The Cost of Curtailing Wind Turbines for Frequency Regulation and Ramp-Rate Limitation

Stephen Rose and Jay Apt

Carnegie Mellon Electricity Industry Center
Department of Engineering and Public Policy and Tepper School of Business
Carnegie Mellon University

Corresponding Author:

Stephen Rose
Ph.D. Student
Carnegie Mellon University, Department of Engineering and Public Policy

Baker Hall 129
5000 Forbes Avenue
Pittsburgh, PA 15213

srose@cmu.edu
+1 412-719-6537

Abstract

We analyze the cost of controlling a wind farm to comply with a power ramp rate limit of 0.1 p.u. per minute and the cost of curtailing wind farm power output to supply primary frequency regulation capacity. The analyses use simulation data from a dynamic wind farm model fed by wind speed data that is a hybrid of empirical and synthetic wind speed measurements. The cost of limiting all power increases and decreases to 0.1 p.u./minute power ramp rate is the loss of 18% of energy production. However, only power *increases* can be limited to 0.1 p.u./min (the typical structure of current grid code requirements for wind turbines) for a cost of 1.4% of energy production. A wind farm can provide grid frequency up-regulation capacity at a cost of 1.2 – 1.5 MWh lost per MW-h of capacity supplied by curtailing power output, but the cost per unit of regulation capacity is very high for the first ~ 0.05 p.u. of curtailment. If a wind farm must be curtailed for frequency regulation capacity, it is more efficient to curtail a few turbines deeply than to equally curtail all the turbines by a small amount.

1. Introduction

When large numbers of wind turbines are connected to the electrical grid, the rapid variability of wind power on short time scales can cause the grid frequency to deviate significantly from its nominal value. [**1**,**2**] In the many regions where pumped hydroelectric storage is not available, the grid frequency is typically regulated by adjusting the power output of fast-ramping gas turbines. Gas turbines can be expensive to operate and produce power less efficiently and with higher levels of NOx emissions when quickly varying their power output. [**3**]Other technologies are capable of compensating for the short-term variability of wind power, but they are either currently too expensive to be practical or cannot be scaled large enough to meet the rapidly-increasing penetration of wind power on the electrical power grid. Batteries and flywheels are technically well-suited to rapidly generating or absorbing power but commercially available units are too expensive on the scale needed for the penetrations of wind power expected in the next 10 – 20 years, although some promising systems are in the development phase. Hydroelectric power, and especially pumped hydro storage, is technically well-suited to rapidly changing power output and is relatively inexpensive. However, little new pumped hydro storage is being developed.

Denmark, Ireland, Great Britain, and Germany now include requirements in their national grid codes that wind farms limit the rate of increase or decrease in power output and be able to increase or decrease their power output to aid in regulating the grid frequency. [**4**,**5**,**6**,**7**] The power output of a wind farm can be decreased by dynamically reducing the aerodynamic efficiency of the wind turbines or completely shutting down some turbines, but it is impossible to increase the output of a wind farm beyond the power level provided by the current wind velocity. Operating a wind farm at less than the currently available wind capacity ("curtailing") creates a reserve of energy that allows power output to be increased on demand. Prior research has demonstrated the technical feasibility of curtailing the power output of a wind farm to regulate the grid frequency. [**8**,**9**,**10**,**5**] Other research has demonstrated the feasibility of curtailing a wind farm to reduce the variation in power output. [**11**,**12**] However, the revenue lost due to curtailment may be greater than the cost of procuring the same primary frequency regulation from traditional sources such as gas turbines or hydroelectric power plants, or using an energy storage technology such as a battery to store a reserve of energy. [**9**,**10**]

Here we assess the cost of complying with a hypothetical ramp rate limit of 0.1 p.u. per minute, averaged over 1 minute. We enforce our hypothetical ramp rate limit for all operating conditions, including falling wind speed. No grid code yet imposes a strict ramp rate limit for all conditions, but we expect that grid operators will impose similarly strict limits in the future as the penetration of wind power increases. The grid code of Ireland is currently the strictest but it does not yet limit the rate of power decrease caused by falling wind speed. [**7**] We choose a ramp rate limit of 0.1 p.u. per minute because most grid codes that do impose a power ramp rate limit on wind farms choose that value. [**4**,**13**]

We also assess the cost of curtailing wind power to provide frequency regulation service. Previous research investigated the level of curtailment required to achieve given levels of power smoothing. [**14**] We perform an engineering-economic analysis to compare the cost of curtailing a wind farm for frequency regulation to competitive market prices. We recommend the conditions that justify using the frequency-control capabilities specified for wind turbines by many countries' grid codes. The advantage of implementing frequency regulation by curtailing a wind farm, rather than using energy storage, is that controlled curtailment can be implemented quickly in existing wind farms with technology available today at a small fraction of the capital cost of storage.

2. Experimental Procedure

We use a simulation of a large wind farm driven by a hybrid of empirical and hybrid wind speed data to calculate the costs of controlling power ramp rates and providing regulation capacity. The wind farm model simulates only real power output; we assume that the wind farm is connected to a strong grid and that reactive power is not a problem.

The wind farm simulated in these experiments consists of 2 MW turbines arranged in a grid of 7 East-West rows and 7 North-South columns, for a total of 49 turbines and a maximum output of 98 MW. Turbines are spaced 10 rotor diameters apart. We assume the terrain is flat and uniform. In these simulations a wind farm control system controls the aggregate power output of the wind farm by sending power setpoints to each turbine in the wind farm. [**15**] The control system receives estimates of available power from each turbine and sends power setpoints to each turbine proportional to their available power. Individual turbines cannot be curtailed below 0.2 p.u., though the power output of a turbine can fall below 0.2 p.u. when the wind speed is low.

Each turbine in the wind farm is a separate dynamic simulation, which is an improvement over previous studies that used steady-state turbine models or aggregate farm models. [**16**,**17**,**18**] The turbines are pitch-regulated, variable speed turbine with an 80 m rotor, modeled using the Wind Turbine Blockset, v3.0 developed by Aalborg University. [**19**] To increase the simulation speed, the turbines use a lossless first-order generator model. [**20**] This choice of generator model is justified because the analysis in this paper is only concerned with real power output at time scales slower than one second. The turbine design parameters, control scheme, and control parameters are those recommended by the Risø National Laboratory in Denmark. [**20**]

The wind farm is driven by wind speed data that are a hybrid of empirical and simulated wind speed data. Hybrid wind speed time series are created by combining low-frequency wind speed measurements with high-frequency simulated wind turbulence that "fills in" the fast fluctuations not captured by the measured data. [**21**] The high-frequency turbulence is described by the Kaimal spectral model recommended by the IEC wind turbine design standard. [**22**]The wind speed time series for an individual wind turbine is calculated by shifting the low-frequency data according to the mean wind speed and the distance from the first upwind turbine, and simulating high-frequency turbulence using a standard coherence model. [**17**]

The long-term wind speed variation of each day are empirical wind speeds from a measurement mast at a wind farm site in west Texas, USA; 15 days are sampled randomly from each season (spring, summer, autumn, winter) in the period between April 2007 and September 2009 for a total of 60 days. The empirical data selected for the simulation have a mean wind speed of 7.1 m/s and a turbulence intensity of 13% (defined as the 10-minutes standard deviation divided by mean). The wind direction is fixed at 0º (North). These wind speed characteristics result in a capacity factor of 33% for the wind farm when it operates without any ramp rate limits or curtailment.

For the experiments described here, we generated hybrid wind speed data sampled at 1 Hz for each of the selected 60 days. We generated separate time series for each turbine in the wind farm using the coherence model given by Sørensen. [**17**] These generated wind speed time series are used to simulate the wind farm for all of the experiments described below. This is the advantage of conducting these experiments in simulation—the results of the simulations can be directly compared because the wind input is the same for each experiment and only the wind farm control parameters change.

2.1. Simulation Experiments

We conduct experiments by driving the wind farm model with wind speed data described above and varying two wind farm control parameters that the Danish grid code specifies the grid operator must be able to control: the delta curtailment level δ and the ramp rate limit on the power setpoint λ_{max}. [22] The delta curtailment sets the desired reduction in wind farm power output below the output possible at current wind conditions, and the ramp rate limit is the maximum rate of change of the power setpoint sent by the wind farm controller to the turbines it controls. Each experiment simulates the wind farm operating in identical wind conditions, but with a unique combination of δ and λ_{max} values. The experimental scenarios are summarized in Table 1.

Table 1: Experimental scenarios are different combinations of ramp rate limits (λ_{max}) and curtailment (δ). The Reference scenario (A) is the normal operation of the wind farm without any constraints.

Name	Ramp Rate Limit λ_{max}	Curtailment δ
(A) Reference	∞	0
(B) Ramp-Up Only	0.1 p.u./min, up only	0
(C) Strict Ramp Rate Limit	0.1 p.u./min, up and down	0.01 – 0.3 p.u.
(D) Regulation Capacity	∞	0.01 – 0.3 p.u.

2.2. Ramp Rate Limit Simulations

The experiments to calculate the cost of reducing violations of the power ramp rate limit λ_{max} compare the results of the Reference (A), Ramp-Up Only (B), and Strict Ramp Rate Limit (C) scenarios described in Table 1. Reference (A) scenario is the normal operation of the wind farm with no power ramp rate restriction and no curtailment. The Ramp-Up Only (B) scenario limits the rate of increase of the wind farm power λ_{+} to 0.1 p.u./min by adjusting the turbine blade pitch angles, but it cannot limit the rate of power decrease λ_{-} when the wind speed decreases because there is no reserve of power. The Strict Ramp Rate Limit (C) scenarios limit both the rate of power increase and decrease by curtailing the power output to create a reserve of power that can be used when the wind speed decreases, as described in Appendix A1.

We run a separate set of simulations for each level of curtailment δ between 0.01 p.u. and 0.10 p.u. in increments of 0.01 p.u., and for each level of curtailment δ between 0.10 p.u. and 0.30 p.u. in increments of 0.02 p.u. For a given set of simulations, the curtailment level δ is constant and always active.

2.3. Primary Regulation Capacity Simulations

The experiments to calculate the cost of creating primary frequency regulation capacity compare the results of the Reference (A) and Regulation Capacity (D) scenarios described in Table 1. Reference (A) scenario is the normal operation of the wind farm with no power ramp rate restriction and no curtailment. The Regulation Capacity (D) curtails the power output of the wind farm by adjusting the turbine blade pitch angles to create a reserve of power as described in Appendix A1; i.e. the wind farm is always producing less power than is possible for the given wind conditions.

We run a separate set of simulations for each level of curtailment δ between 0.01 p.u. and 0.10 p.u. in increments of 0.01 p.u., and for each level of curtailment δ between 0.10 p.u. and 0.30 p.u. in increments of 0.02 p.u. For a given set of simulations, the optimum curtailment level $\delta(k)$ for the kth hour is chosen independently to give the lowest cost per MW of capacity for that hour, assuming that the optimum level of curtailment can be know in advance. It is realistic to change the level of curtailment $\delta(k)$ each hour because regulation capacity is typically bid into markets in 1-hour intervals. The assumption that the optimum curtailment δ can be known in advance is not realistic, but it provides the best-case cost of curtailing a wind farm to create primary regulation capacity.

3. Analysis

3.1. Cost of Complying with a Strict 0.1 p.u./min Ramp Rate Limit

We calculate the cost of reducing ramp rate violations by retrospectively analyzing the wind farm simulations described in Section 2.2. We define the 1-minute ramp rate in the kth minute $\lambda(k)$ as the difference between the mean power during one minute and the mean power during the previous minute, where I_{ramp} = 1 minute. [**16**]

$$\lambda(k) = \frac{\mathrm{P}_{1\text{-min}}(k) - P_{1-\mathrm{min}}(k-1)}{\mathrm{I}_{\mathrm{ramp}}} \qquad \text{(eq. 1)}$$

The level of ramp-rate limit violations v is the number of 1-minute intervals in which a ramp rate limit is violated, divided by the total number of 1-minute intervals in the 60 days of simulation K_{ramp}:

$$v = \frac{\sum_k \left(1 \mid \lambda(k) > \lambda_{\max}\right)}{K_{ramp}} \qquad \text{(eq. 2)}$$

The cost of complying with the ramp-rate limit is the quantity of energy lost when the wind farm is does not increase power output as fast as the available wind is increasing or lost when the power output is curtailed. We express the cost $E_{loss,frac}$ as a fraction of the energy that could have been produced if the turbine were not limited:

$$E_{loss,frac} = \frac{\sum_k \left(P_{poss,1-min} - P_{1-min}\right)\cdot I_{ramp}}{\sum_k P_{1-min}\cdot I_{ramp}} \qquad \text{(eq. 3)}$$

For each level of curtailment, we calculate the cost $E_{loss,frac}$ and the level of ramp rate violations v.

3.2. Cost of Providing Primary Frequency Regulation Capacity

Primary frequency regulation capacity is the ability of a generator to increase or decrease its power output on demand to regulate the grid frequency. We calculate the cost of providing "up-regulation" capacity C_{Up}, which is the ability to increase power output on demand. This is difficult for wind turbines because a wind turbine cannot simply add more fuel the way a conventional generator can. The power output of a wind turbine can be curtailed to create a reserve of power that can be dispatched, but the curtailment will reduce the amount of energy, and thus the revenue, that the turbine produces.

We calculate the up-regulation capacity that the wind farm can provide by retrospectively analyzing the wind farm simulations described in Section 2.3. The up-regulation capacity $C_{Up}(k)$ that a wind farm can supply for the kth time interval of length I_{reg} is the smallest difference between possible power and actual power in that interval $I(k)$:

$$C_{Up}(k) = \min\left(P_{poss}(t) - P(t)\right) \quad \forall t \in I_{reg}(k) \qquad \text{(eq. 4)}$$

We set the time interval for regulation I_{reg} to 1 hour to correspond with the bidding period for primary frequency regulation capacity in the ERCOT (Texas) market.

Up-regulation capacity $C_{Up}(k)$ is always less than or equal to the delta curtailment $\delta(k)$, and the difference between delta curtailment and regulation capacity increases with greater wind speed variability and more restrictive ramp-rate setpoints. We do not consider down-regulation capacity here because it is essentially costless to provide down-regulation capacity.

These calculations of up-regulation capacity assume perfect foresight: the wind farm owner/operator knows in advance exactly how much regulation capacity the wind farm can provide for each interval. Perfect foresight is an unrealistic assumption, but the purpose of these calculations is to determine whether regulation capacity from a curtailed wind farm can be cost-competitive with regulation capacity from other technologies such as gas turbines under any circumstances. A more realistic assumption would allow the wind farm to provide only some fraction of the maximum possible regulation capacity for a given level of delta curtailment. In that case, the cost of regulation capacity would increase inversely proportional to the fraction of regulation capacity the wind farm is allowed to provide.

The up-regulation capacity $C_{Up}(k)$ created for each 1-hour period k and each level of curtailment δ is grouped with the results from the other 1-hour periods into bins by regulation capacity range. If two different levels of curtailment give regulation capacities that fall into the same bin, only the lower capacity is used because regulation capacity can only be bid into the market in integer multiples of 1 MW.

We calculate the cost of providing up-regulation capacity by retrospectively analyzing the wind farm simulations described in Section 2.2. The per-MW cost of providing regulation capacity $R_{Up}(k)$ for a time interval k is the energy generation lost in that interval due to curtailment and ramp rate limitations $E_{loss}(k)$ divided by the quantity of up-regulation capacity provided during that interval $C_{Up}(k)$:

$$R_{Up}(k) = \frac{E_{loss}(k)}{C_{Up}(k)} \qquad \text{(eq. 5)}$$

The cost of providing down-regulation capacity is zero because the turbine is not curtailed in order to provide that capacity.

Here we define energy loss as an absolute quantity of energy, in megawatts, instead of defining it as a fraction of possible energy generation as we did in eq. 3. The energy loss $E_{loss}(k)$ in the kth interval of length I_{reg} is the integral of the power lost at each instant during that interval. Power lost is the difference between possible power (from the unconstrained wind farm) and power actually produced.

$$E_{loss}(k) = \int_0^{T_{reg}} \left(P_{poss}(t) - P(t) \right) dt \qquad \text{(eq. 6)}$$

4. Results

4.1. Ramp Rate Limits

The duration curve for the 1-minute ramp rate of the reference simulation in Figure 1 shows that the wind farm power very rarely exceeds the 0.1 p.u./min ramp rate limit for the wind conditions we modeled. The reference wind farm exceeds the 0.1 p.u./min limit ramp rate limit only 0.03% of the period simulated.

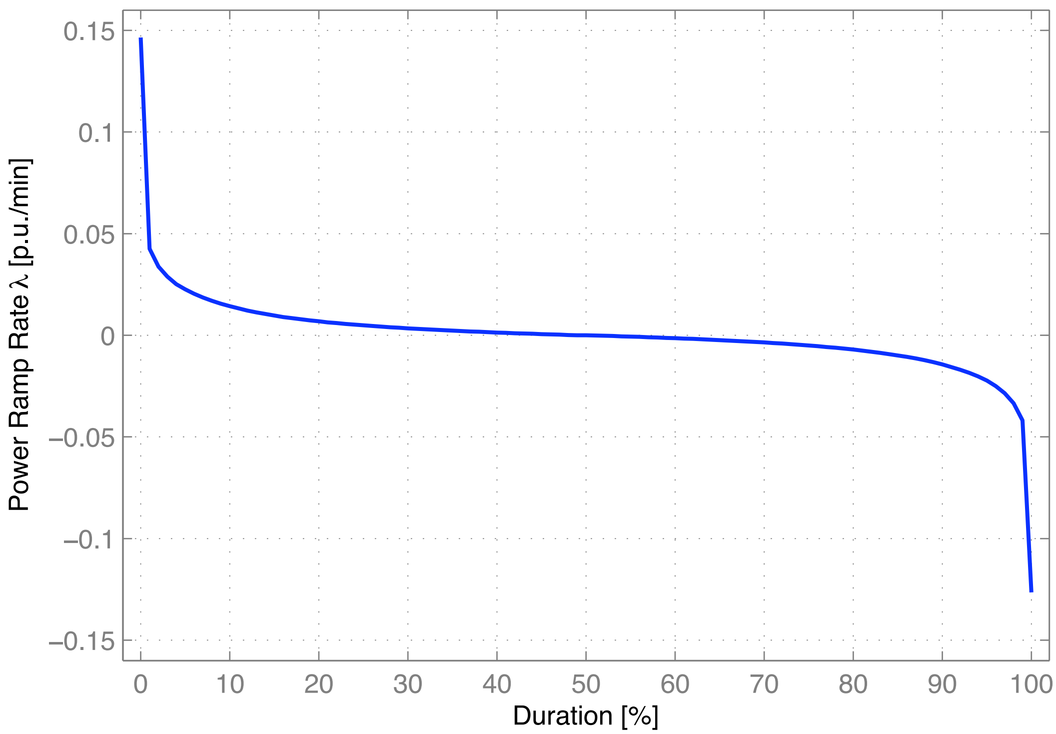

Figure 1: Duration curve for the power ramp rate of the unconstrained wind farm in normal operation. The win farm exceeds the 0.1 p.u./min ramp rate limit very rarely both for power increases and decreases. Future work will examine the cost setting a much more restrictive limit on the power ramp rate, such as 0.05 p.u./min.

More than half of the ramp rate limit violations are increases in power, and they can be eliminated by controlling the blade pitch of the wind turbines to limit their rate of power increase to 0.1 p.u./min. That control strategy reduces violations of the ramp rate limit to 0.009% at a cost of 1.4% of the energy that could have been produced during that period.

The remaining violations of the ramp rate limit, all of them power decreases, can be eliminated by curtailing the wind farm to create a reserve of power that can be used to slow the decrease of power when the wind speed decreases. However, this strategy wastes significantly more energy than limiting the rate of power increase. Figure 2 shows that the cost $E_{loss,frac}$, in terms of energy generation lost, increases sharply for ramp rate violation levels below 0.009%, where curtailment must be introduced. All violations of the ramp rate limit can be eliminated by constantly curtailing the wind farm by 0.12 p.u., at cost of 18% of the energy that could have been produced during that period.

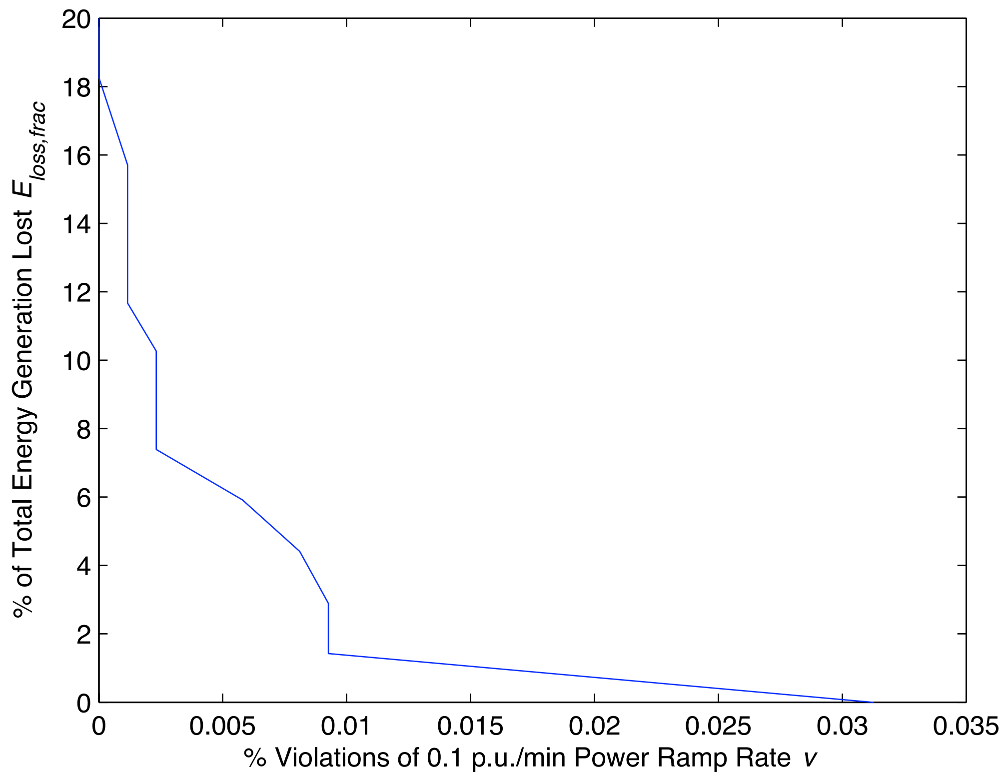

Figure 2: Large amounts of energy must be lost to reduce ramp-rate limit violations to levels near zero. At 0.009%, all ramp-up limit violations have been eliminated, leaving only ramp-down violations that require curtailment to prevent.. Cost is the percent of total energy generation wasted in order to prevent violations of the ramp rate limit. Each point represents a constant level of curtailment (0 – 0.3 p.u.).

The cost of reducing the ramp rate limit violations can be significantly reduced by forecasting future power ramps and curtailing the turbine appropriately. The power decreases that exceed the limit occur only 0.009% of the simulated period, so it is inefficient to constantly curtail the wind farm the we did for this simulation. Even less energy could be wasted if the curtailment is limited to periods when the electrical grid was most sensitive to fast power ramps.

4.2. Frequency Regulation

The per-unit cost and marginal cost of providing frequency up-regulation capacity are plotted in Figure 3 and Figure 4, respectively. We do not show results for frequency down-regulation because the cost of down-regulation capacity is nearly zero. We do not calculate the *energy* produced or not produced when regulation capacity is dispatched to regulate frequency.

Figure 3 plots the statistical distribution of per-unit costs $\frac{E_{loss}(k)}{C_{Up}(k)}$ to achieve the same regulation capacity in different 1-hour periods. Each data point (summarized by the box plots) represents the minimum level of curtailment δ needed to achieve a specific up-regulation capacity $C_{Up}(k)$ for a given 1-hour period. The median per-unit costs of up-regulation capacity are 1.2– 1.5 MWh/MW-h, with the median and range decreasing as the capacity increases.

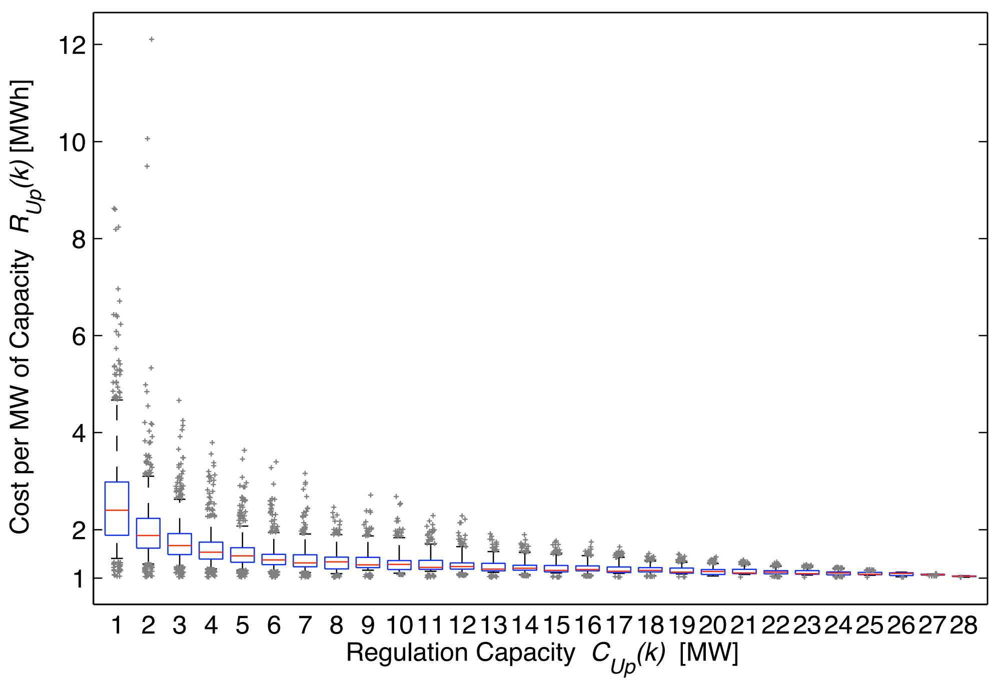

Figure 3: The per-unit cost of up-regulation capacity is measured in MWh of energy lost per MW of up-regulation capacity provided. Each box shows the distribution of the lowest per-unit costs of up-regulation capacity for the regulation capacities that fall into that interval. In the box plots above, the center mark is the median, the lower and upper limits of the filled box are the 25th and 75th percentile values, the ends of the "whiskers" are the 5th and 95th percentile values, and open circles show any outliers beyond the whiskers.

The per-unit cost and range of per-unit costs decreases as the regulation capacity increases because the first MW of capacity is much more expensive than the rest. Figure 3 shows that the cost of the first MW of capacity is far more than additional MWs of capacity. The supply curve in Figure 4 supports this conclusion—it shows that the marginal cost to add an additional MW of regulation capacity is nearly constant across the entire range of regulation capacity.

We believe the variations in per-unit cost in Figure 3 are the result of different wind conditions that affect how much up-regulation capacity $C_{Up}(k)$ can be produced for a given delta curtailment δ. When the variations in wind power are the same size or greater than the delta curtailment, the available up-regulation $C_{Up}(k)$ becomes very small relative to the curtailment δ to create it, which causes the sharp increase in per-unit cost.

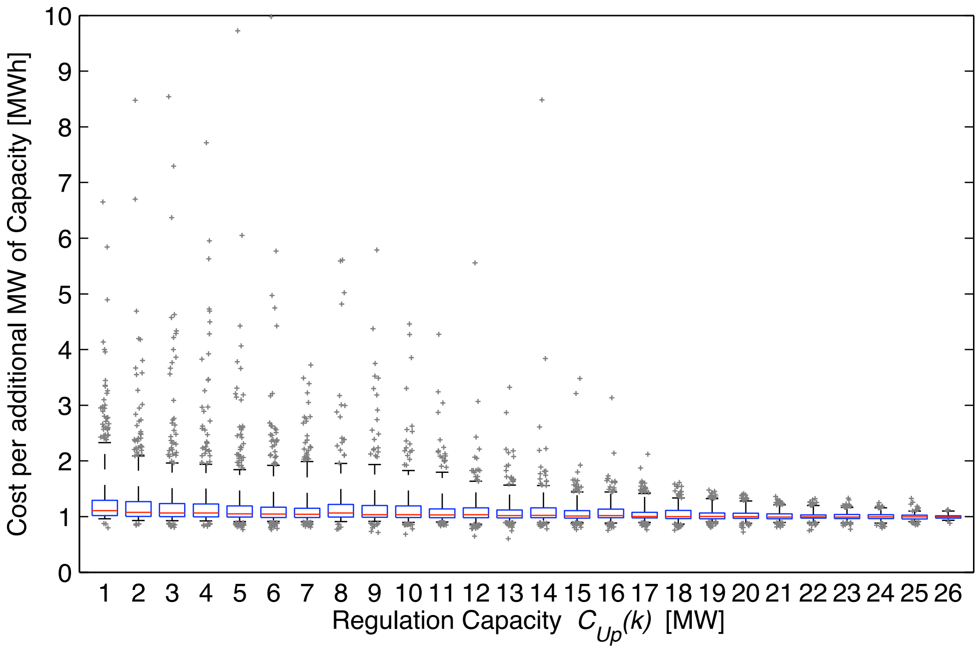

Figure 4: The supply curve above gives the marginal energy lost to provide an additional MW of regulation capacity for 1 hour. The marginal cost of increasing up-regulation capacity is approximately constant across all levels of capacity. In the box plots above, the center mark is the median, the lower and upper limits of the filled box are the 25th and 75th percentile values, the ends of the "whiskers" are the 5th and 95th percentile values, and open circles show any outliers beyond the whiskers.

The supply curve for regulation capacity in Figure 4 plots the marginal cost of adding an additional MW of up-regulation capacity to the curtailment levels with the lowest per-unit costs plotted in Figure 3. The marginal costs are nearly constant at 1.1 – 1.2 MWh/MW-h across the entire range of capacities we considered. This demonstrates that the first MW of capacity is the most expensive and the cost of that first MW affects the average cost even at higher regulation capacities.

Figure 3 does not explicitly put a monetary value on the cost of providing frequency up-regulation capacity because wind farms sell their power at different prices. We assume that a wind farm owner would sell up-regulation capacity for at least the opportunity cost of the energy not produced.

Several factors put wind farms at a disadvantage in a competitive market for regulation capacity. First, the opportunity cost of unproduced energy is increased by the structure of government subsidies for wind energy. Wind power producers are typically subsidized based on production, so a producers loses both the revenue and the subsidy for the curtailed power output. Second, conventional generators have lower opportunity costs for unproduced energy because their loss of revenue is partially offset by fuel savings. Wind turbines have no fuel to speak of, so they receive no offsetting savings for curtailment.

These calculations neglect the revenue that a wind farm receives when some of its up-regulation capacity is dispatched to help regulate the grid frequency. The occasional dispatch of some of the available capacity reduces the opportunity cost because a wind farm is not always curtailed to its full extent. The dispatch should be taken into account when calculating the monetary cost of curtailing a wind farm to provide primary frequency regulation.

5. Policy Implications

5.1. Ramp rate

Limiting the ramp rate of wind farm power output to a maximum of 0.1 p.u./minute is achieved at a cost of 18% of energy production in the wind conditions used in this simulation. However, the energy lost when implementing this ramp-rate limit in a real wind farm is likely to be significantly higher because these experiments assume that the wind farm operator has perfect knowledge of future wind conditions in order to pick the optimum curtailment level.

Given these costs, wind farm owners will be severely affected by grid connection rules that impose a strict 0.1 p.u./min ramp-rate limit on both power increases and decreases. However, wind farm owners will be affected much less if only the rate of power *increases* is limited, which is typical of the rules imposed by grid codes at this writing. We showed in Figure 2 that the majority of the cost results from eliminating power *decreases* that violate the limit. The owner of the wind farm considered here would lose 1.4% of energy production to comply with a 0.1 p.u./min limit on power increases, but would lose 18% of his energy production to comply with a limit on power increases *and* decreases of the same magnitude . The effect on wind farm owners can also be significantly reduced by limiting ramp rates only when the grid is most sensitive to ramp changes in generation, such as overnight periods when wind power penetration is high and many of the gas turbines that provide primary regulation are offline.

The structure of wind power production subsidies (such as the production tax credit in the U.S.) increase the monetary cost of limiting the power ramp rate because they increase the monetary opportunity cost of lost energy. The monetary loss to wind farm owners could be reduced by paying them the subsidy for energy that *could have been* provided as well as the energy actually provided. Some grid operators already do this to compensate wind farms for forced curtailment, and many governments have long experience paying farmers to reduce their agricultural output. However, this depends on what value society receives for subsidizing these actions. Electricity prices may decrease if limiting wind power ramp-rates allows slower-ramping, less-expensive generators to be dispatched and NOx emissions may be reduced if gas turbines are able to ramp more slowly [**3**], but further work is needed to quantify the effect of wind power ramp rates on ramp rates of the entire grid.

5.2. Frequency regulation

Frequency up-regulation provided by curtailed wind farms is not likely to be competitive with up-regulation from gas turbines because of the cost structure and subsidy structure of wind power. The lack of fuel savings when curtailing a wind turbine and the loss of production subsidies makes curtailment expensive. It may be worthwhile to regularly curtail wind farms for frequency regulation in electrical grids where fast-ramping conventional generators are very expensive such as Hawaii, which depends heavily on diesel generators.

If it is necessary to curtail a wind farm to provide frequency up-regulation, the way the curtailment is implemented can have a large effect on its cost effectiveness. We find that low levels of curtailment are very inefficient and result in a very high cost of up-regulation capacity. It is much more efficient to deeply curtail one wind farm to carry the burden of others than to curtail all the farms equally, or to deeply curtail a few individual turbines to carry the regulation burden of an entire wind farm. For example, the German grid code requires that wind farms larger than 100 MW must be able to increase or decrease power output by 2% of maximum rated power and sustain that level for 15 minutes. [**5**] If this requirement is implemented by curtailing every turbine in the farm equally, the actual reduction in power will be highly variable and often much less than the intended 2%. Curtailing a few turbines deeply would reduce the variability of the power reduction and result in a decrease of power output closer to the desired 2%.

Curtailing a wind farm to provide frequency up-regulation is most likely to be useful for emergency situations. Curtailing a wind farm has a high operating cost, the opportunity cost of unproduced energy, but almost no capital cost. From the perspective of the grid operator, requiring this capability from wind farms creates an emergency source of frequency regulation that may become more useful as wind power penetration increases. From the standpoint of a wind farm owner, installing the capability to regulate frequency is virtually costless; it is only expensive to use it.

6. Conclusion

Curtailing wind turbines to limit their power ramp rate and to provide primary frequency up-regulation capacity is not cost-effective in most cases. Limiting the rate of both power increase and decrease to 0.1 p.u./min for a large wind farm requires a curtailment of 0.12 p.u. and a loss of 18% of total energy production. Curtailing a wind farm to provide up-regulation capacity costs an average of 1.2 – 1.5 MWh of energy lost for each MW-h of capacity provided. Given the cost of wind energy and the structure of production subsidies for wind turbines, the regulation capacity provided by a wind farm will rarely be cost-competitive with regulation capacity from gas turbines.

Limiting only the rate of power increase of a wind farm is much more cost-effective than limiting the rate of both power increase and decrease. The rate of power increase can be limited to 0.1 p.u./min at a cost of only 1.4% of total energy production. If it is necessary to also limit the rate of power decreases, the cost could be significantly reduced by only curtailing the wind farm during periods when large power decreases are forecast and when the grid is most sensitive to fast changes in power generation.

Curtailing wind farms to provide frequency regulation is best used as an emergency measure. Using wind farm curtailment for regulation capacity is well suited to emergencies because most many wind farms can be modified to regulate frequency with virtually no capital cost. Most modern wind farms require only some additional control software to be able to regulate frequency. Grid operators can require wind farms to have this capability without imposing large costs on the wind farm owners, Grid operators can then curtail some wind farms for regulation capacity during periods when the supply of regulation capacity is insufficient. When a wind farm is curtailed to provide frequency regulation, it is much more efficient to deeply curtail a few turbines than to spread the curtailment equally over all turbines in the farm.

Acknowledgments

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A1. Control of the Wind Farm

Two wind farm control parameters, defined in the Danish Grid Code are varied in these simulations: the "delta curtailment setpoint" δ and "ramp-rate setpoint" λ. [22] The delta curtailment setpoint sets the desired reduction in wind farm power output below the possible power output. The ramp-rate setpoint sets the magnitude of the desired maximum rate of change of the wind farm power output; the sign is understood to be negative for decreasing power output and positive for increasing power output.

Figure 5 illustrates the operation of a wind farm with delta curtailment and ramp rate control, with specific examples labeled by letters. Ramp rate control limits the rate of increase (A) and decrease (B) of power setpoint of each turbine, and delta curtailment limits the power output of the entire wind farm to a fixed amount below the power possible at any given moment (C). When the delta curtailment and the ramp rate limit conflict, the ramp rate limit has higher priority. Point (D) shows the system violating the delta curtailment limit in order to enforce the ramp rate limit. If the power decreases too rapidly, the reserve of power created by the delta curtailment will fall to zero and the ramp rate limit will also be violated (E).

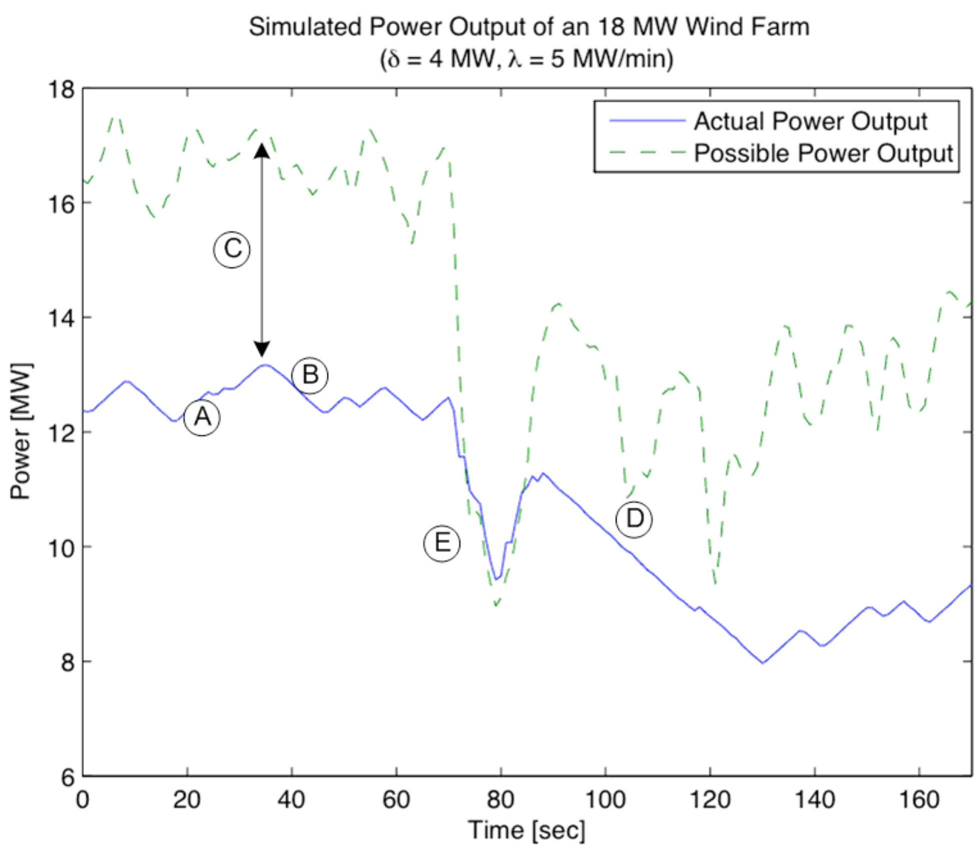

Figure 5: Demonstration of how the actual wind farm power output is influenced by ramp-up rate limit (A) and ramp-down rate limit (B) and delta curtailment (C). At point (D) the delta curtailment is violated in order to enforce the ramp-rate limit. At point (E) the possible power decreases too fast (due to a lull in the wind) to be absorbed by the delta curtailment, and so the ramp rate limit is violated.

A2. Nomenclature

$C_{Down}(k)$	Capacity available to decrease power for frequency regulation during the kth interval [MW-h]
$C_{Up}(k)$	Capacity available to increase power for frequency regulation during the kth interval [MW]
$E_{Loss}(k)$	Energy lost in the kth interval [MWh]
$E_{loss,frac}$	Energy lost as a fraction of possible energy production
I_{ramp}	Duration of ramp rate time interval [sec]
I_{reg}	Duration of frequency regulation time intervals [sec]
k	Index of time intervals
K_{ramp}	Total number of ramp intervals of length I_{ramp} in the simulated period
K_{reg}	Total number of freq. regulation intervals of length I_{reg} in the simulated period
$P(t)$	Instantaneous real power output of the wind farm [MW]
$P_{poss}(t)$	Instantaneous power possible in current wind condition [MW]
$P_{1\text{-}min}(k)$	1-minute average real power output in the kth interval [MW]
$P_{poss,1\text{-}min}(k)$	1-min average possible power in the kth interval [MW]
$R_{Down}(k)$	Per-unit cost of frequency down-regulation in terms of energy lost to provide it [MWh/MW-h]
$R_{Up}(k)$	Per-unit cost of frequency up-regulation in terms of energy lost to provide it [MWh/MW-h]
v	Violations of the ramp rate limit λ_{max}, as a fraction of the total simulated period.
$\gamma_{[r,c]}(f)$	The coherence function between two wind turbines r and c.
δ	Curtailment of wind farm power output below the possible power output [MW]
λ	Power ramp rate [MW/min]
λ_{max}	Power ramp rate limit [MW/min]
λ_{+}	Positive ramp rate [MW/min]
λ_{-}	Negative ramp rate [MW/min]

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