

A REVIEW OF LARGE-SCALE RENEWABLE ELECTRICITY INTEGRATION STUDIES

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As a result of state renewable portfolio standards and federal tax credits, there is growing interest and investment in renewable sources of electricity in the United States and worldwide. Wind and solar energy are the fastest growing renewable sources of electric energy with U.S. wind power capacity increasing from 8.7 GW in 2005 to 33.5 GW 2009 and solar increasing from 211 MW to 603 MW over the same period [EIA:2010]. However wind and solar power plants are intermittent and variable: that is, they do not produce power at all times of day; and even when power is being produced, output can change rapidly. Biomass, geothermal and hydroelectric energy sources do not suffer from intermittency and variability to the same extent, however growth of these sources has been limited¹. The U.S. electric system, which was developed throughout the 20th century, was designed around power plants that are primarily intended to deliver constant power. In order to enable a ten-fold increase in the percentage of intermittent and variable resources from the present 2%, as envisioned in a number of state renewable portfolio standards, electricity systems require significant changes in technology, operating policies, and infrastructure.² To understand this need, numerous government, academic, and electricity industry organizations have studied the challenges and opportunities for integrating wind, and to a lesser extent solar, resources into electricity infrastructures. This paper summarizes the conclusions from these studies and highlights a number of areas where additional research is needed to facilitate good decision-making regarding the increase of renewable power integration. Our review covers two DOE-sponsored national studies [DOE:2008], six regional studies covering Texas [ERCOT:2008], New York [NYSERDA:2005], Minnesota [MN:2006], California [CEC:2010], the South-central U.S. [SPP:2010], the Eastern U.S. [NREL:2010], four European reports [EWIS:2010, EWEA:2009, CEER:2009, EPRI:2010], and several academic reports. This paper provides an overview of the results from industry studies (Section 1), a brief discussion of related academic publications in this area (Section 2) and a more detailed analysis of several of the industry reports (Section 3).

1. Industry integration reports and gaps requiring additional research

None of the existing studies suggest that there are insurmountable technical barriers to a 10-fold increase in wind and solar electric energy production. The experience of European countries that presently obtain significant percentages of their electric energy from wind and solar, such as Spain (15% from 24% of capacity) [EPRI:2010, Spain:2009]), Denmark (19% [EIA:2008]) and Ireland (9% [EIA:2008]), suggest that large-scale wind integration is technologically feasible, but requires careful dispatch of thermal power plants and storage for balancing, advanced wind forecasting methods, and revised operating procedures. In the cases of Spain and Denmark, high-levels of wind and solar are facilitated in part through imports and exports with neighboring countries. Several studies (e.g., [MN:2006]) suggest merging small control areas (balancing authorities) into larger ones to reduce the regulation and reserves requirements. All of the existing studies agree that substantial changes in market structure and regulatory environments will be required to facilitate increasing renewable generation.

¹ Geothermal capacity is stable at 3.1 GW, with a capacity factor of 56% in 2009.

² For context, the 2008 U.S. average net generation is 470 GWh / hour, from a total generating capacity of 1010 GW. In 2008 non-hydro renewable generation was 14 GWh/hour from 38 GW of capacity. Data from [EIA:2010].

Several of the reports in our review analyze the resource potential for wind electricity production in the U.S. [DOE:2008] and in Europe [EWIS:2010]. All agree that there are sufficient geographically accessible resources to increase wind production above 20% energy, given that new transmission lines can be located to interconnect supply and demand. In its 2008 report [DOE:2008] the DOE argues that there is about 600 GW of on-shore wind that could be economically connected at levelized costs of \$60-\$100/MWh. Approximately another 200 GW of wind can be connected at higher costs. However, it is notable that wind power plant capital costs, as reported by the DOE Energy Information Agency, have nearly doubled between 2007 and 2009, so these costs are likely to be low relative to current market prices. To achieve a 10-fold increase in wind electric energy production would require roughly 300 GW of new wind capacity.

While there is some agreement regarding these general conclusions, there are a number of issues where agreement does not exist. There are also methodological issues that require additional research and development. Our review noted a number of opportunities for improvement of existing methods for wind integration analysis. In the following paragraphs we discuss critical issues where we have identified research gaps.

Existing integration studies frequently use either anemometer measurements or data from meteorological models to produce wind speed data for the estimation of wind power from projected wind turbine sites. Few studies systematically compare and contrast the results from these two sources, both of which have advantages and disadvantages in terms of accuracy. In the one study that did perform a comparison [EWEA:2009], the meteorological models appear to damp out higher-frequency variability. Anemometer measurements are difficult to obtain for some locations at the altitude at which wind turbines operate. Furthermore many studies are primarily based on data sampled at a rate of 1 to 12 samples per hour, which can result in a misunderstanding of the impact of higher frequency variability. In some cases studies synthesized data to fill in the gaps between samples, however the methodology for this synthesis often does not reproduce the underlying variability[for an example of the complexity involved, see Rose:2010]. When data are not available, all of the studies that we reviewed assume that wind varies according to Gaussian (bell-curve) statistical models, an assumption that is not supported by empirical data.

A number of the studies estimate the amount of additional load-following, contingency reserves, and regulation that will be required as a result of additional wind production. In [SPP:2010] analysts argue that additional contingency reserves are not required since the largest power plant was larger than the probable short-term drop in wind production. However, since there are significant regional correlations [Katzenstein:2010] in wind speeds, this assumption may not hold as wind production increases. This is particularly true during lower-demand (nighttime) periods, when wind will necessarily be a higher fraction of the total demand. As previously mentioned, some of these studies performed analysis of the reserve requirements that would be needed to support wind integration. However, most of the existing reserve requirement estimation methods assume a bell-shaped probabilities of events (called by specialists a normal, or Gaussian distribution). By using Gaussian methods, low probability but high impact events are not properly modeled, which may result in an underestimation of load-following, reserves or regulation requirements. By missing "black swan" events (also known as "fat tailed" distributions), such models failed to predict the nearly two weeks of perfectly calm winds that idled over 1000 wind turbines in the Pacific Northwest in January 2009. There is very little existing research on

methods for accurately estimating reserves and regulation requirements given the measured statistical nature of wind.

As previously stated, all of the studies suggested that geographic diversity in wind resources would reduce wind power output variability. However, no detailed/quantitative analysis of the impact of geographic diversity on variability was performed. In addition, a recent academic study suggests that the benefits of geographic diversity may be overrated [Katzenstein:2010]. Closely related to the idea of smoothing out power variability through geographic diversity, is the issue of transmission requirements. Transmission requirements and construction costs are a huge uncertainty. Many of the available integration studies did not include transmission constraints while others modeled transmission systems using inaccurate methods. Only two studies performed power flow analysis, and these used a DC power flow model. It is not clear whether using AC power flow models would change results, but the reactive power issues that played a large role in the 8/13/2003 blackout require AC analysis.

Other strategies could be deployed to reduce the power output variability associated with wind energy. While some of these studies discuss storage in a qualitative matter, only one study [CEC:2010] analyzed the role energy storage could play to support wind integration in a systematic way. In addition, none of these studies analyzed how other renewable sources (pumped hydro, run of the river hydro, solar or biomass) could be developed to support wind power. The CEC/KEMA study [CEC:2010] alone looked at integrated systems of solar and wind. Finally, none of these studies identifies detailed operational strategies that could be used to reduce variability.

Due to the intermittent and variable nature of wind power, there is some concern associated with the ability to meet electric load in a system with large percentages of wind power generation. For this reason understanding electric load and how this load could be managed, could serve in identifying strategies that support renewable power generation. None of these studies looked at the role of customer load control to support wind/renewable integration. In addition the studies did not consider the effect major new loads (like electric vehicles) would have on wind power development.

Other issues not properly covered in the integration studies reviewed include:

- There is, as of yet, no research on the interactions between cascading failure risk and wind penetration.
- Dispatch models are critical to the analysis of wind integration. The reports of the studies provided very limited detail on the dispatch models used.
- Wind power forecast are currently available and the mean absolute error for these forecasts for large, RTO-sized areas, is about 15% a day in advance. None of these studies analyzed nor quantified whether reducing forecast error can reduce wind integration costs. It is also unclear whether reducing such forecast error is even possible, or what the costs of reducing it would be.
- Finally, the studies conclude that new market structures will need to be developed in order to accommodate renewable power. No details are offered, however, on what these market structures should look like. It is also not clear what the role of

government regulation will be in supporting the technological methods that would allow for larger renewable penetration.

2. Discussion of recent academic publications

While some of these shortcomings are addressed in the academic literature, there is very little consensus on methodologies for studying the impact of wind integration. Several papers estimate the reserves requirements as a function of wind penetration (e.g., [Doherty:2005a, Weber:2010, Troy:2010, Strbac:2007]). Counter-intuitively, several of these papers argue that as wind penetration increases beyond a threshold reserve requirements begin to decrease. In contrast, an academic study of the Irish system [Denny:2007] reports that the net benefits of wind, including environmental externalities saturate at about 35% by capacity as a result of intermittency. While there is some research into the affect of wind deployment on regulation and frequency deviation much of the academic work is based on hourly wind data (e.g., [Doherty:2010]), which means that the impacts of intra-hour variability are neglected. As quantified in [Katzenstein:2010a], intra-hour variability substantially increases costs associated with wind integration. As was the case in the industry studies, the assumption that wind varies according to Gaussian statistics is common (e.g., [MacCormack:2010]), emphasizing the need for research into the operational and economic impacts of the measured statistical nature of wind [Apt:2007] and solar [Curtright:2007] generation.

3. Detailed comments on industry integration studies

In this section we provide detailed comments about the most significant of the industry-produced wind integration reports.

In 2005, GE performed an analysis of the effects of integrating wind power on transmission system planning, reliability and operations for the New York State Research and Development Authority [NYSERDA:2005]. This is a study of 3,300 MW of wind power in New York State. Most of the wind is modeled to be located in upstate NY. As with other studies in this review, GE uses AWS TrueWind to generate wind data and then GE-MARS to estimate the reliability impacts of large-scale wind. They use a 2008 (projection from 2005) power flow case to identify transmission bottlenecks. GE completes some engineering analysis and finds that power factor correction at the wind generation sites, enabling the plants to operate in the +/- 0.95 power factor range, has significant reliability benefits. GE does some detailed power-flow/voltage analysis and from this recommend that wind farms build voltage controls and low voltage ride through capability. Voltage control is standard for most new wind farms. The study does a good job of separating the analysis among the different time scales, providing conclusions within time scales mostly appropriate for the scale studied. They do perform some wind and load forecasting. As other studies have done, they use a unit commitment model to estimate the additional unit commitment costs associated with increased load-forecast uncertainty. As with many of the other studies, GE uses Gaussian methods for reserves calculations. In Gaussian methods, the properties of normal distributions are assumed. As a result they are problematic for modeling low probability, high impact events.

The 2006 Minnesota wind integration study [MN:2006], looked at 15%, 20%, and 25% wind integration in MISO for the year 2020. One of the main conclusions in this report is that increasing spatial diversity dramatically reduces the number of “no-wind power” events, and thus

reduces reserve requirements, given the assumptions in the study. This study has many positive attributes: they obtain 5-minute wind data from a respected weather simulation model; they include an accurate transmission system model (through GE-MARS and PROMOD) in their simulations; the unit commitment method is appropriate for hourly analysis and the outcomes are believable (\$2-\$4/MWh penalty for variability). However, there are a number of shortcomings that render their conclusions for sub-hourly time scales far less than believable: they depend heavily on Gaussian statistics to calculate reserve requirements; the reliability models are hourly models, whereas they have 5 minute data, therefore there is an analysis gap for short-term analysis.

In 2007, the California ISO produced a report on the integration of renewable resources into the CAISO region [CAISO:2007]. This study does not perform a comprehensive integration analysis, but rather identifies theoretical wind plants that could be built in 2010. They also report on the transmission construction required to connect these new plants to the grid. They report on analyses regarding the impact of the new wind plants under different conditions. For example, they analyzed functional characteristics necessary to achieve static and dynamic performance. They also analyzed the power factor requirements. This analysis was performed using the WECC wind integration requirements as a benchmark. They found that using Type 1 turbines would be problematic for grid integration but if Type 3 and 4 wind generators were used³, all WECC transmission requirements would be met. They also performed an analysis of regulation, reserve and ramping requirements for the wind plants. They used AWS TrueWind data to model wind speeds and power potential for the area, and then used these to generate hourly energy generation data. 2006 minute-to-minute wind variability data and statistical tools were used to determine wind generation variability. Gaussian probabilistic modeling was used to estimate load and wind forecast and forecast errors, which was then used to estimate reserve requirements.

In 2008 GE produced a wind impact and integration analysis for ERCOT [ERCOT:2008]. This analysis consisted of data analysis on how net load (load minus generation from wind) is affected by different wind penetration scenarios. Wind data was developed based on Mesoscale models, while the analysis of load was based on actual minute-by-minute load data for 2005 and 2006. They also performed an analysis of ancillary services (A/S) requirements at different levels of wind penetration. This study performed some good data analysis and reached some reasonable conclusions. For example they verified that both wind and load are variable and generally out-of-phase and that seasonal variations are also present. They also identified some issues that would affect A/S requirements. For example, they identified that with increased wind penetration, regulation and reserve requirements also increase. This study lacks in several areas. For one, (like all other studies) it uses Gaussian models when analyzing reserve requirements, which may ignore some fat-tail events that can have important implications for reserve requirements. In addition, the study does not include a model to analyze grid impacts so it doesn't identify transmission constraint or operational concerns.

An often-cited report from 2008 is NREL's "20% Wind by 2020" [DOE:2008]. This is a very broad report that includes discussion about the status of wind technology, and the material

³ There are four types of wind turbine generators. Type 1 and Type 2 wind plants use induction generators. These turbines consume reactive power and do not meet Low Voltage Ride Through standards. Type 3 is a doubly-fed induction generator (DFIG), which partially converts the power from AC to DC to control the real and reactive power output of the machine. A Type 4 generator fully converts the AC power from the generator to DC power, and then converts it back to AC at 60 Hz with full control over the real and reactive power output of the machine (up to the limit of the input power). Type 3 and 4 wind plants can produce reactive power and meet Low Voltage Ride Through standards.

requirements for wind development. They also perform a very broad analysis of the costs of building new transmission to meet increased demand for energy. This is not technically an “integration” study. It is more of a projection of technology and economic requirements to achieve 20% wind by 2030. The modeling methods are largely standard engineering-economic scenario analysis, with very little treatment of uncertainty or even sensitivity analysis. The strength of the study is in comparing the available wind power at various wind speed class levels. The weakness is the use of the WindDS model, which uses a transportation model of the power grid. In this model, transmission lines are built when no available lines exist, but power line operating constraints/requirements are not included. The study recommends the construction of an extensive 765kV transmission backbone across the country. However the amount of transmission required between the U.S. Midwest and the East is (according to this study) fairly minimal, which is surprising since there are already major transmission bottlenecks between the East and the Midwest. This may be the result of the inaccurate transmission system model used for this study.

In 2009, TradeWind and the European Wind Energy Association published a report titled “Developing Europe’s power market for large-scale integration of wind power” [EWEA:2009]. This study focused on transmission flows and transmission needs. It works on the assumption that regional diversity is sufficient to deal with the variability of wind power. It does not include an analysis of short-term events and it does not include a discussion about reserves and regulation requirements. Interestingly, this study notes that “load and wind energy production are positively correlated...” This is the opposite of what is reported for wind production in the U.S. where load and wind energy production are negatively correlated.

In 2010 the California Energy Commission released a report, produced largely by KEMA researchers, titled "Research evaluation of wind generation, solar generation, and storage impact on the California grid" [CEC:2010]. For this study a second by second model of the grid was developed to model 3 different renewable portfolio standards (RPS). The model treats each of California, the Southwest, the Northwest, and the mountain region (Colorado and Wyoming) as tightly connected groups of generators. Within each area generators are modeled using dynamic models that account for generator rotation, frequency controls and the actions of balancing authorities to regulate flows in and out of each area (regulation). The model (KERMIT) is run for periods of one day at a time. Historical data on wind and solar output were used and scaled up to meet the different RPS modeled. It was also assumed that the forecast error remained constant in years to come. Using KERMIT, the study estimates the need for regulation services and the role of storage in supporting these regulation requirements. Unlike other studies, KEMA includes an analysis of the impacts of both wind and solar resources. The focus of this study is on short-term operational issues, such as frequency deviation and regulation to control area control error, and is the only study in this review that addresses these issues using dynamic modeling. However, they do not address longer time-scale issues, such as dispatch costs, reserves or load-following requirements. Notably, the study concludes that to reach 20% or 33% renewable penetration California will need to invest in substantial amounts of high ramp-rate power resources, such as battery storage.

Also in 2010, Charles River Associates released a fairly detailed study of wind integration in the Southwest Power Pool region [SPP:2010]. This study looks at 10%, 20%, and 40% regional wind deployment, by energy, however the analysis is less detailed at the 40% level. This study is quite detailed in that it performs detailed contingency analysis for a variety of AC power flow cases for

each wind penetration level. However the study does not report on the transmission and voltage impacts in any time-series analysis. The study proposes a new heuristic method for calculating the quantity of regulation required to meet NERC requirements for Area Control Error (ACE). Rather than calculating the regulation requirements from the standard deviation of the short-term variability of wind (a Gaussian approach that is common to most of the studies that estimate regulation requirements) the study uses the 95 and 5 percentile measurements of the variability. Additional research is required to determine if this approach will meet NERC requirements for ACE, and if ignoring the quantity of variability beyond the 5 and 95 percentile bounds will have adverse effects on system reliability.

The U.S. Department of Energy's most recent wind integration study is titled "Eastern Wind Integration and Transmission Study" [DOE:2010]. This study is, in our opinion (along with the CEC study, which had a more limited scope), the most technically sound of the studies reviewed in this paper. The study models the Eastern Interconnect in 2024 as being managed by seven large balancing authorities and with market structure that uses day-ahead bidding. This study uses NREL's Mesoscale wind data from 2004, 2005, and 2006 to simulate power production in 10-minute intervals, then aggregates it to a day-ahead, 6-hour ahead, and 4-hour ahead timeframe. Energy and load data for 2004-2006 from the PowerBase database and from FERC were used. Power flow data from 2006 was also used. The study developed 4 wind penetration scenarios for 2025:

- Scenario 1: 20% penetration using high-quality wind resources in the great plains with some development in the east coast shore.
- Scenario 2: 20% penetration moving east some of the generation from the Great Plains. Some offshore resources are also developed.
- Scenario 3: 20% penetration with increasing local resources close to load centers being developed as well as aggressive offshore generation
- Scenario 4: 30% penetration with aggressive on- and offshore generation.

The study models transmission requirements for each scenario. These are modeled using a deterministic chronological production-cost model called PROMOD IV. From this model, hourly transmission line-flows are calculated. As a result of the modeling, the study identifies that significant transmission investment is required to support large-scale wind deployment. To estimate costs of this investment, they identify potential transmission overlays and they also simulate construction of high voltage direct current lines and ultra-high voltage AC lines. It should be noted that the simulations in the study use DC power flow, so that the study does not consider issues associated with voltage control and reactive power requirements. However the DC power flow model is a substantial improvement over the transportation model used in [DOE:2008]. The report very explicitly identifies this model limitation.

The study performs a statistical analysis of regulation requirements. These requirements are modeled using the power plant fleet designed to meet the load. So most of the requirements are met using natural gas power plant or older more inefficient power plants that the dispatch model took out of operation as wind capacity increased. Unlike [CEC:2010], this study does not model energy storage as a mechanism of meeting regulation requirements.

This study does a better job at analyzing the broad set of issues related to wind integration than the other studies we have read. We feel that they at least made an effort to include in their

optimization many of the issues that were not included in other studies, most notably transmission constraints. They also performed an analysis of reserve requirements. However, like in other studies, Gaussian statistical methods are used in this analysis. Finally, the power flow is modeled as DC power flow so that voltage control and reactive power requirements are not included.

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