short-term forecasting means different things to different people, when used in the wind power forecasting sense, the terms "hour ahead" or "short term" generally refer to forecasts for the time span from now through the coming five hours, This forecast is often updated frequently and presented with frequent time steps (such as every ten minutes).

Probabilistic forecast – A forecast that shows not only the expected value, but also a measure of the probability distribution or confidence around the value. This distribution may be obtained from various indicators including the degree of agreement between multiple weather models (see ensemble forecast), historical performance under similar conditions, the location on the turbine power curve for the predicted wind speeds, and other such considerations.

Ensemble forecast – A method of forecasting that uses multiple weather forecast models and/or a weather forecast model with a range of perturbed input conditions, based on the uncertainty range of the measurements. It is generally found that intelligently using a set of weather forecasts, rather than a single weather forecast, can provide a better consensus solution, and the spread of values can be a useful indication of the certainty in the result.

Weather Situational Awareness – Any of a large range of technologies intended to convey information to an operator or user in an actionable form. For example, a system that presents general weather information could be made more "actionable" for an operator by visually or numerically converting the information into warnings and alerts of impacts that are more directly useful to the operator or user.

Ramp Risk forecast – See ramp forecasting above. This could refer to a ramp forecast that expresses indications of risk in a generalized sense, although this is an area of active research and the best way of expressing wind ramp risk and wind ramp information is not yet clear.

Next-day forecast – The term "next-day forecast" (as contrasted with the term short-term or next-hour forecast) is traditionally used in the wind power forecasting sense to define a forecast that runs out over the coming days (such as for the next five days). This forecast may be presented with hourly time steps or can be shown with shorter time steps, although the updates of the major weather forecasts that are used in creating the forecasts are seldom available only every few hours.

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[84] These basic definitions of forecasting products were formulated with significant input from, and included herein courtesy of Mark Ahlstrom.

Wind plant high-resolution forecast – Weather models are rapidly evolving toward higher resolutions, so even generalized weather forecasts are getting to be quite high resolution, but doing customized higher resolution modeling around wind power plants may provide additional benefit in certain circumstances. Such efforts come with additional complexity and cost, so the benefits and maintainability of such systems must be weighed against such cost and complexity.

Nodal injection forecast – Separate aggregated forecast generated for each node in the transmission system. This forecast may be useful to transmission system operators for the congestion planning and management.