Providing Minute-to-Minute Regulation from Wind Plants

Preprint

B. Kirby, M. Milligan and E. Ela

National Renewable Energy Laboratory

To be presented at The 9th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems and Transmission Networks for Offshore Wind Power Plant
Québec, Canada
October 18-19, 2010

Conference Paper
NREL/CP-5500-48971
October 2010

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information

P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Providing Minute-to-Minute Regulation from Wind Plants

Brendan Kirby, Michael Milligan and Erik Ela

Abstract-- **Our earlier work showed that it may be both technically and economically feasible for wind plants to supply minute-to-minute regulation under some circumstances. In this paper, we extend the previous analysis using time series data from existing wind plants, system loads, and regulation and energy markets. Both wind plant response performance requirements and power system needs are addressed. In present-day regulation markets, the regulation market price is typically based on the supplier's opportunity cost in the energy market. With a near-zero marginal production cost, wind would not be expected to be an attractive regulation supplier most of the time. Minimum load problems, typically on nights with high wind, and the need for conventional generators to incur additional costs when operating above minimum loads appear to make regulation from wind an economical option for some hours of the year. Unlike contingency reserves whose prices are generally low at night, the price for regulation typically remains high around the clock. In this paper, we examine wind and regulation markets in several regions to assess the viability of the concept.**

***Index Terms*— operating reserves power system economics, power system operations, power system reliability, power systems, wind power generation, wind energy**

I. Introduction

POWER system frequency regulation is the use of on-line generation, storage, or load that is equipped with automatic generation control (AGC) and that can change output quickly (MW/min) to track the moment-to-moment fluctuations in customer loads and to correct for the unintended fluctuations in generation. Regulation helps to maintain interconnection frequency, manage differences between actual and scheduled power flows between control areas, and match generation to load within the control area [1]. Previously, [2] showed that, at least theoretically, it may be attractive for wind plants to provide regulation under some circumstances. For this analysis we particularly consider regions with energy and ancillary services markets that are co-optimized as these provide dynamic prices to present the value of both energy and ancillary services products. Fig. 1 shows that the regulation bid price a conventional generator must ask in order to break even when providing regulation depends on the price of energy and the generators marginal production cost (including increased losses). Fig. 1 also shows that wind's near zero marginal production cost results in a higher opportunity cost (no fuel savings) when a wind generator forgoes selling energy in order to be able to provide regulation than when a conventional plant provides regulation. Still, analysis of energy and regulation prices from Texas and California show that in practice there are currently a significant number of hours each year when selling regulation from wind is likely profitable. This trend is likely to continue as higher wind penetrations both drive down the price of energy and reduce the supply of regulation, especially at night.

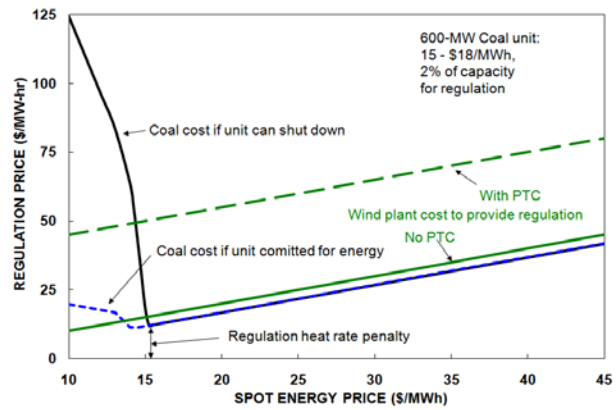

Fig. 1. The cost of supplying regulation is a function of the price of energy for both thermal plants and wind generators.

Regulation is a single bi-directional product in some regions and two separate products (up and down) in others. This complicates the analysis but does not fundamentally change it. Accounting for the energy imbalance that is necessarily associated with how the system operator deploys regulation also complicates both the analysis of regulation supply in general as well the discussion of bi-directional vs separate regulation products. We show that any benefit that a wind plant can derive from one regulation structure vs. the other depends on how the system operator uses regulation (any bias in up vs. down deployment, for example) rather than on a fundamental difference between the structures.

II. Energy and Regulation Prices

Regulation is the control of real power (either generation or load) over a time frame that is faster than the fastest market clearing or scheduling interval. It is used by system operators to meet the North American Electric Reliability Corporation (NERC) Control Performance Standards 1 and 2 (CPS1&2). CPS1&2 are based on one-minute and ten-minute averages of balancing area (BA) area control error (ACE) and frequency [3]. Regulation is a balancing control function and should, over some reasonable interval, be energy neutral with up regulation balancing down regulation. In some regions, regulation is split into two separate up and down services and we discuss the distinction at length below. The primary cost incurred when a generator provides regulation is the opportunity cost of withholding some of the generator's production capacity from supplying energy.

With balanced up and down regulation, half of the regulating range is unavailable for providing energy. When regulation is defined as a single service, 1 MW of regulation refers to a 2 MW range of ±1 MW. It is appropriate, therefore, to compare the lost opportunity cost of providing 1 MW of energy (energy price – marginal cost) with the price and cost of 1 MW of regulation. Equation (1) shows the relationship of the marginal regulation provider, where P_{reg} is the price of regulation, C_{reg} is the cost of regulation (excluding lost opportunity), P_e is the price of energy, and C_e is the cost of energy. Note that the second term is the lost opportunity cost and is non-zero if by providing regulation service the unit is withholding providing energy while it would have been profitable *or* if the unit is forced to supply additional unprofitable energy in order to provide regulation. With separate up and down regulation services, the lost opportunity cost of energy can be compared with the combined up and down regulation price, again assuming that the system operator is using balanced amounts of the services. When analyzing either up regulation or down regulation separately, the amount of unavailable energy capacity depends on how the system operator actually uses the regulation. If it is assumed that a 50% regulation duty cycle results in half of the energy capacity being lost, then it is appropriate to compare the energy lost opportunity cost with twice the up or down regulation price. All of this is discussed in greater depth later in the paper.

$$P_{reg} = C_{reg} + |P_e - C_e| \tag{1}$$

Wind's near-zero production cost results in an opportunity cost that is equal to the energy price. Wind must receive the same compensation for providing a MW of balanced regulation for an hour (MWh of regulation) as it would have received for a MWh of energy. Conventional generators, of course, require less compensation since they save fuel when they do not produce energy.[1] Not surprisingly, regulation prices tend to be lower than energy prices, though regulation prices do not drop as much as energy prices do at night. Fig. 2 and Fig. 3 show average hourly energy and regulation prices for West Texas in 2008 and 2009, and California for 2008. In 2008, both cases had regulation prices that tended to stay high at night with average regulation prices exceeding energy prices for several hours in West Texas. In both West Texas and California, down regulation was more expensive at night and up regulation was more expensive during the day. This is because conventional generators must be scheduled above their economic operating point in order to have the capacity to regulate down to their minimum generation.

[1] Conventional generator heat rates are degraded when they supply regulation, reducing the fuel savings somewhat, as shown in Fig. 1.

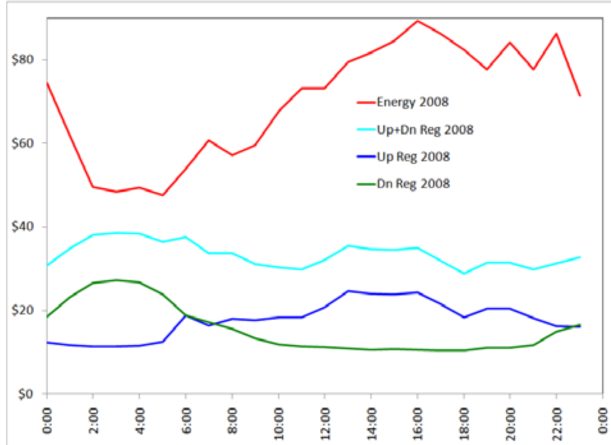

Fig. 2. Energy and regulation prices show a typical daily pattern in West Texas, with regulation prices exceeding energy prices for some hours at night.

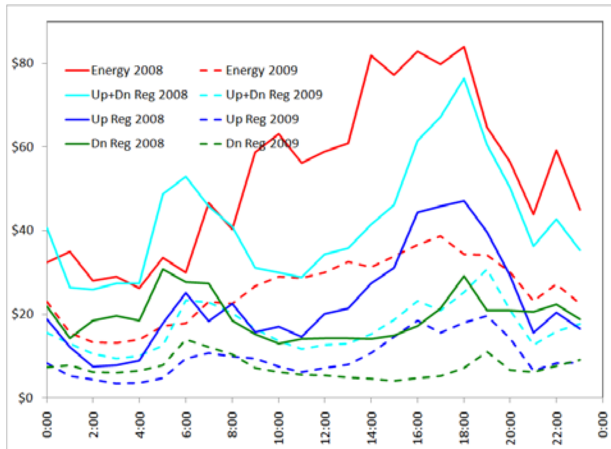

Fig. 3. Energy and regulation prices show a similar daily pattern in CAISO.

For the 2009 prices in West Texas, the economic downturn depressed load growth and energy prices throughout the country. Regulation prices were similarly impacted. But the basic relationship between regulation and energy remained the same.

Fig. 2 and Fig. 3 present annual hourly average prices. Real-time prices vary considerably. The price of regulation exceeded the price of energy during 3282 hours in West Texas in 2008 and 2120 hours in 2009. During those hours the regulation price (up plus down) exceeded the energy price by \$40.40/MWh in 2008 and \$21.48/MWh in 2009, making regulation provision fairly attractive. Regulation price only exceeded energy for 673 hours in California in 2008, but it exceeded it by an average of \$63.70/MWh when it did.[2] Of course, wind generation was not available during all of those hours in either state. Specific data from West Texas is examined below.

[2] Congestion and losses were not considered in this part of the analysis as they are location specific and the exact wind plant location is not known. Since wind plants are generally located further from loads, the losses component would generally lower the total energy price making provision of regulation more attractive and the analysis more conservative. Congestion limits opportunities, complicates the analysis, and is addressed briefly later in the paper.

III. Regulation From Wind

To begin determining the possible economic benefits of a wind plant providing regulation, we examined energy and regulation prices from 2008 along with minute-to-minute output from a single 120-MW wind plant in West Texas and the entire 4700-MW ERCOT wind fleet. We then examine a wind plant in the western U.S. along with its BA's ACE, to demonstrate its potential regulation deployment.

A. Regulation from a Single 120 MW Wind Plant

A wind plant incurs an opportunity cost when it reduces output to create head room to provide regulation; it foregoes energy sales in order to sell regulation. The 15-minute balancing energy market price was used as a proxy for the energy value to calculate the opportunity cost. Since wind has near-zero marginal production cost, the hourly regulation price has to exceed the hourly (average of four 15-minute intervals) energy price to make the provision of regulation profitable. Interestingly, even though the average hourly regulation price (up plus down) exceeded the average hourly West Texas energy price during only six hours a day (Figure 2) in all of 2008, the actual hourly regulation price exceeded the energy price during 3282 hours; greater than 37% of all hours.

Fig. 4 shows the hourly regulation and West Texas energy prices for an example day; May 7, 2008. The price of regulation (up plus down) exceeded the price of energy during sixteen of the 24 hours.

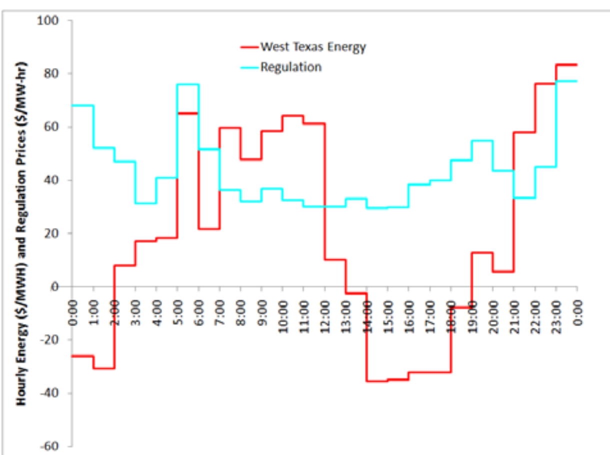

Fig. 4. Hourly regulation and West Texas energy prices for May 7, 2008.

We assume that the wind plant can provide regulation by curtailing energy production to create head room for up regulation. The plant also needs to be operating above zero so that it can regulate down. To be able to provide the full range of contracted regulation throughout the hour, the regulation up swing is also limited to the wind plant's minimum production during the hour.[3] It is likely that a wind plant would be further limited in the range of regulation that it can provide, but we did not include any additional limitations in this preliminary analysis. Such limitations include the wind energy potential forecast error and transmission limitations. If wind conditions are such that the minimum generation during the hour could be 80 MW, for example, we allow the plant to move its operating point down 40 MW below the minute-to-minute available wind and sell 40 MW of up and down regulation for the hour as shown in Fig. 5. Since regulation procurements are limited by a response time (typically 5-15 minutes), it would have to be ensured that the wind plant can provide this response within the desired time period. It has been demonstrated that with pitch control, large state-of-the art wind turbines have very quick relative response rates and therefore entire wind plants should be capable of very fast and accurate response when providing regulation service [4].

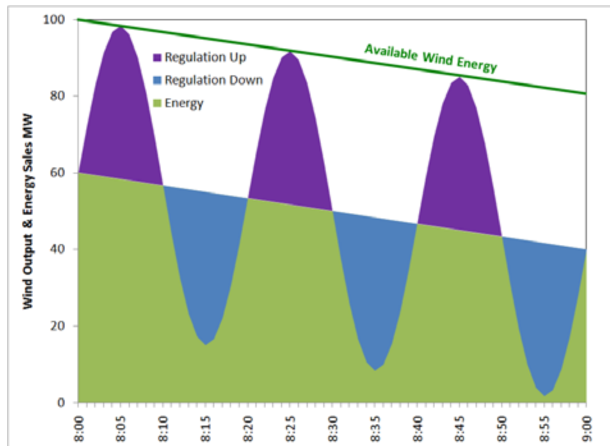

Fig. 5. Providing regulation from wind requires controlling the plant below the available wind.

One could require that a wind plant first flatten its output by curtailing to the minimum production for the hour before providing regulation, as shown in Fig. 6. However, this would unnecessarily waste valuable energy and provide economically inefficient regulation. Providing regulation by controlling the output (based on the system operator's AGC signal) below the currently available wind, as shown in Fig. 5, aggregates the plant's natural variability with the rest of the wind and load before controlling the lesser net variability.

Fig. 7 shows an example plant on May 7, 2008. We do not have the actual ERCOT AGC regulation signal, so we used an unrelated regulation signal from PJM purely as an illustration. The amount of regulation supplied varies from hour to hour, depending on the hourly minimum wind. The plant provides no regulation during the eight hours that the regulation price is lower than the energy price.

Modeling all of 2008, the wind plant was producing at least a small amount during about 2800 of the 3282 hours when regulation was more profitable than energy for wind. The wind plant would have earned an additional \$3.5 million in 2008 if it had sold regulation whenever the price of regulation exceeded the price of energy (including the lost energy revenue). That is an additional \$9.96/MWh spread over the plant's entire production. If the wind plant had to flatten its output prior to providing regulation, it would spill 31,396 MWh or about 10 MW during the hours it provided regulation. The value of the lost energy was \$150,865, or about 4% of the value of the regulation.

[3] We are also ignoring the very real forecasting problem at this point in the preliminary analysis. Regulation is typically scheduled day-ahead for each hour. The wind plant would have to know its minimum production for each hour of the following day. Not a trivial restriction.

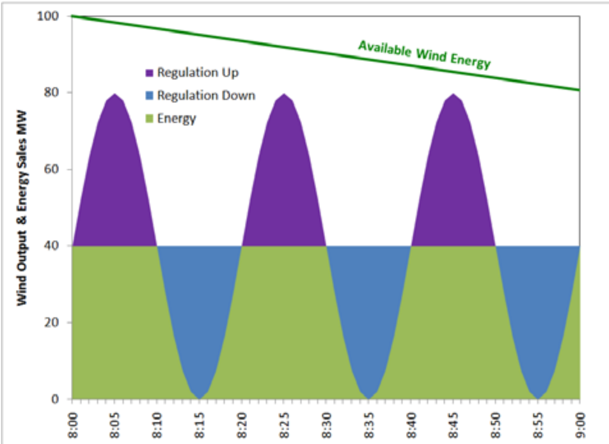

Fig. 6. Wind could be curtailed to the hourly minimum while supplying regulation.

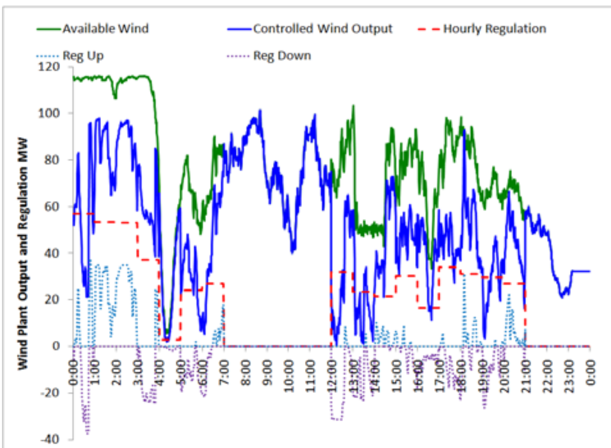

Fig. 7. The wind plant supplied regulation during 16 hours on May 7, 2008 in our analysis.

Transmission congestion can reduce energy prices in export constrained areas and may make regulation relatively more attractive to provide. In reality, getting regulation up service from an area that is export constrained may not be possible since it would lead to overloading transmission system limits. West Texas had significant transmission congestion in 2008 as is evidenced by the 1150 hours of negative energy prices. By using the unconstrained North Texas zone prices, more realistic regulation prices still exceeded uncongested North Texas energy prices during 2469 hours in 2008. The wind plant could have provided regulation during about 2040 hours, generating an additional $2 million; 57% of the revenue it would have made in the congested zone. This estimate is conservative because the plant output reflects congestion curtailments. With congestion removed, the plant could provide additional regulation as well as additional energy.

B. Regulation from the ERCOT Wind Fleet

ERCOT's regulation requirement varies from hour to hour and day to day, but is typically in the range of 700 MW to 1000 MW of both up and down, as shown in Fig. 8.[4] ERCOT's wind fleet could provide more regulation than is required during many hours. Limiting the wind fleet regulation contribution to the hourly average regulation requirement (or the wind fleet capability, whichever is lower) during times when regulation is more expensive than energy would result in $101 million additional annual revenue or $6.76/MWh for all the wind energy produced.[5] This would also result in wind supplying 32% of the ERCOT regulation requirement. With transmission congestion removed (using North Texas energy prices), the annual additional revenue drops to $64 million or $4.31/MWh of wind energy. Wind still supplies 22% of the ERCOT regulation requirement.

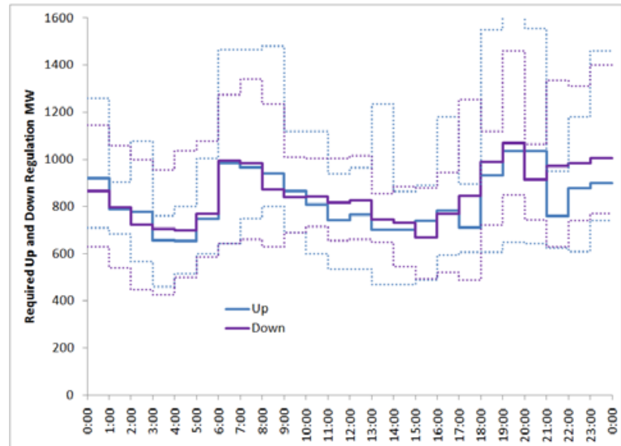

Fig. 8. ERCOT regulation requirements vary from hour to hour and day to day, but are typically in the 700-MW to 1000-MW range for up and down.

C. Wind Plant Regulation with Synchronized ACE

High resolution data from a wind plant in the western U.S. and the ACE from its associated BA were used to simulate exactly how the wind plant would provide the regulation service. An AGC signal was created using a proportional and integral term. In this example, the BA has established a ±150 MW regulation requirement and the wind plant is assigned 10% of the total regulation needed. The total wind potential (what the wind provides without regulation), its energy set point, and AGC deployed signal are shown on the same plot as the ACE in Fig. 9 for a one-hour time period.

In this example, the wind plant offers regulation capability to the system operator and defines any limitations on that capability including ramp range, up and down ramp rates, and any costs associated with providing regulation. The BA system operator co-optimizes regulation and energy production from this wind plant along with the other wind plants and conventional resources. The system operator, with its centralized wind forecast, is in the best position to schedule regulation and energy from all of the offering wind plants.

[4] Regulation requirements are based on the 2009 data and methodology.

[5] Regulation prices would likely decline with wind entering the market, but the opportunity cost would limit the price reduction.

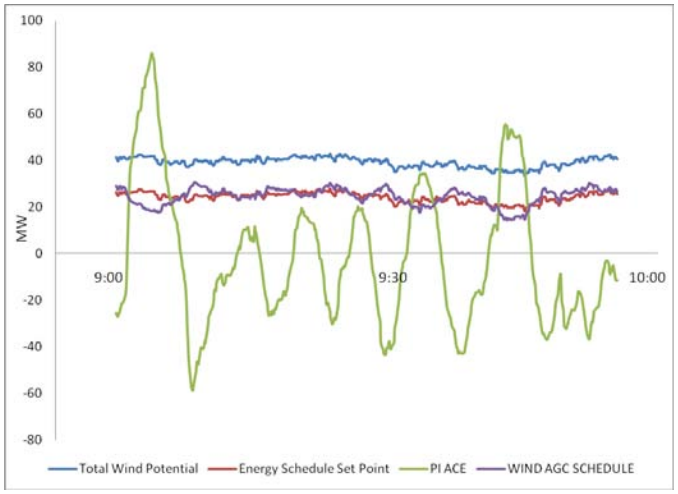

Fig. 9. Wind plant providing 15-MW regulation to a system with 150-MW requirement.

Fig. 9 shows that the wind plant AGC schedule did not differ substantially from its energy set point. The wind plant was providing 15 MW of regulation in both directions, which meant its neutral position (set point) was 15 MW below its potential. Fig. 10 shows the response for the same hour if the BA reduced its estimated regulation requirement to 75 MW and assigned 20% to the wind plant (still 15 MW).

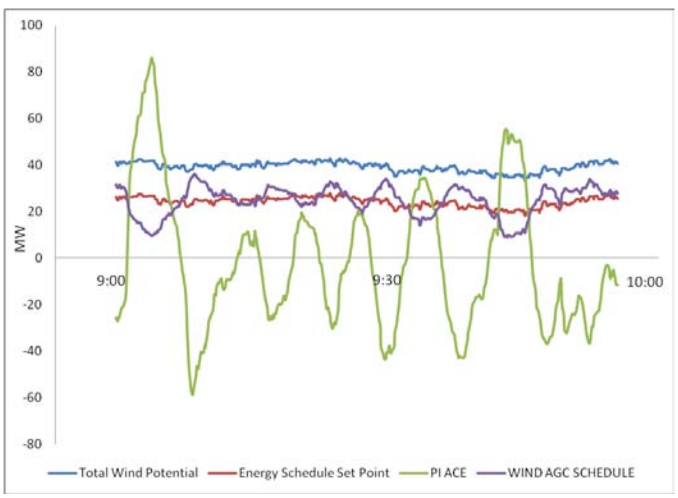

Fig. 10. Wind plant providing 15-MW regulation to a system with 75-MW requirement.

The wind plant would have continued to provide the regulation service as shown in Fig. 10 and used more of its regulating range. However, a few hours later, if the wind plant was still given the 15-MW regulation schedule, it would have encountered an issue, as is seen in Fig. 11.

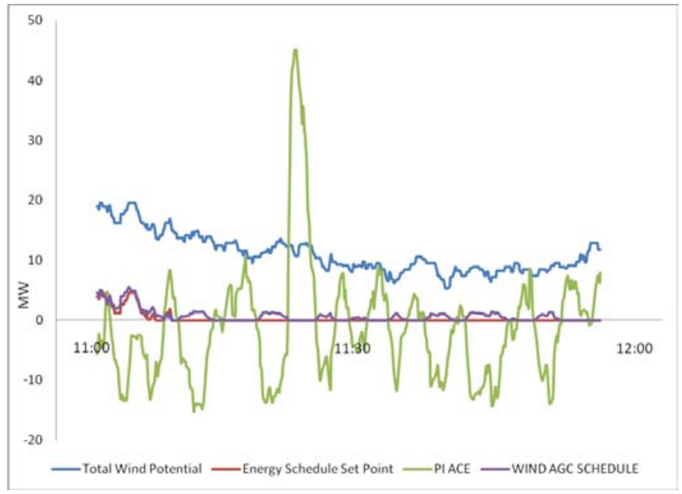

Fig. 11. Wind plant providing 15-MW regulation to a system with 150- MW requirement. Because of low wind power potential, the wind plant is set at zero and can only provide up regulation.

The wind power potential during this hour was lower than the previous hours and lower than forecast (had the wind reduction been forecast, 15 MW of regulation would not have been assigned to the wind plant). In fact, for most of the hour, wind potential was less than 15 MW. The wind plant was only able to provide up regulation and would not have been able to regulate up the full 15 MW for most of the hour. However, had the system operator forecast the energy production accurately, it may have reduced its regulation schedule to 5 MW rather than 15 MW. As is seen in Fig. 12, being able to predict the energy level of the wind plant can avoid issues of poor quality regulation service from the wind plant.

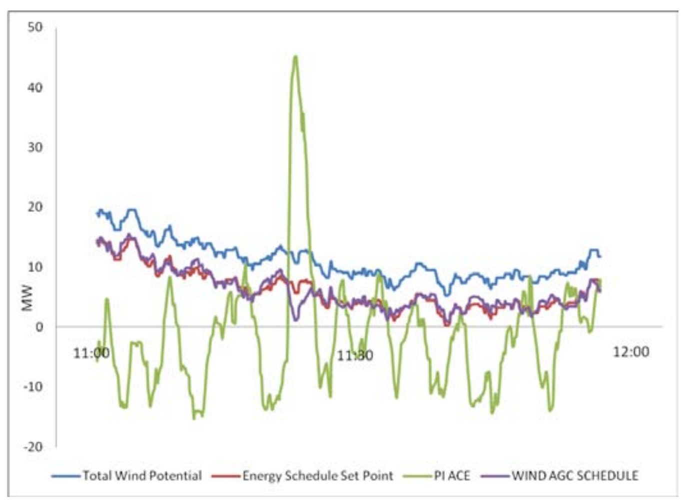

Fig. 12. Wind plant providing 5-MW regulation to a system with 150-MW requirement during reduced wind output.

This analysis shows that being able to forecast the wind power is important. However, by being conservative in scheduling wind-provided regulation levels rather than scheduling half of wind's potential as regulation, it is less likely that the wind plant could run out of regulation as a result of an inaccurate forecast. The forecast error of the wind plant's energy would still remain an issue, as it is today, but forecast error's impacts on wind-provided regulation would not be as common. Since it may be possible that downward ramps in wind generation can lead to zero wind potential of a wind plant, the wind plant in this case would not be able to solve the problem that it caused. Depending on further analysis, it may be suitable to have a maximum percentage of the total regulation requirements to be served by wind generation or a maximum percentage of an individual wind plant's expected energy to be allowed to be set aside for regulation service. Using a centralized wind forecast and distributing regulation supply among multiple wind plants further reduces the risk of inadequate regulation from wind. Future analysis will likely be able to draw upon emerging methods that quantify the likelihood of wind variations to determine operating reserve constraints in systems with large wind penetrations [5].

IV. Separate vs. Combined Up and Down Regulation

A near-zero marginal energy-cost wind plant selling down regulation may appear on the surface to be more attractive than selling up regulation or a balanced up and down regulation product. The actual situation is more complex and involves both energy arbitrage (between the imbalance energy market and the wind plant energy sale) and regulation provision. The energy arbitrage question is outside the scope of this paper and we will attempt to separate it from regulation provision.

Fig. 13 shows a stylized 10-MW regulation requirement split into up regulation (reg-up) and down regulation (reg-down) products that the system operator can purchase separately in some regions and as a single product in others. A generator (or responsive load) may wish to sell up regulation capability, down regulation capability, or both to the system operator. Some systems (e.g., NYISO and ISONE) treat regulation as a single up and down service while others (e.g., CAISO and ERCOT) split up and down regulation into two separately priced products. Though it is important to keep the energy accounting correct, the question of when and if wind should provide regulation is basically the same under both systems. We will discuss separate up and down regulation first.

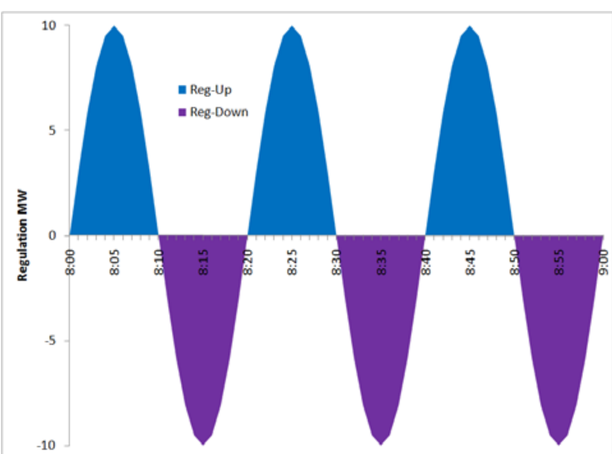

Fig. 13. The total regulation requirement can be split into up regulation (reg up and down regulation (reg down) components.

A 100-MW wind plant operating at 100 MW might offer to sell 10 MW of down regulation. If selected, it puts 10 MW of control on AGC, letting the system operator move the wind plant over the output range of 100 MW down to 90 MW. The wind plant gets paid the down regulation price for the hour. Accounting for the energy is a bit more complex.

The system operator will move the wind plant up and down (or more properly, down and up) throughout the hour, making use of the 10 MW of down regulation the system operator purchased. The amount of energy that the wind plant will generate is not known before the start of the hour. It could be as low as 90 MWh or as high as 100 MWh, but will likely be somewhere in the middle. The uncertain energy delivery will be settled through the imbalance energy market in one of two ways, depending on how the wind plant elects to sell the energy to its primary customer.

Presumably the wind plant was selling 100 MW of energy to a customer before the hour it started selling 10 MW of down regulation to the system operator. The wind plant could elect to reduce the energy sale to its customer to 90 MW, sell 10 MW of down regulation to the system operator, and sell the residual energy above the 90 MW to the imbalance energy market as shown in Fig. 14.

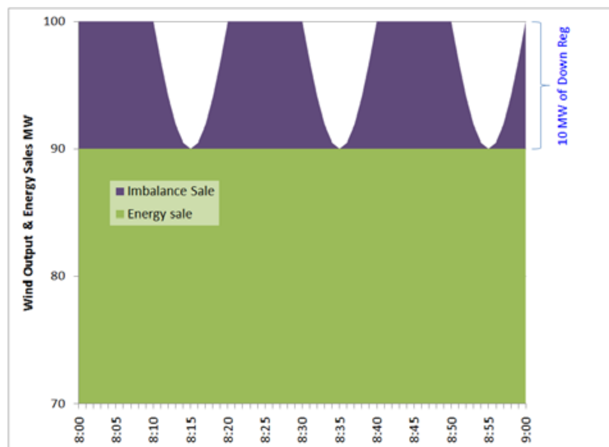

Fig. 14. Wind selling down regulation could under-sell to its customer and account for the residual energy in the imbalance energy market.

Alternatively, the wind plant could continue selling 100 MW of energy to its customer, sell 10 MW of down regulation to the system operator, and make up for failing to deliver the full 100 MWh to the customer by purchasing from the imbalance energy market as shown in Fig. 15.

Which alternative is best for the wind plant depends on the price difference between the imbalance market and what the customer is paying the wind plant for its energy. In a fully transparent market the energy prices will be equal, on average, making the two alternatives economically equal. It is also possible that the wind plant customer may not accept imbalance market energy as a substitute for wind energy if the customer values the environmental benefits of wind, though the customer may also recognize that wind providing regulation has environmental benefits when compared with thermal plants providing regulation.

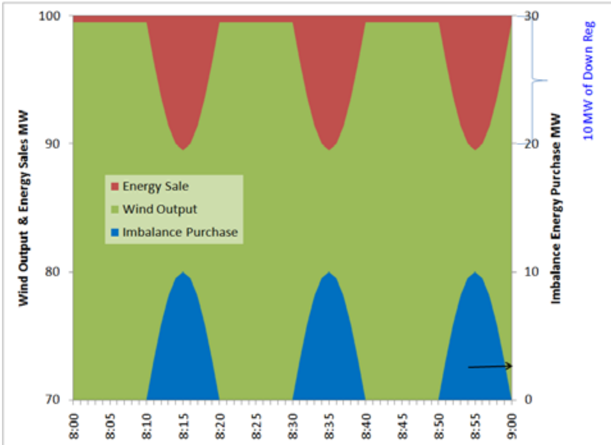

Fig. 15. Wind selling down regulation could over sell to its customer and replace the shortfall from the imbalance energy market (the wind output is reduced slightly in the figure to show the continuous 100 MW energy sale).

There is an analogous situation if the wind plant elects to sell up regulation. In this case the wind plant reduces output to 90 MW, puts 10 MW of control on AGC, and lets the system operator move the plant between 90 MW and 100 MW. As with selling down regulation, there are two ways the wind plant can transact in the energy market. The wind plant can sell 90 MW to its energy customer, 10 MW of up regulation to the system operator, and the excess energy that results from up regulation to the imbalance energy market, as shown in Fig. 16.

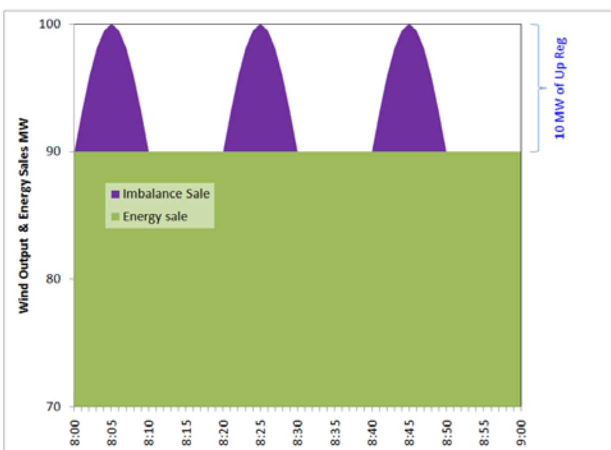

Fig. 16. The wind plant selling up regulation could under sell to its customer and account for the residual energy in the energy imbalance market.

Alternatively, the wind plant can sell the full 100 MW to the energy customer, 10 MW of up regulation to the system operator, and purchase the energy shortfall from the energy imbalance market, as shown in Fig. 17. As with down regulation, the best economic choice depends on the relative prices of the energy sale and imbalance energy, as well as the customer's willingness to accept imbalance energy in place of wind energy.

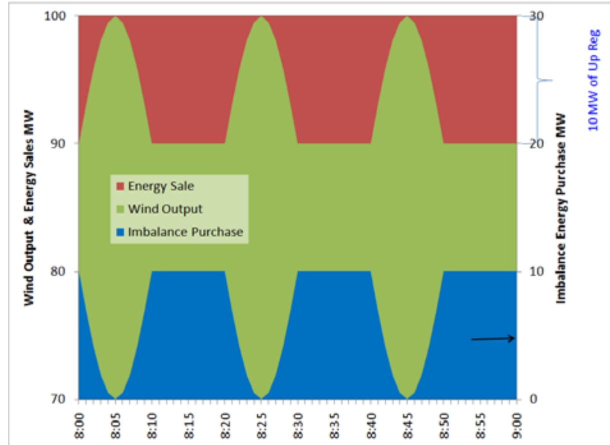

Fig. 17. As with down regulation, a wind plant selling down regulation could over sell to its customer and replace the shortfall from the imbalance energy market.

The wind plant has another alternative; it could sell both up and down regulation, as shown in Fig. 18. Here the wind plant sells 95 MW of energy to its customer along with 5 MW of up regulation and 5 MW of down regulation to the system operator. The system operator still controls 10 MW of wind plant output through AGC. The wind plant buys energy from the imbalance market when its hourly average energy output is below 95 MW and sells to the imbalance energy market when it averages over 95 MW. If the system operator balances its use of up and down regulation, then the imbalances net for the wind plant. The wind plant could elect to operate this way in a market with both up and down regulation, and is forced to operate this way in market areas with only a single regulation product.

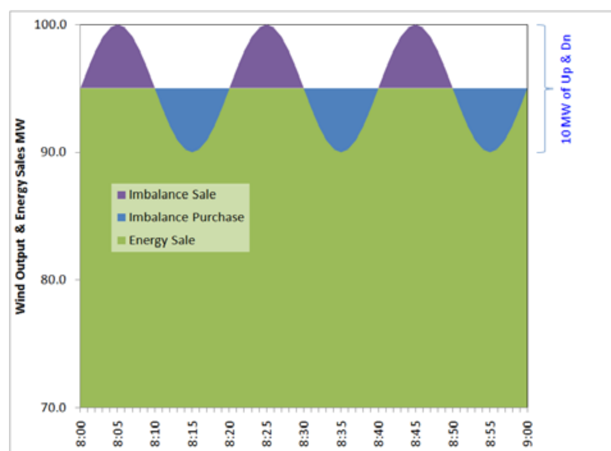

Fig. 18. A wind plant could sell both up and down regulation and net the imbalance purchases and sales.

A. Energy Arbitrage

As can be seen from the above discussion, the relative price in the imbalance energy market versus the energy price the wind plant receives from its customer appear to greatly influence which method of selling regulation is best. While this is true, it tends to mask the real question of if the wind plant should provide regulation at all. Presumably the wind plant could arbitrage these two prices without selling regulation. For example, a conventional generator with a bilateral contract would be incentivized to reduce its output through hour-ahead scheduling if the imbalance or spot energy price were below its own marginal production cost. It would supply its bilateral obligation from the spot market and profit from the price difference. Similarly, a conventional generator would sell any surplus capability into the spot market whenever the spot price was above its marginal production cost. With a near-zero marginal production cost, wind would seldom see an opportunity to profitably use the spot energy market as a substitute for its own production. To better study the question of wind plants providing regulation, we eliminate the arbitrage benefit by assuming either that the purchase and sale of imbalance energy is equal (balanced up and down regulation) or that the average price of imbalance energy is equal to the wind energy sale price.

V. Conclusions, Limitations, and Future Work

This preliminary analysis is meant to show some of the potential economic benefits for wind providing minute–to-minute regulation for systems with combined up and down regulation services and those with separated products. Further analysis on the physical capabilities is suggested to understand other benefits to system operations and additional economic benefits. The analysis assumes very aggressive maneuvering of wind plant control. The effects on wind turbine maintenance costs and plant life must be studied and incorporated to determine realistic limitations. The analysis has shown that there is a potential for wind plants to aid power system reliability and increase their own profits by providing regulation. The issues appear to warrant further study.

The issue of wind energy forecast error must be addressed further as well. Regulation is typically scheduled while making the day-ahead unit commitment. In some areas, economic dispatch programs run every five minutes and the regulation schedules are co-optimized with those of energy. Either a very good wind energy forecast is required to enable scheduling of wind plants to provide regulation day-ahead or selecting regulation from all resources would need to be done much closer to the operating interval for wind to effectively supply regulation. By making the regulation selection decision closer to real-time, the wind energy forecasts used to predict the wind energy potential and then designate a portion of wind output for regulation would be much more accurate.

Both Production Tax Credits (PTCs) and Renewable Portfolio Standards (RPSs) complicate the analysis. By valuing renewable energy, these incentives effectively create a negative marginal production cost and increase the opportunity cost for renewables providing regulation. Conventional generators typically incur an efficiency penalty when they provide regulation, however, and the minimum load restriction also increases emissions when thermal plants provide regulation at times of low net system load. Providing regulation also requires conventional generator capacity. After studying the emissions and capacity benefits, it may be appropriate to credit renewable generation in both the PTC and RPS for providing regulation.

We have focused on wind energy because it is available at night and we assume that regulation prices would exceed energy prices mostly at night, as evidenced by Fig. 2 and Fig. 3. While this is largely true, there were still 814 hours between 9:00 and 17:00 when the price of regulation exceeded the price of energy in West Texas in 2008. That is 25% of the total excess hours in 38% of the time, though the excess regulation average price was also higher at night. Still, it may be worth investigating provision of regulation from solar.

Lastly, the quality of regulation from wind (and solar) will likely be greater than from thermal units. Both use electronic conversion which provides extremely fast and accurate control. Pitching of wind blades is also faster and more accurate than turbine fuel and steam control in thermal plants. A higher price may be justified for regulation from more accurate sources and several ISOs are developing tariffs which pay a premium for accurate regulation [6].

VI. References

[1] B. Kirby, 2004, Frequency Regulation Basics and Trends, ORNL/TM 2004/291, Oak Ridge National Laboratory, December.

[2] B. Kirby, M. Milligan, 2009, Capacity Requirements to Support Inter-Balancing Area Wind Delivery, NREL/TP-550-46274.

[3] B. Kirby and E. Hirst, 2000, Customer-Specific Metrics for The Regulation and Load-Following Ancillary Services, ORNL/CON-474, Oak Ridge National Laboratory, Oak Ridge TN.

[4] M. Cardinal and N. Miller, 2006, Grid Friendly Wind Farm Controls, WindPower.

[5] GE Energy, 2010, Western Wind and Solar Integration Study. Available at www.nrel.gov.

[6] Transcript: Technical conference to provide guidance on issues pertaining to Frequency Regulation Compensation in the ISO/RTO Markets (AD10-11-100). Federal Energy Regulatory Commission. May 26, 2010, Washington, DC. Available: http://www.ferc.gov/EventCalendar/Files/20100607104253-Transcript.pdf

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* October 2010	**2. REPORT TYPE** Conference Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Providing Minute-to-Minute Regulation from Wind Plants: Preprint

5a. CONTRACT NUMBER
DE-AC36-08GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
B. Kirby, M. Milligan, and E. Ela

5d. PROJECT NUMBER
NREL/CP-5500-48971

5e. TASK NUMBER
WE10.4231

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-5500-48971

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
In this paper, we extend the previous analysis using time series data from existing wind plants, system loads, and regulation and energy markets.

15. SUBJECT TERMS
operating reserves; power system economics; power system operations; power system reliability; power systems; wind power generation; wind energy.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18