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Markets to Facilitate Wind and Solar Energy Integration in the Bulk Power Supply

An IEA Task 25 Collaboration

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***Abstract*—Wind and solar power will give rise to challenges in electricity markets regarding flexibility, capacity adequacy, and the participation of wind and solar generators to markets. Large amounts of wind power will have impacts on bulk power system markets and electricity prices. If the markets respond to increased wind power by increasing investments in low-capital-cost/high-marginal-cost power, the average price may remain in the same range. However, the experiences so far from Denmark, Germany, Spain, and Ireland are that the average market prices decreased because of wind power. This reduction in price may result in additional revenue insufficiency, which may be corrected with a capacity market; however, capacity markets are difficult to design. Further, the flexibility attributes of the capacity need to be considered. Markets facilitating wind and solar integration will include possibilities for trading close to delivery (either by shorter gate closure times or intraday markets). Time steps chosen for markets can enable more flexibility to be assessed. Experience from 5- and 10-minute markets has been encouraging.**

Kewords-wind energy; solar energy; electricity markets; wind integration; solar integration

I. Introduction

Large amounts of wind power will have impacts on electricity market prices. Wind power production will usually be a price taker in the energy markets, bidding at a zero price. Subsidies such as green certificates paid according to wind power production can even make it profitable for wind power producers to generate at negative prices. Day-ahead market prices will be lowered during hours of high wind power production forecasts—depending on how much wind power will push higher marginal cost generation out of market. During times of low wind generation, the market prices can be higher, resulting in increased price volatility. If the markets respond to increased wind power by increasing investments in low-capital-cost/high-marginal-cost power, the average price may remain relatively unchanged [1]. However, the experiences so far from Denmark, Germany, Spain, and Ireland are that the average market prices decreased because of increased adoption of wind power [2] . Estimating any type of price or impact requires a comparison of one outcome from reality against a simulated reality that is based on some alternative assumptions. The assumptions for the alternative system are always critical for the resulting price impact [6].

Wind and solar power forecast errors are larger per unit than those for load or other generation sources. This can mean increased trade in intraday markets, and will also impact the real-time/balancing markets. The increased demand in balancing markets often increases the prices for up/down regulation more steeply than in energy markets. Conversely, the prices in the balancing market usually follow the spot prices; this means that even if wind power increases the balancing market prices, the overall price impact can be more moderate.

With increased wind power, other generators close to marginal costs will likely experience lower capacity factors because of the merit order effect described in [1]. Some of the plants may be pushed into retirement because of revenue insufficiency. This in turn can risk capacity adequacy during high load times, unless there are market or regulatory processes that can mitigate this risk. Another concern is the flexibility available from the remaining power plants, which is at risk because combined-cycle natural gas generation tends to be the marginal generation much of the time and provides some of the most flexible operating characteristics of the generation fleet. On the other hand, a power system with more variable sources will lead to more variable prices, which will also lead to higher income for power plants that can more easily follow the changing net demand, assuming markets that compensate for this flexibility.

This paper describes some of the key issues related to wind integration. Section II focuses on basic market functions, and Section III describes some of the key market implications for wind plants that sell energy in wholesale markets. Sections IV and V describes general market structures that may be necessary to motivate potential providers of services that are needed for efficient power system operation with high penetrations of wind. This discussion focuses on two key issues: (1) resource adequacy and (2) flexibility. Section VI outlines some potentially useful general principles for market design, and Section VII concludes.

II. Overview of Market Functions

Markets provide various mechanisms and signals to both consumers and producers. In the complete absence of market power, along with assumptions of perfect competition, it is easily shown that a stable, long-run equilibrium can be achieved that maximizes social welfare [7]. Electricity markets do not fit into the perfectly competitive mold as a result of industry inception and subsequent development, resulting in large monopolies of centralized dispatchable units to take advantage of economies of scale that, although beneficial, distort the pure market outcome [8]. This motivated public regulation of the power system industry. It is also the reason that electricity markets are very difficult to design, and why it may be necessary to separate some ancillary service markets from an energy-only market.

There are some basic issues that must be examined to determine whether a market design can be effective, both in the long run and in the short run. Introduction of variable renewables pose further challenges as penetrations and the various market signals change through time, resulting in potential mismatches between signals provided by the market today for future generation resources.

As an example, Fig. **1** illustrates a feedback loop that links short-term and long-term time frames. Given an initial system configuration with a set of operating constraints and some level of wind and solar energy, these constraints—along with the load level, generation mix, etc.—set prices. In a system experiencing shortages, one would expect prices to be somewhat higher than in an adequate system. These high prices would signal that new generation may be needed and that profit can be earned. After a new plant is built, months or years later, the system has a new set of flexibility attributes that result in a set of prices that signal future investors, continuing the cycle.

Wind energy tends to lower spot prices, potentially resulting in negative prices when base-load generation is running at minimum loading levels, demand is low, and wind output is high, with no possibilities of export. Other conditions lead to high prices as well.[1] Thus, it is possible that price volatility increases with significant wind and solar penetrations. This leads us to ask two key questions:

1. Are fast and potentially more volatile energy markets sufficient to stimulate investment in flexibility enhancements?
    a. If so, are these markets stable?
    b. If not, what might be needed?
2. Does the reduction in capacity factor from some generators result in (or exacerbate) revenue insufficiency?

[1] These include ramp constraints, fuel prices, and many other conditions in the power system. See Bolinger, M & Wiser, R paper: www.osti.gov/bridge/servlets/purl/962658-J0nfxd/962658.pdf.

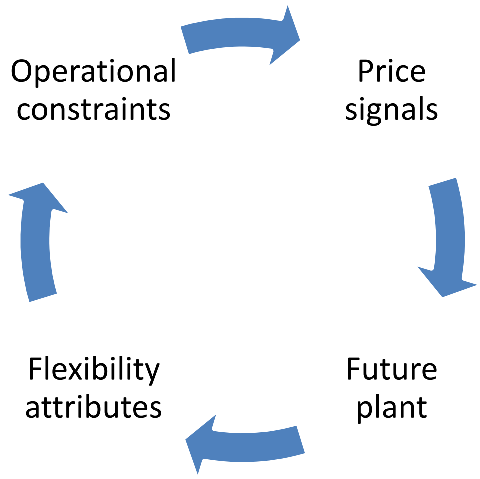

Fig. 1. Long-term decisions (investments) are made based in part on price signals today.

III. Wind Integration in Electricity Markets: The Producer's View

The operation of wind power plants in electricity markets is a good way to integrate wind power in the scheduling and dispatch process. However, there are certain market rules that can either help the wind power producers acting in the market or make the market operation very costly. The existence and liquidity of intraday markets (trading as close as possible to real-time) as well as balancing markets throughout large geographic areas are cornerstones for wind integration. In the absence of intraday markets, the exposure of wind generators to market risks of price, volume, and balancing is likely to hinder wind integration. Trading across large geographic areas may include different control zones or power systems whose products and rules need to be harmonized (e.g., closure gate times, transmission capacity allocation, reserves time response, etc.) [28]. Also, additional markets that recognize wind power capabilities are important. For example, the participation of wind and solar generators to offer flexibility and ancillary services should be made possible —even at higher prices to compensate for losses in generation, this can prove valuable for the system in critical times when other sources of flexibility are scarce. The basic challenge is to have market rules that result in an efficient operation of the whole integrated power system [28].

IV. Markets to Incentivize Flexibility and Resource Adequacy with High Wind Penetrations

A well-designed market will deliver the economically optimal mix of power generation, subject to the degree of competition and other constraints on the system. Conversely, markets that induce suboptimal power supplies are not efficient. The potential for market power is typically viewed as the key motivator for various market regulations and market monitors in the United States and Europe.

With high penetrations of wind energy in the power supply, other non-wind generators will still be needed but will operate at lower capacity factors. This implies that at least some of these units generate less energy and therefore receive reduced energy payments from the energy market. It follows that this reduced revenue stream, in at least some cases, may be insufficient to cover both the variable and fixed costs of production. Over time, this may induce generators to retire with little prospect of replacement capacity. On the other hand, if this happens, there will be more situations with available capacity closer to the limit that will result in higher prices, which then will increase the interest of investments in either low-capacity-cost units as open-cycle gas turbines or flexible demand.

Additional flexibility is needed to integrate large amounts of wind energy [16]. This need for flexibility includes several characteristics, such as short notification and start-up times, short minimum up- and down-times, and fast ramping. Of course, any power system needs some of this flexibility, but large amounts of wind and/or solar energy will require additional flexibility. [19] showed that fast energy markets can help elicit at least some ramping capability. One issue that has not been resolved is whether fast energy markets with volatile energy prices will be sufficient to elicit the needed level of ramping, and whether the emergence of the needed ramping level (in terms of installed capability) will depress the market, causing oscillations in the market for ramping capability.

A. Capacity Markets

Generators that participate in energy-only markets rely on the prospect that the sum total of energy payments will be sufficient to cover both the variable cost of operation and the fixed investment cost of the plant. Retail prices are typically not reflective of production cost; therefore, the end consumer will not receive price signals, resulting in one form of market failure because supply and demand are not rectified. The main problem in the electricity markets is then an irresponsive demand. Markets are functional as long as all participants (including consumers) have the same opportunities and information to respond to price signals. Traditionally, the equilibrium in the market has been achieved on the supply-side exclusively. With high penetrations of wind energy (or solar energy), it has been shown that conventional plants' capacity factors decline as a result of the near-zero marginal cost of wind energy [13]. Because of a combination of political and market manipulation concerns, some energy markets have price caps that limit payments available during scarcity hours, contributing to what is often referred to as the "missing money" problem, and contributing to the need for capacity markets to ensure adequate recovery of capital and operating costs [18]. In Europe, capacity markets often respond to protecting market incumbent's revenues rather than system adequacy. This has triggered overinvestment in national power generation capacity in some countries. Indeed, the design of a capacity market is not straightforward. Whilst addressing the missing money problem, they may create others externalities and market distortions. Although PJM has assessed its capacity market and found that it functions well, the Independent System Operator of New England (ISO-NE) has tried several alternative market designs, at least two of which have not been effective[17]. At the same workshop, [20] suggested that markets will obtain whatever is rewarded, whether that is the object of the market designers' desire or not. The point is that markets must be well-designed, clear and consistent in their objectives, and reward the delivery of the desired product.

If the objective of a capacity market is to provide the "missing money" so that fixed costs can be covered by the capacity market, the capacity market must compensate generation owners in a consistent way during the time period during which the debt (or other financial instrument) is retired. It follows that capacity markets that offer single-year payments will likely not result in resource adequacy in the long run. This is because capacity auctions in a given year that can elicit the required new generation capacity may not be repeated in the following year(s). If the auction does not provide sufficient capacity payments to the generation developers/owners, then the objective of the capacity market will not be met.

Conversely, it is also important that the combination of a capacity market with an energy market does not result in overcompensation. Although simple in principle, this implies that the required level of compensation to elicit the needed level of capacity is known.

In the Nordic market, an alternative capacity market is implemented, a so-called selective capacity market [22]. In this type of market, only a limited amount of power receives funding. The impact from wind power on this market was studied in [7]. The result was that in a system where wind power is added as extra power to an existing power system, the required volume of reserve power decreases. However, in a system where the market installs less power when wind power is expanded, the required volume of reserve power increases.

B. Flexibility Markets

High penetrations of wind energy require additional flexibility from the remaining generation fleet, or must be combined with flexibility that is provided by the wind power plants themselves [21]. Markets that reward only energy provide an incentive for generators to produce as much energy as possible, which may result in the overdevelopment of large base-load generation that can run at very high capacity factors. In any power system, even absent wind energy, some flexibility is needed, which is why a typical generation portfolio (regardless of ownership) consists of a combination of base-load, mid-merit, and peaking generation. Efficient markets are defined as markets that can provide for the type of product and in sufficient quantities to deliver what society values. In the case of power generation with significant penetrations of wind energy, this means that sufficient flexibility needs to be elicited by the market—not too much, and not too little.

Market suppliers respond to incentives; therefore, whatever incentives are provided by the market must be in line with what is physically needed to operate the power system reliably and economically. Generally, a flexible unit (or responsive load) can react quickly to changing needs. Large systems may have multiple flexible units, and they can be called upon based on their cost, allowing for the economical acquisition of flexibility in real time. One can also define flexibility to have multiple attributes, each of which is needed in wind-rich power systems:

- Fast ramping capability (up and down)
- Low turn-down capability
- Fast start-up and shut-down
- Short minimum up-times and down-times

Energy-only markets that run in short intervals, such as 5 min, can extract significant ramping capability as a by-product. This was shown by [19]. Fig. 2 provides a simple example.

The base-load unit, with a hypothetical price of $10/MWh, cannot ramp fast enough to keep up with load increase, although it does have sufficient capacity to meet the higher load level. A peaking unit, with a hypothetical price of $90/MWh, provides the needed ramp capability until the base-load unit can catch up, at which point the peaker is no longer needed. During the period of high load-ramping, when the peaker is called into service, the energy price is $90/MWh, rising to that level because of the out-of-merit dispatch that is required to meet the ramping needs.

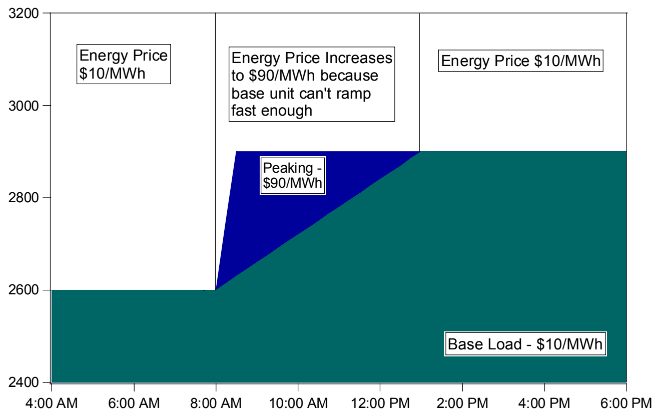

Fig. 2. Using an energy-only market, it is possible to extract fast ramps.

The question is whether this type of market price spike will induce the development and deployment of fast-ramping capability, both in the short run and in the long run.

This question has not been satisfactorily answered in the research literature or in practice. In this example, the market rewards the peaking unit, which would therefore provide an incentive for the development and deployment of such resources. On the other hand, in this energy-only market example, the base-load unit is rewarded for a capability that it does not possess, which does not provide an incentive for the base-load unit to develop the needed ramping capability.

One side of the debate argues that this perverse incentive to the base-load unit will result in market failure. In this line of reasoning, a ramp-constrained period should trigger the activation of a new market to supplement the energy market. Thus, when the merit-order dispatch stack does not have the required ramping capability, a ramp product would be utilized, paying the peaking unit (or whatever technology can respond as needed) a price of $90/MWh, but keeping the energy market–clearing price at $10/MWh. If a generation owner were then to develop additional ramping capability, it would be rewarded by the market; however, if a base-load unit could not respond, it would not be rewarded for its lack of response. This is the way that the balancing markets operate.

However, the other side of the debate argues that an energy-only market is sufficient to elicit the needed level of flexibility. As illustrated in Fig. 2, there may be times when a high energy price is needed to compensate high-cost generation, such as combustion turbines that have the ability to ramp quickly enough in the absence of other flexible units. The resulting price volatility would then provide price signals to generation owners to increase their flexibility.

A general challenge for power system investments is the risk of market power, defined as the ability for a single market actor to influence the market-clearing price. In the example in Fig. 2, the base-load unit may have no incentive to invest in a better ramp rate performance because that will lower the marginal price and reduce the income. But if one assumes a competitive market with many players, there may be other base-load units that will have an incentive to improve their ramping capability.

There may be other approaches that can help elicit flexibility in real-time markets. One example is the use of a probability-weighted locational marginal price (LMP), as described in [25]. The output from a stochastic unit commitment and dispatch is used to calculate the distribution of likely outcomes. Using the probabilities associated with the outcomes, a weighted average price can be calculated. Simulation evidence shows that periods of uncertainty cause prices to respond accordingly, allowing risk to be priced into the dispatch.

This approach also has two additional benefits: (1) negative profit is reduced, which then reduces the need for uplift payments; and (2) this method allows for a relatively simple way to convert the output of a stochastic to a single value that can be used for discrete dispatch decisions.

V. What Kind of Capacity Is Needed?

The previous two sections discussed the issues of capacity and flexibility, but have not linked them together. It is important to be able to assess whether there is adequate capacity to serve the future level of load. With high levels of wind and solar energy, it is also important to ensure that the capacity that meets the resource adequacy also has the flexibility attributes needed by wind/solar generation. At present, there is no single accepted method for determining the level of flexibility that is needed, nor how it can be supplied.

However, there has been some progress in this regard. [26] developed a series of ramp envelopes, based on 10-minute wind and solar power data, along with load data. An example is shown in Fig. 3. This graph was assembled from data used to evaluate the proposed Energy Imbalance Market in the Western United States, and the data covers the entire Western Interconnection, absent those areas served by the California Independent System Operator and Alberta Electric System Operator.

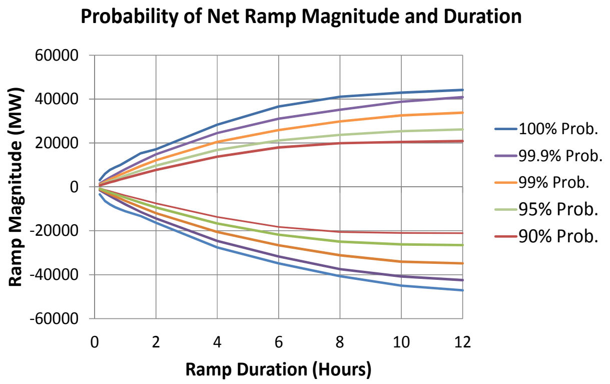

Fig. 3. Ramp envelopes for alternative risk levels can inform the need for ramping.

Resource adequacy assessment utilizes probabilistic methods that account for the forced outage rates of generators. This technique can be adapted to ramping need and capabilities, as developed in [27]. The effective ramping capability (ERC) is calculated based on ramping needs and the capabilities of the generation fleet, adjusted to account for forced outages. The relationship between effective load-carrying capability and ERC is shown in Fig. 4

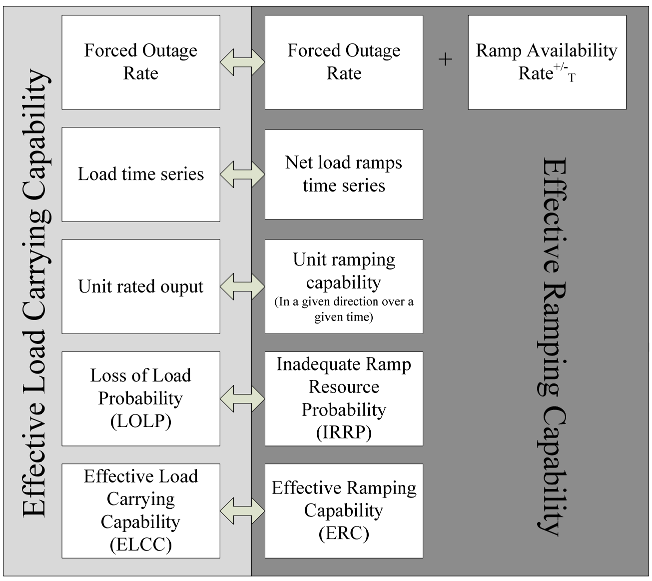

Fig. 4. Relationship between effective ramping capability and effective load-carrying capability.

VI. Potentially Useful Principles for Market Designs

Although market design details are very complex and difficult to design so that unintended consequences are avoided, we offer a few simple principles that may be helpful for market designers. Some of these were adapted from [10].

A. Horizontal Consistency

Two market suppliers that produce the same (or similar) product or performance should be paid the same (or similar). This principle applies to the deployment (commitment or dispatch) of the resource, not necessarily to bids. For example, two units (A and B) that provide the same ramping performance, as measured in MW/minute during the same market period, should be paid the same amount.

B. Vertical Consistency

Elaborating on the previous example, if unit A provides a faster ramp than unit B, A should be paid more than B.

C. Technology-Neutral

Markets should be blind to the technology behind the product. Instead, performance metrics should be developed that normally include either incentives for good performance relative to the market or penalties (or reductions in payments) for poor performance. A performance-based market metric (or family of metrics) results in a form of competition between technologies that may be able to provide the same or similar service. This type of metric also allows for the development of new capabilities, such as wind turbines that can provide various levels of control to provide ramping or other valuable products to the power system while also providing other benefits, such as reduced greenhouse-gas production, water usage, and low marginal cost. [10] described an example of a coal unit that consumes regulation, showing that performance-based analysis is more appropriate than technology-based.

D. Market Interface

Trading between balancing areas can help mitigate variability and uncertainty. The Nordic power system provides a good example. Imbalances in Denmark can be counterbalanced in Finland within 10 min if the Finnish regulating bid is the cheapest one and there is room in the transmission system through Sweden (which is in between Denmark and Finland). Market operators in the United States are also improving interactions at market boundaries, moving toward shorter scheduling periods of 15 min instead of hourly schedules. Trading across large geographic areas may include different control zones or power systems whose products and rules need to be harmonized (e.g., closure-gate times, transmission capacity allocation, reserves-time response, etc.) [28].

E. Thought Experiments

Simple analyses can help determine whether the market will achieve its objectives. These thought experiments are not substitutes for more rigorous analyses or stakeholder inputs during the market development process; however, they can be useful to determine whether the market does indeed reward suppliers who provide what the market is asking for. They can also help determine whether there are any unintended incentives for poor behavior, whether there are sufficient rewards for desired behavior, or whether the market focus has been achieved with minimal side effects. This is discussed further in [10].

VII. Summary and Conclusions

Wind and solar power will give rise to challenges in electricity markets regarding flexibility, capacity adequacy, and the participation of wind and solar generators to markets.

It seems clear that market structures to reward flexibility are beginning to be designed, yet more work is needed to (a) further develop the conceptual framework and market design, and (b) conduct pilot and other market tests. Testing, both through simulation and by pilot projects, will be critical to ensure that the proposed market structures behave as intended. There are two aspects of flexibility markets: (1) long-term market signals must be sufficient to induce the needed flexibility to be built, and (2) once built, the operational market must provide a sufficient revenue stream to ensure the financial viability of the flexible unit (or load). All of this should be accomplished in an economically efficient manner.

The experience with capacity markets appears to be uneven. As indicated by the ISO-NE, this is an evolving area and additional research and/or experimentation is needed. This type of market is particularly difficult to test in practice because it can potentially cover a period of years.

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IX. References

[1] C. Weber and O. Woll, MERIT-ORDER-EFFEKTE VON ERNEUERBAREN ENERGIEN—ZU SCHÖN UM WAHR ZU SEIN? EWL Working Paper No. 01/07, University of Duisburg-Essen, 2007 (in German).
[2] H. Holttinen, "The impact of large-scale wind power production on the Nordic electricity system," Ph.D. dissertation, Espoo, Finland: VTT Publications 554, 82 pp. + app. 111 pp, www.vtt.fi/inf/pdf/publications/2004/P554.pdf.
[3] E. Clifford (EirGrid) and M. Clancy (SEAI), Impact of Wind Generation on Wholesale Electricity Costs in 2011, Mar., www.seai.ie/Publications/Energy_Modelling_Group/Impact_of_Wind_Generation_on_Wholesale_Elec_Costs/Impact_of_Wind_Generation_on_Wholesale_Electricity_Costs_in_2011.pdf
[4] P. E. Morthorst, "Impact of wind power on power spot prices," 2007, www.optres.fhg.de/events/workshop-2006-10-12/Copenhagen/Morthorst%20Cph(1206).pdf.
[5] F. Sensfuß, M. Ragwitz, and M. Genoese, "The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany," Energy Policy, vol. 36 no. 8, 2008.
[6] H. Holttinen et al., "Design and operation of power systems with large amounts of wind power," International Energy Agency Wind Task 25, Phase one 2006–2008, Espoo, Sweden: VTT Research Notes 2493, 2009, 200 pp. + app. 29 pp, www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf.
[7] H. Varian, Microeconomic Analysis, Norton, 1978.
[8] S. Stoft, Power System Economics: Designing Markets for Electricity, Wiley Interscience, 2002.
[9] H. Holttinen and A. Stenberg, "Wind power balancing costs for different size actors in the Nordic electricity markets," European Wind Energy Conference and Exhibition Proceedings, Brussels, Mar. 14–17, 2011.
[10] M. Milligan et al., Cost-Causation and Integration Cost Analysis for Variable Generation, NREL/TP-5500-51860, Golden, CO: National Renewable Energy Laboratory, 2011, 37 pp., www.nrel.gov/docs/fy11osti/51860.pdf.
[11] H. Holttinen, "Optimal electricity market for wind power," Energy Policy, vol. 33, no. 16, pp. 2052–2063, 2005.
[12] J. King, B. Kirby, M. Milligan, and S. Beuning, Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection, NREL/TP-5500-52330, Golden, CO: National Renewable Energy Laboratory, 2011, 100 pp., www.nrel.gov/docs/fy12osti/52330.pdf.
[13] GE Energy, Western Wind and Solar Integration Study, NREL/SR-550-47434, Golden, CO: National Renewable Energy Laboratory, 2010, www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf.
[14] V. Neimane and F. Carlson, A Massive Introduction of Wind Power: Changed Market Conditions? Elforsk report 08:41, 2008, www.vindenergi.org/vindforskrapporter/v_132.pdf.
[15] H. Holttinen and G. Koreneff, "Imbalance costs of wind power for a hydro power producer in Finland," Wind Engineering, 2012 (in press).
[16] International Energy Agency, Harnessing Variable Renewables: A Guide to the Balancing Challenge, IEA 9, Rue de la Federation, Paris, executive summary available at www.iea.org/Textbase/npsum/Harness_Renewables2011SUM.pdf.
[17] R. Coutu, "Capacity markets in the United States," Utility Wind Integration Group Workshop on Market Design and Operation with Variable Renewables Proceedings, Fredericia, Denmark, June 22–23, 2011.
[18] P. Cramton and S. Stoft, "Forward reliability markets: Less risk, less market power, more efficiency," Utilities Policy, vol. 16, no. 3, 2008, doi:10.1016/j.jup.2008.01.007.
[19] M. Milligan and B. Kirby, Market Characteristics for Efficient Integration of Variable Generation in the Western Interconnection, NREL/TP-550-48192, Golden, CO: National Renewable Energy Laboratory, 2010, 51 pp.
[20] M. Milligan, "Why are we talking about capacity markets?" NREL/PR-5500-52138, presented at the Market Design and Operation with Variable Renewable Workshop, Frederica, Denmark, June 22, 2011, 22 pp.
[21] B. Kirby, M. Milligan, and E. Ela, "Providing minute-to-minute regulation from wind plants," NREL/CP-5500-48971, 9th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants Proceedings, Quebec, Canada, Oct. 18–19, 2010.
[22] L. Soder and H. Holttinen, "On methodology for modeling wind power impact on power systems," International Journal of Global Energy Issues, vol. 29, no. 1–2, pp 181–198, Feb. 2008.
[23] L. Soder, "Analysis of pricing and volumes in selective capacity markets," IEEE Transactions on Power Systems, vol. 25, pp. 1415–1422, June 2010.
[24] A. Ott, "Evolution of conventional, renewable, and alternative resources in PJM market operations," IEEE Power and Energy Society General Meeting Proceedings, San Diego, CA, July 22–26, 2012.
[25] E. Ela and M. O'Malley, "Probability-weighted LMP and RCP for day-ahead energy markets using stochastic security-constrained unit commitment," NREL/CP-5500-53524, 12th International Conference on Probabilistic Methods Applied to Power Systems Proceedings, Istanbul, Turkey, June 10–14, 2012.
[26] M. Milligan, J. King, and B. Kirby, Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection, NREL/TP-5500-52330, Golden, CO: National Renewable Energy Laboratory, 2011, www.nrel.gov/docs/fy12osti/52330.pdf.
[27] E. Lannoye et al., "Integration of variable generation: Capacity value and evaluation of flexibility," IEEE Power and Energy Society General Meeting Proceedings, Minneapolis, MN, July 25–29, 2010.
[28] M. Milligan, H. Holttinen, L. Söder, and C. Clark, "Market structures to enable efficient wind and solar integration," IEEE Power and Energy Society General Meeting Proceedings, San Diego, CA, July 22–26, 2012.
[28] I. Pineda and P. Wilczek, "Creating the internal market, the role of wind energy," European Wind Energy Conference and Exhibition Proceedings, Copenhagen, Denmark, Apr. 16–19, 2012.