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The Limits of Wind Power

by William Korchinski
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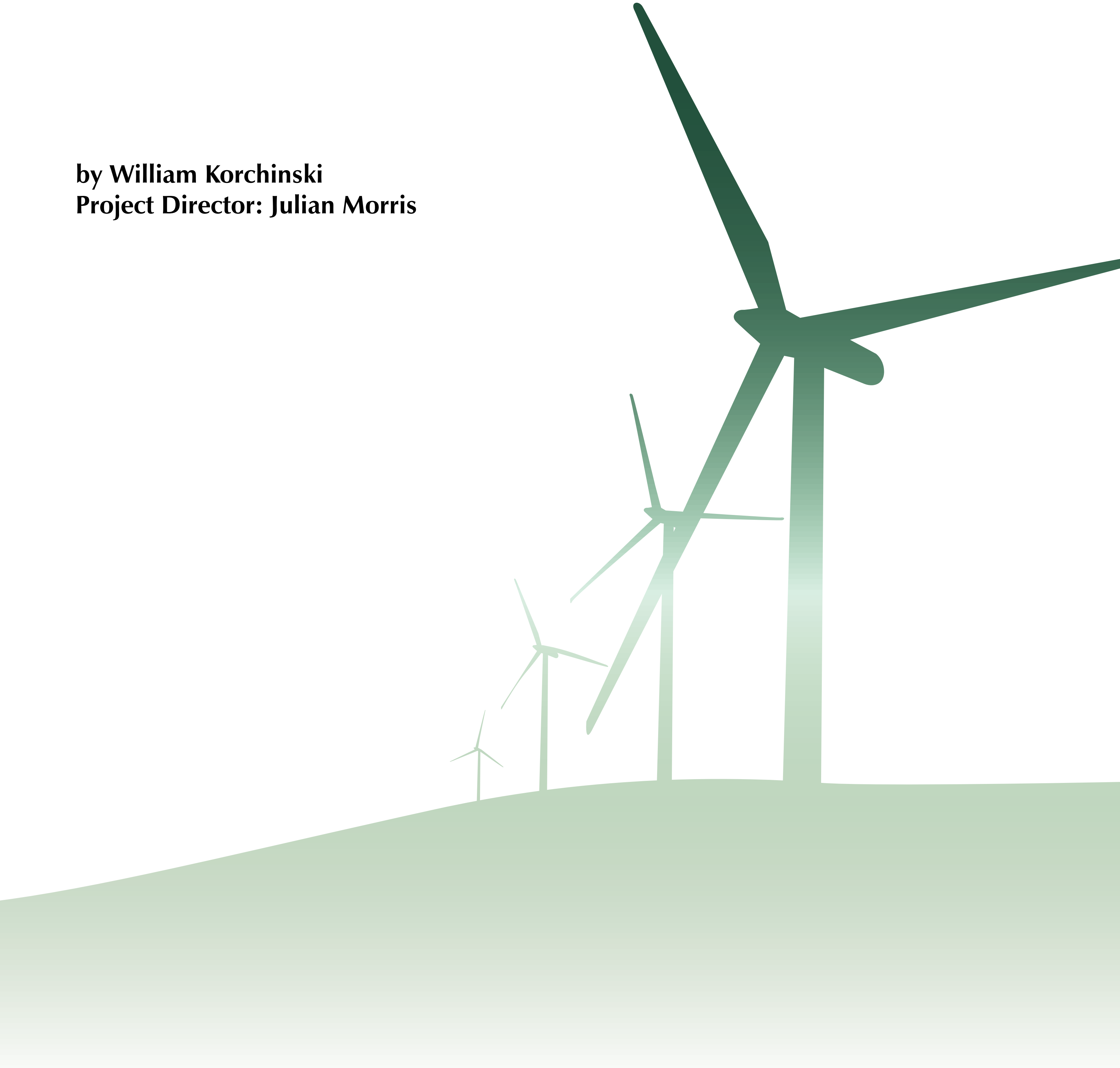

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The Limits of Wind Power

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Executive Summary

Environmentalists advocate wind power as one of the main alternatives to fossil fuels, claiming that it is both cost effective and low in carbon emissions. This study seeks to evaluate these claims.

Existing estimates of the life-cycle emissions from wind turbines range from 5 to 100 grams of CO_2 equivalent per kilowatt hour of electricity produced. This very wide range is explained by differences in what was included in each analysis, and the proportion of electricity generated by wind. The low CO_2 emissions estimates are only possible at low levels of installed wind capacity, and even then they typically ignore the large proportion of associated emissions that come from the need for backup power sources ("spinning reserves").

Wind blows at speeds that vary considerably, leading to wide variations in power output at different times and in different locations. To address this variability, power supply companies must install backup capacity, which kicks in when demand exceeds supply from the wind turbines; failure to do so will adversely affect grid reliability. The need for this backup capacity significantly increases the cost of producing power from wind. Since backup power in most cases comes from fossil fuel generators, this effectively limits the carbon-reducing potential of new wind capacity.

The extent to which CO_2 emissions can be reduced by using wind power ultimately depends on the specific characteristics of an existing power grid and the amount of additional wind-induced variability risk the grid operator will tolerate. A conservative grid operator can achieve CO_2 emissions reduction via increased wind power of approximately 18g of CO_2 equivalent/kWh, or about 3.6% of total emissions from electricity generation.

The analysis reported in this study indicates that 20% would be the extreme upper limit for wind penetration. At this level the CO_2 emissions reduction is 90g of CO_2 equivalent/kWh, or about 18% of total emissions from electricity generation. Using wind to reduce CO_2 to this level costs $150 per metric ton (i.e. 1,000 kg, or 2,200 lbs) of CO_2 reduced.

Very high wind penetrations are not achievable in practice due to the increased need for power storage, the decrease in grid reliability, and the increased operating costs. Given these constraints, this study concludes that a more practical upper limit for wind penetration is 10%. At 10% wind penetration, the CO_2 emissions reduction due to wind is approximately 45g CO_2 equivalent/kWh, or about 9% of total.

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Introduction

The Push for Wind

There are many advocates of increasing wind power in the U.S. and other countries. For example, the American Wind Energy Association (AWEA) industry calls itself "a national trade association representing wind power project developers, equipment suppliers, services providers, parts manufacturers, utilities, researchers, and others involved in the wind industry." Its stated mission is to "promote wind energy as a clean source of electricity for consumers around the world."

Another such wind advocate is the U.S. Department of Energy, which has implemented a "National Offshore Wind Strategy" designed to ensure the creation of a "robust and environmentally responsible wind energy industry in the U.S."[1] Part of the rationale of this wind strategy is to "address the daunting challenges of reducing CO_2 emissions in a rapid and cost-effective manner."

In the United States, electricity from coal-fired plants accounts for approximately 42% of the total.[2] Wind power currently accounts for a small fraction of total generation. As can be seen clearly in Table 1 and Figure 1, which list the U.S. electrical generation for 2011 by source, the majority of U.S. power derives from coal, natural gas, nuclear and hydroelectric. At present, wind power produces less than 3% of the total.

Table 1: Electricity Sources in the U.S. by Type: 2011

Electricity Source	2011 Net Generation (1000 MWh)	%
Coal	1,734,265	42.2
Natural Gas	1,016,595	24.8
Nuclear Electric Power	790,225	19.2
Conventional Hydroelectric	325,074	7.9
Wind	119,747	2.9
Biomass (wood)	36,946	0.9
Petroleum	28,162	0.7
Biomass (waste)	19,786	0.5
Geothermal	16,700	0.4
Other Gases	11,269	0.3
Solar Thermal and Photovoltaic	1,814	0.0
Hydroelectric Pumped Storage	-5,912	-0.1
All Energy Sources	4,105,734	100.0

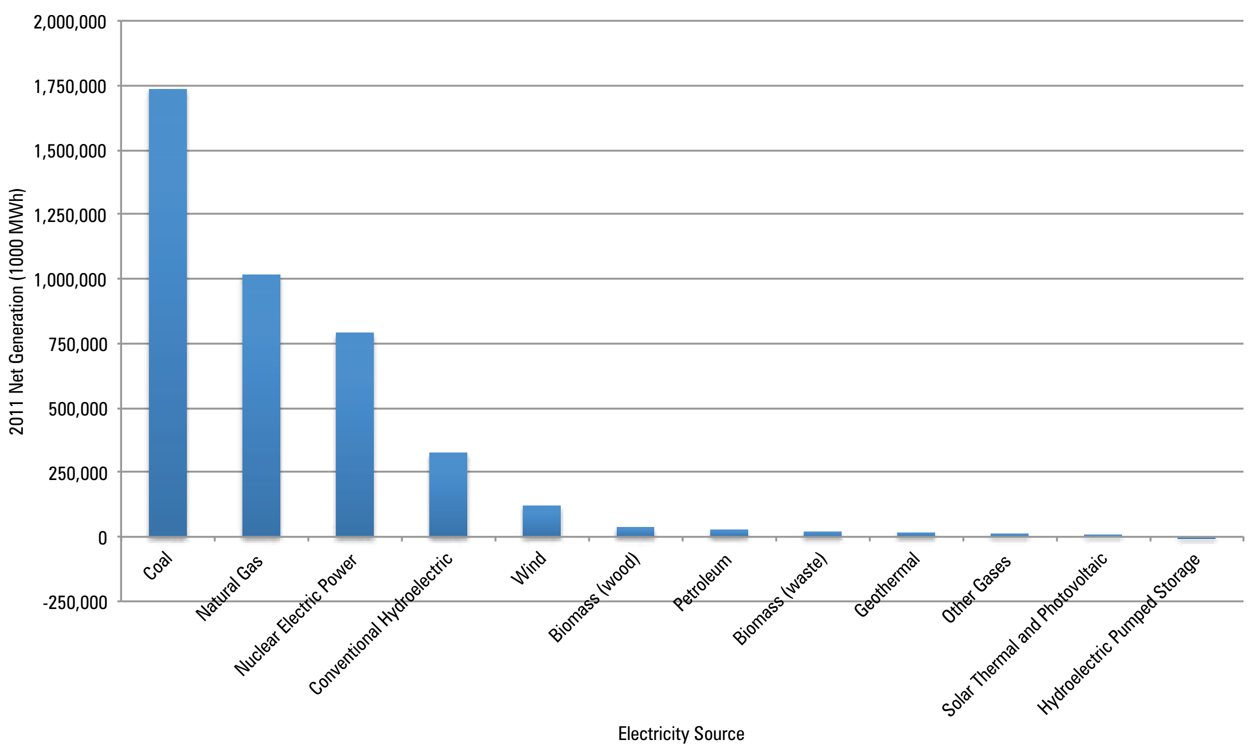
Source: U.S. Energy Information Administration.

Wind advocates make various arguments for subsidizing and mandating the expansion of wind power from this very low base. Among the most popular of these are "energy security" and "climate change." This paper addresses the second of these arguments, looking at the impact of wind power on emissions of "greenhouse gases" (GHGs).

Various attempts have been made to quantify the impacts of wind power on GHG emissions. In a study for the International Atomic Energy Agency, Daniel Weisser produced estimates of the GHG emissions from wind and other power sources amortized over the life of the asset.[3] Table 2 below gives a summary of Weisser's results, using an average of his range of estimates (emissions are given as "CO_2 equivalent," which is a standard measure of GHGs).

As can be seen from Table 2, most of the CO_2 produced by wind turbines comes from turbine construction and installation; the remainder comes predominantly from maintenance, transport and decommissioning; emissions during day-to-day operations are minimal. On the basis of this evaluation, it appears that wind is similar in overall emissions to nuclear and is far lower in GHG emissions than either coal or natural gas.

Figure 1: Electricity Sources in the U.S. by Type



Source: U.S. Energy Information Administration.

Table 2: Greenhouse Gas Emissions from Various Sources over the Course of their Life-Cycles, in Grams of CO_2eq/kWh

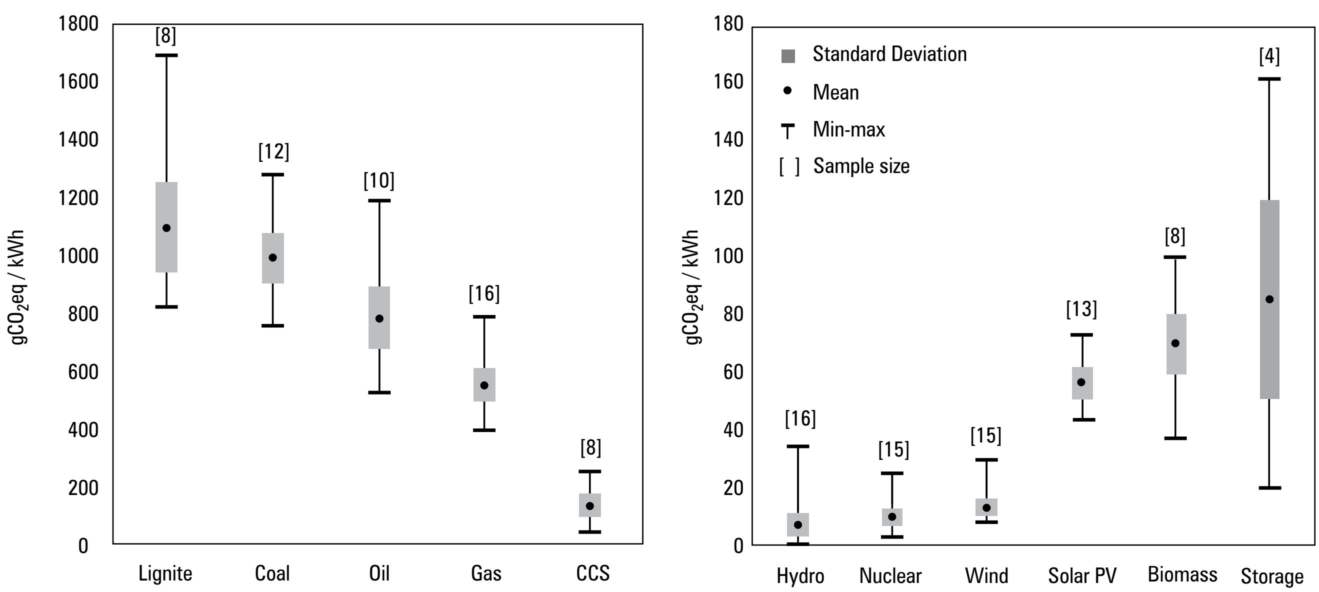
	Wind	Coal	Nat Gas	Nuclear
Fuel processing	-	150	70	11
Equipment manufacture, facility construction	16.0	-	-	-
Day-to-day operation	-	900	470	1
Maintenance	1.50	150	70	-
Decommissioning	1.50	-	-	-
Total	19 .0	1,200	610	12

Source: Daniel Weisser, *A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies* (Vienna: International Atomic Energy Agency, 2007).

Figure 2, also from Weisser's study, provides a more comprehensive survey of emissions, giving ranges. Generally, hydroelectric power has the lowest rate of CO_2 emissions, followed closely by nuclear power, and then wind. Hydrocarbon-based sources of power, such as gas and coal, emit at least an order of magnitude more CO_2 emissions per kWh than wind. The term "Storage" in Figure 2 refers to the cost of storing energy using various technologies. At the low end, storing energy using compressed air costs 19g CO_2eq/kWh. Using Vanadium Redox Batteries on the other hand costs 161g CO_2eq/KWh.

But are Weisser's estimates valid? Other recent life-cycle assessments of emissions from wind power range from a low of 5.5 grams/kWh to 100 grams/kWh. These are summarized, along with Weisser's, in Table 3.

Figure 2: Estimates of Greenhouse Gas Emissions from Various Sources (Showing Ranges)



Source: Daniel Weisser, *A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies* (Vienna: International Atomic Energy Agency, 2007).

Table 3: Comparing Estimates of Life-Cycle GHG Emissions from Wind				
	Weisser (2007)[4]	Endres (2008)[5]	World Nuclear Association (2009)[6]	Flanagan (2010)[7]
Total Grams of CO_2eq/kWh	19	26	5.5 – 29	10 – 100

The reason for the higher upper estimate provided by Flanagan is these include emissions from different types of wind storage (e.g. pumped hydro, compressed air, batteries). This paper seeks to explore these issues in more detail. Part 1 looks at how wind penetration affects life-cycle emissions. Meanwhile, Part 2 details an empirical investigation looking more closely at a specific example and extrapolating the implications of increasing wind penetration.

Part 1

Wind Penetration and "Spinning Reserves"

If wind generation becomes more popular and replaces some part of the electricity currently supplied by gas and coal, total CO_2 emissions due to electricity generation will decrease. In a report for the U.K. Energy Research Council (and partly funded by the Carbon Trust—a U.K. government-funded organization dedicated to promoting reduced emissions of carbon dioxide), Gross et al. estimate that a 1% increase in wind penetration results in a 0.5% reduction of CO_2 emissions.[8] If this is correct, moving from 0% penetration to 20% penetration would reduce CO_2 emissions by about 10%.

Wind is a variable and intermittent energy source; output varies by wind speed and sometimes it blows too hard or too softly to enable any power to be generated. (To see the effects of attempting to produce electricity from wind when the wind is too strong, conduct a search of the Internet for "exploding wind turbine" and watch the various videos.) In order to meet consumer demand, wind power generation requires backup sources of power, known in the jargon as incremental "spinning reserves" because they must be running continuously, synchronized to the grid, and ready to increase or decrease power on short notice. Typically, natural gas or diesel generators fill this role because they may be ramped up easily—about 1% of total power per minute. The point is well made by one of the world's largest wind energy companies:

> *Wind energy is only able to replace traditional power stations to a limited extent. Their dependence on the prevailing wind conditions means that wind power has a limited load factor even when technically available. It is not possible to guarantee its use for the continual cover of electricity consumption. Consequently, traditional power stations with capacities equal to 90% of the installed wind power capacity must be permanently online in order to guarantee power supply at all times.*[9]

Estimates of the spinning reserves required by wind generation range from 27% to 89% of the total wind power.[10] If all of the required spinning reserves were supplied in the form of natural gas turbines, the spinning reserve requirements for wind would be between 165 and 540g CO_2eq/kWh (based on the natural gas numbers in Table 2).

A. Reliability, Forecasting and Wind

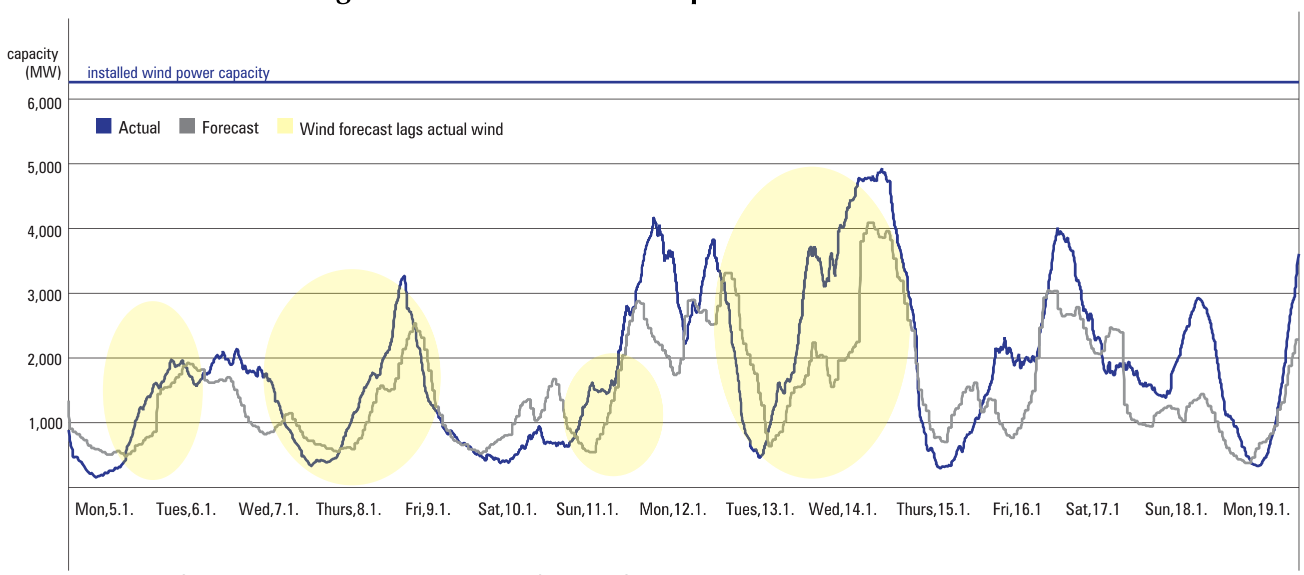
Demand for electricity can change significantly in a matter of minutes, and if supply does not match demand there will be brown- or blackouts. In order to ensure that supplies match demand, power supply companies rely on detailed forecasts of electricity demands over periods ranging from minutes to hours to days. By being able to anticipate demands accurately, the companies can reliably schedule power plant loadings at minimum cost and maximum reliability.

However, if wind is part of the generation mix, power supply companies must not only forecast demands accurately, but must also include wind forecasts so that if the power supplied by wind turbines suddenly decreases or stops, they can bring backup power on line quickly to maintain system reliability.

But wind is difficult to forecast and its speed and direction can change quickly. This is a problem because we demand extremely high reliability from our electrical system. Hannele Holttinen et al. conclude in their analysis of wind power for the International Energy Agency that "While the total balancing energy needed for the integration of wind power stems from the mean forecast error, the need for reserve power is closely connected to the largest forecast errors, i.e. the tail in the probability density function (pdf) of forecast errors."[11] In other words, as wind penetration increases, system reliability will be adversely affected disproportionately—unless adequate reserve power is made available.

Several power companies have substantial experience in addressing the issues relating to wind forecasts. Take the example of E.ON, a large German power company that in 2004 had approximately 7,000 MW of installed wind power (7,600 turbines) covering a wide geographic area. Figure 3 shows a wind forecast used by E.ON over a two-week period in 2004. The gray line shows the forecasted wind power and the blue line shows the actual wind power over time. Note that for

Figure 3: Wind Forecast Compared with Actual Wind



Source: Wind Report 2005, Munich: E. ON Netz, GmbH 2005, p. 10.

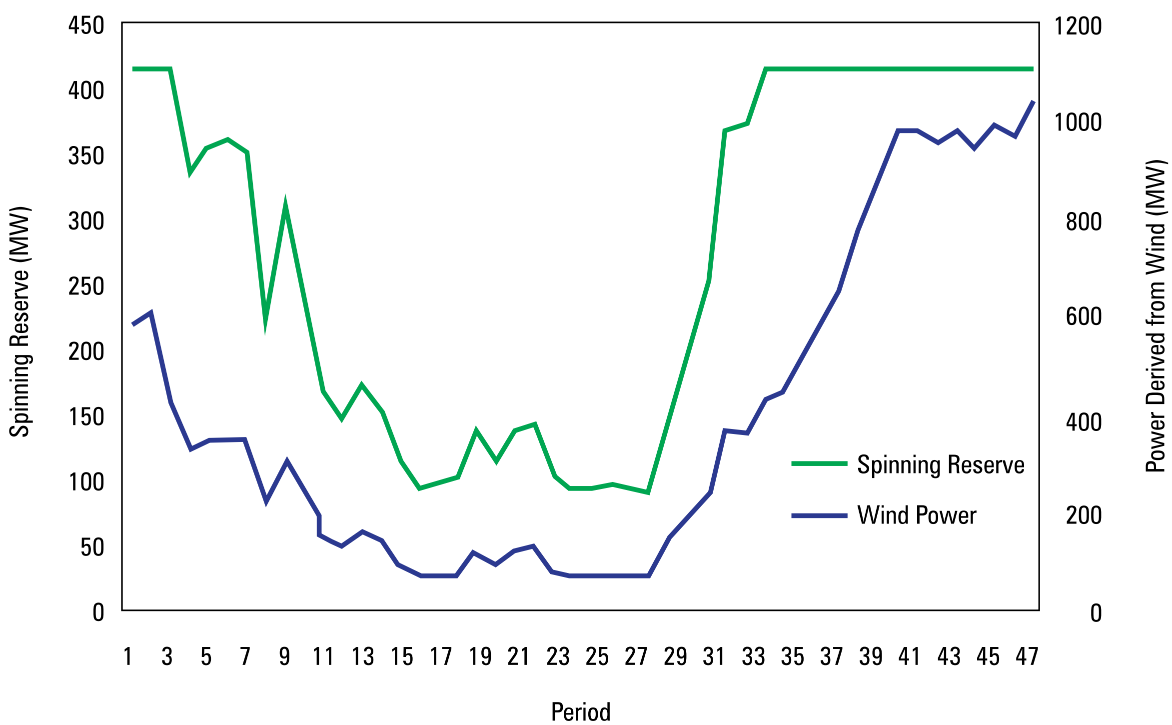
much of the forecast period (tan-colored circles), the wind forecast is actually behind in time as compared to the actual wind; this is because wind speed and direction have large random components, even when averaged over a large geographic area as in this case.

One consequence of wind's variability is that it may actually lead to increased emissions as other generators (e.g. coal and gas) in a grid must rapidly respond to wind events. In a report prepared for Independent Petroleum Institute of Mountain States, Bentek Energy reports large increases of SOX and NOX emissions due to the inclusion of wind power into a grid in Colorado.[12] Furthermore, Bentek reports that wind's net impact on CO_2 emissions is ambiguous.

B. Reserve Requirements and Wind Penetration

As wind penetration increases, power companies will require additional spinning reserves. Figure 4, taken from a wind integration study in New Zealand, shows how spinning reserves (green line) must closely track wind power (blue line).[13] The size of this reserve margin depends on many things, including the power company's standard procedures for reserve requirements. In the case of incremental wind power, the size of the margin also depends on the wind penetration and the accuracy of the wind forecasts. As wind penetration increases and as forecast error increases, the margin must be a larger fraction of the total grid's power in order to retain the desired level of grid reliability.

Figure 4: The Relationship between Spinning Reserve and Wind Power as Illustrated on a Typical Winter Day on the North Island of New Zealand (periods are 30 minutes)



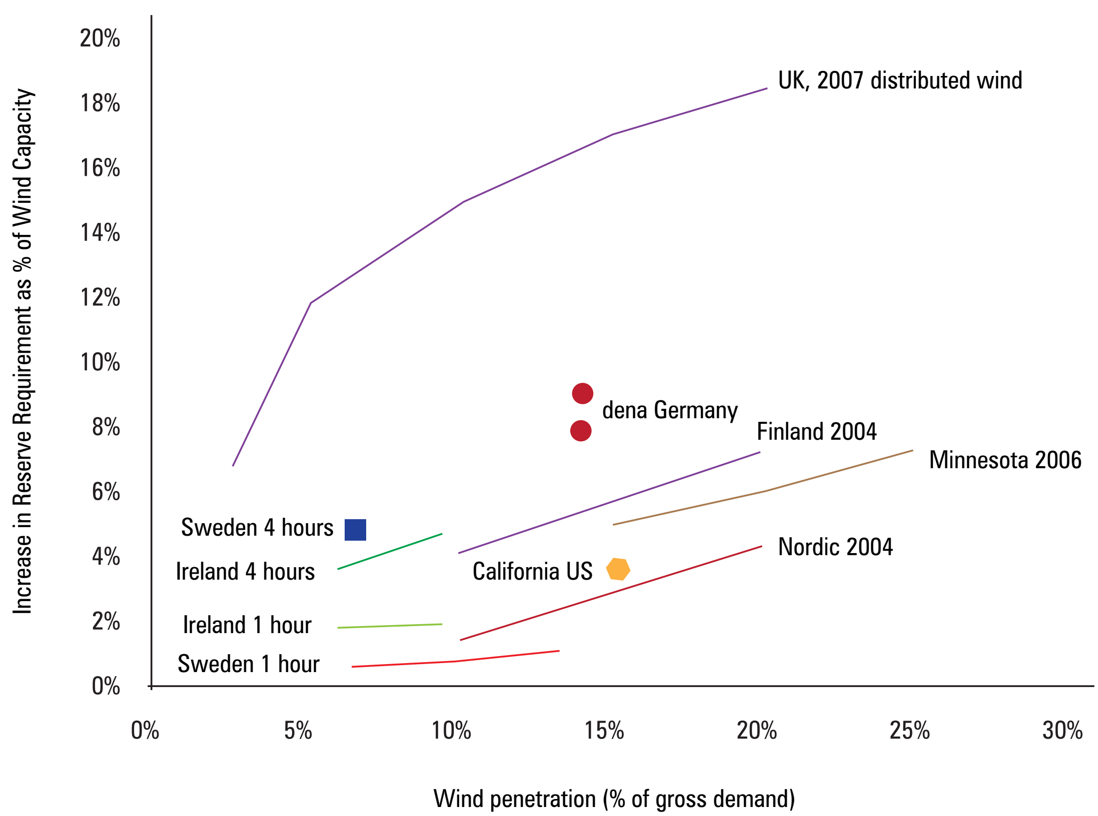
Source: Goran Strbac et al., *Summary of Findings: New Zealand Wind Integration Study* (London: Imperial College, April 2008).

Figure 5 shows results derived by Holttinen et al.[14] As wind penetration increases, reserve requirements also increase. (In the legend, the references to "1 hour" and "4 hours" refer to the time-scale of the wind forecasts, with longer-term forecasts corresponding to more significant variability, because of the greater difficulty of forecasting four hours versus one hour ahead.) Taking the line labeled "Ireland 4 hours" as an example, a wind penetration of 2.5% requires a 7% increase in reserves—based on wind capacity—or a 0.175% increase in reserves—based on grid capacity (0.175% = 2.5% x 0.07). At the high end of the curve a wind penetration of 20% requires an 18.5% increase in reserves—based on wind capacity—or a 3.7% increase in reserves—based on grid capacity (3.7% = 20% x 0.185). Note the high reserve requirements reported for Ireland (especially the "4-hours" line). This is likely because Ireland's electrical grid is not as interconnected as are other countries' grids, and this lack of interconnection makes it more difficult to provide steady wind power with a more "normal" reserve capacity.

Gross et al. show that the approximate range of additional reserve requirements is 0.1% of total grid capacity for each percent of wind penetration for wind penetrations below 20%, rising to 0.3% of total grid capacity for each percent of wind penetration above 20%.[15]

Maintaining high grid reliability is complicated, especially as wind penetration increases. As a concrete example of this, data below describe an actual event that occurred in Germany on Christmas Eve 2004.[16]

Figure 5: Relationship between the Need for Reserve Generation and Installed Wind Capacity



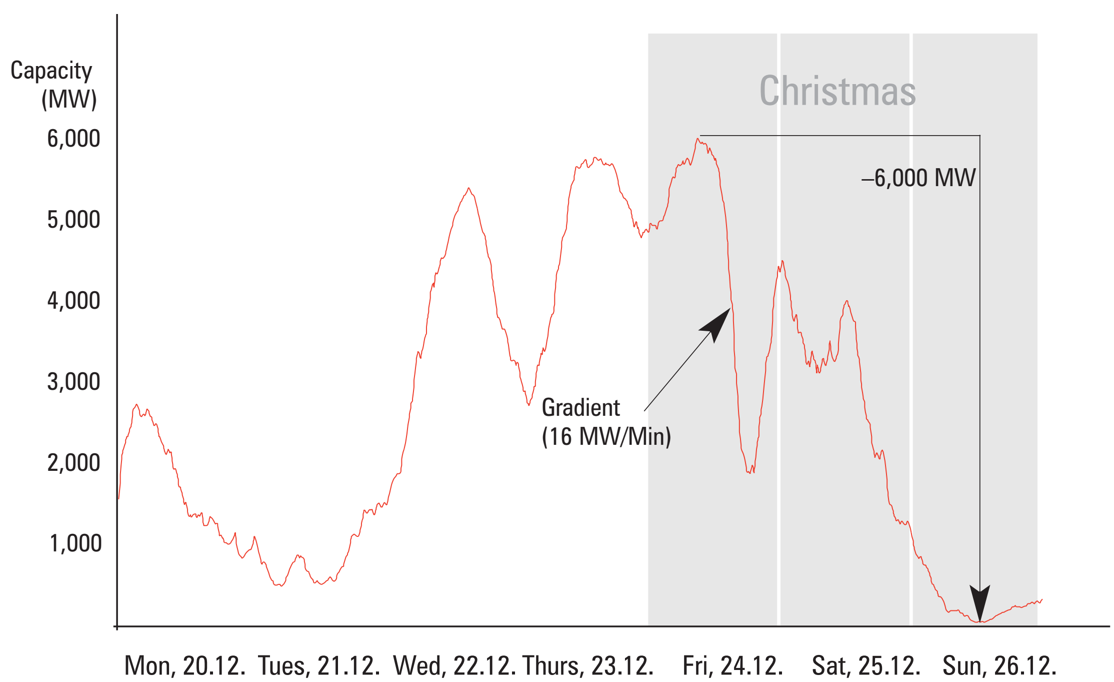
Source: Hannele Holttinen, et al, *Design and operation of power systems with large amounts of wind power,* (Final report, IEA WIND Task 25, Phase one 2006-2008, Finland: JULKAISIJA- UTGIVARE, 2009), p. 170.

Figure 6 shows a summary of the event. E.ON shows wind power in MW over a one-week period. On Christmas Eve, the winds in E.ON's control area quickly died out, dropping wind generation from 6,000 MW down to less than 2,000 MW at a very high rate (16 MW/min). As the E.ON report describes it: "Whilst wind power feed-in at 9.15 am on Christmas Eve reached its maximum for the year at 6,024MW, it fell to below 2,000MW within only 10 hours, a difference of over 4,000MW. This corresponds to the capacity of 8 x 500MW coal fired power station blocks. On Boxing Day, wind power feed-in in the E.ON grid fell to below 40MW. Handling such significant differences in feed-in levels poses a major challenge to grid operators."

Summarizing, this event was a very large disturbance for E.ON, and had the grid operator not acted quickly, could have led to a widespread power outage in Germany. What does E.ON conclude from the above?

> *As wind power capacity rises, the lower availability of the wind farms determines the reliability of the system as a whole to an ever increasing extent. Consequently, the greater reliability of traditional power stations becomes increasingly eclipsed. As a result, the relative contribution of wind power to the guaranteed capacity of our supply system up to the year 2020 will fall continuously to around 4% (FIGURE 7). In concrete terms, this means that in 2020, with a forecast wind power capacity of over 48,000MW, 2,000MW of traditional power production can be replaced by these wind farms.*[17]

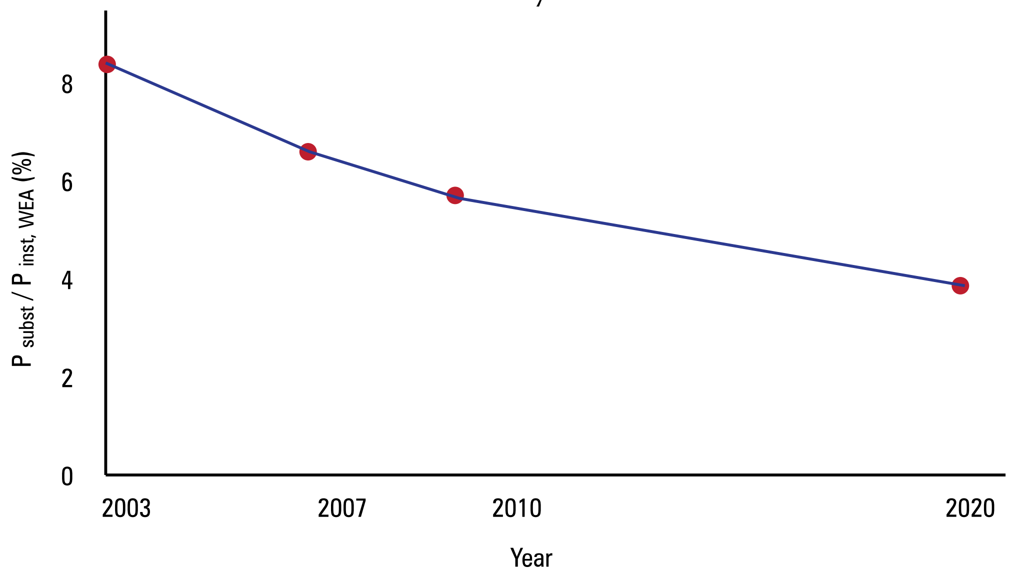
Figure 6: 2004 Christmas Wind Power Variability, Germany



Source: E.ON Netz, *Wind Report 2005*, p. 8.

In other words, the more wind power capacity a grid has, the lower the percentage of traditional power generation wind can replace. Figure 7 summarizes this point of view, and as a result of this falling substitution capacity, E.ON intends in future to limit its total wind penetration to less than 4%.[18]

Figure 7: The Marginal Impact of Increasing Installed Wind Capacity on the Substitutability of Wind

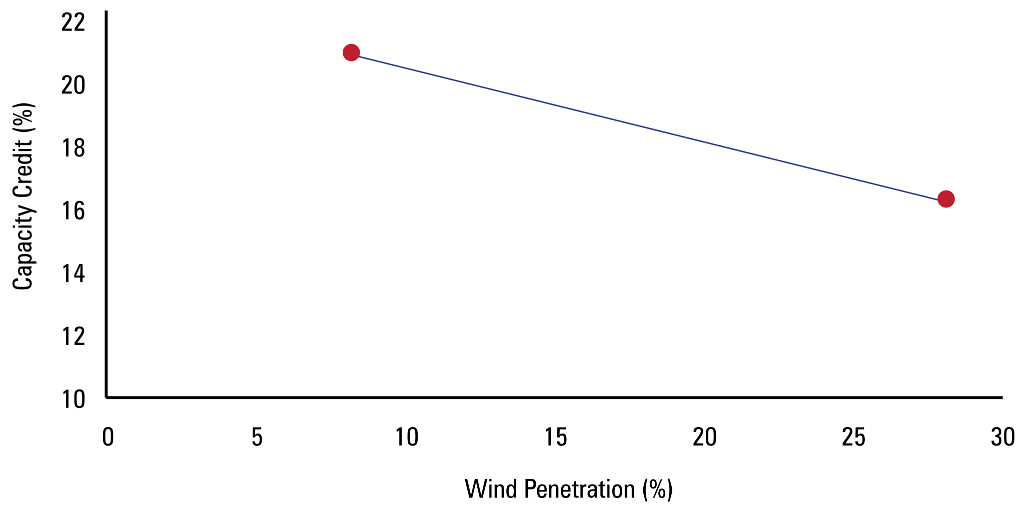


Source: E.ON Netz, *Wind Report 2005*, p. 8. Psubst: power station capacity that can be substituted by wind power. Pinst, WEA: installed wind power capacity.

Another way to look at system reliability is from the point of view of "Capacity Credit," which Gross et al. describe as "a measure of the contribution that intermittent generation can make to reliability. It is usually expressed as a percentage of the installed capacity of the intermittent generators."[19] Gross et al. go on to explain that:

> *There is a range of estimates for capacity credits in the literature and the reasons for there being a range are well understood. The range of findings relevant to British conditions is approximately 20 – 30% of installed capacity when up to 20% of electricity is sourced from intermittent supplies (usually assumed to be wind power). Capacity credit as a percentage of installed intermittent capacity declines as the share of electricity supplied by intermittent sources increases.*[20]

Figure 8: Capacity Credit Decreases with Wind Penetration



Source: Robert Gross et al., *The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of internal generation on the British electricity network* (London: Imperial College/UK Energy Research Center, 2006), p. 57.

Figure 8 from Gross et al. shows that capacity credit decreases as wind penetration increases.[21] This is because at high wind penetrations, additional reserves are required to ensure the same level of grid reliability. Gross et al. show further that the crossover between high and low capacity credit occurs in the neighborhood of 20% wind penetration.[22]

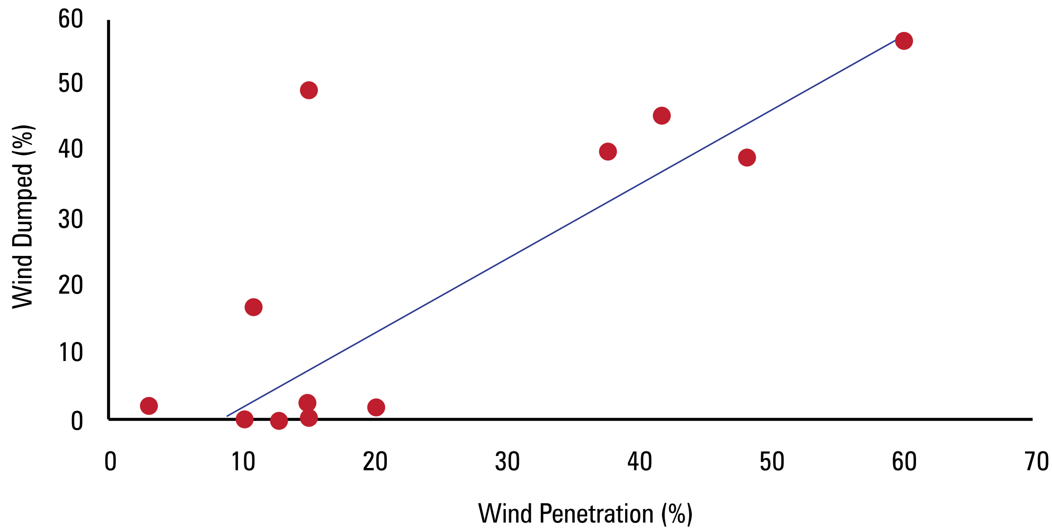
C. Wind Dumping

Sometimes there is too much wind and wind must be "dumped" or "spilled." This can happen when wind speed exceeds the mechanical limitations of the turbine machinery, in which case "feathering" the turbines (i.e. turning the blades so that they do not catch the wind and become non-productive) prevents damage. Likewise, sometimes electrical demand is too low to consume all of the wind power. The interchangeable terms "wind dumping" or "wind spilling" describe these situations.

Figure 9 summarizes wind dumping data from Gross et al.[23] At low wind penetrations, there is very little need to dump wind. Above about 10% wind penetration, however, wind dumping increases linearly with wind penetration.[24]

One implication of wind dumping is that at higher wind penetration levels, it is theoretically possible to build too many wind turbines for the size of the demand, placing an upper limit on wind penetration. When there are too many wind turbines, there will be large periods of time when many of the turbines are "feathered." Due to the high installed cost of wind power, this leads to very expensive electricity. In other words, excessively high wind penetration leads to excessively high electricity costs.

Figure 9: Wind Dumped as a Function of Wind Penetration



Source: Robert Gross et al., *The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of internal generation on the British electricity network* (London: Imperial College/UK Energy Research Center, 2006), Table 3.9.

D. Storage

There are ways to store wind power to reduce wind dumping. Table 4 lists some of these, along with their corresponding CO_2 emissions per kilowatt-hour.

Table 4: CO_2 Emissions from Various Power Storage Options

	gCO_2eq/Wh
Compressed Air Energy Storage	19
Pumped Hydro Storage	36
Polysulfide Bromide Battery	125
Vanadium Redox Battery	161

Source: Daniel Weisser, *A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies* (Vienna: International Atomic Energy Agency, 2007), p. 15.

E. Cost

Table 5 compares electrical generation costs for various technologies. Generally, wind power is on the high end of cost, with coal and nuclear being on the low end. For example, in the UK onshore wind power is 60% more expensive than nuclear;[25] in the EU, onshore wind power is up to twice the cost of nuclear. Note that the costs for wind power assume relatively low levels of wind penetration, and therefore do not include additional costs to pay for spinning reserves as wind penetrations increase to higher levels.

Table 5: Comparison of Electrical Generation Costs						
	MIT 2003	France 2003	UK 2004	Chicago 2004	Canada 2004	EU 2007
Nuclear	4.2	3.7	4.6	4.2-4.6	5.0	5.4-7.4
Coal	4.2		5.2	3.5-4.1	4.5	4.7-6.1
Gas	5.8	5.8, 10.1	5.9, 9.8	5.5-7.0	7.2	4.6-6.1
Wind onshore			7.4			4.7-14.8
Wind offshore			11.0			8.2-20.2

Source: World Nuclear Association, Energy Analysis of Power Systems, p. 13

Table 6 summarizes the costs associated with storing electricity. With current technology, pumped hydro storage is by far the least expensive option. The addition of pumped storage to power systems with high wind penetration increases the cost of wind power. In the UK example the cost of wind power with pumped storage is 170% more expensive than nuclear.[26]

Table 6: Electricity Storage Costs	
	U.S. $/KWh
Pumped Hydro Storage	0.05
Batteries	0.18-0.64
Batteries + Flywheel	0.06-0.57

Source: Piyasak Poonpun and Ward T. Jewell, "Analysis of the Cost per Kilowatt Hour to Store Electricity," IEEE Transactions on Energy Conversion, Vol. 23, No. 2, June 2008, pages 529–534, at p. 533.

F. The Environmental Impact of Spinning Reserve Requirements

This additional spinning reserve capacity, necessitated by the installation of intermittent power sources such as wind generators, comes with its own environmental impacts and costs. If the reserve capacity takes the form of additional natural gas generation, then there are increased CO_2 emissions. If the reserves take the form of water storage (where this is geologically feasible), then there are typically environmental consequences related to reduction of wilderness, in addition to the possible costs of relocating communities. If the reserve capacity uses batteries, there are environmental impacts related to the production, use and disposal of those batteries, including the disposal of toxic chemicals and heavy metals.

Note that although wind power by itself generates very little CO_2—especially at today's low penetrations—the spinning reserves required to ensure system reliability at higher wind penetrations partially offset wind's low CO_2 emissions profile. As wind penetration increases from 0% of total system load to 20%, the additional spinning reserves require that gas turbines be added to the system, thereby increasing total system load by approximately 2%. This means that the additional gas turbines are now adding an additional 2% CO_2 emissions to the system, even as the additional wind power is reducing CO_2 emissions.

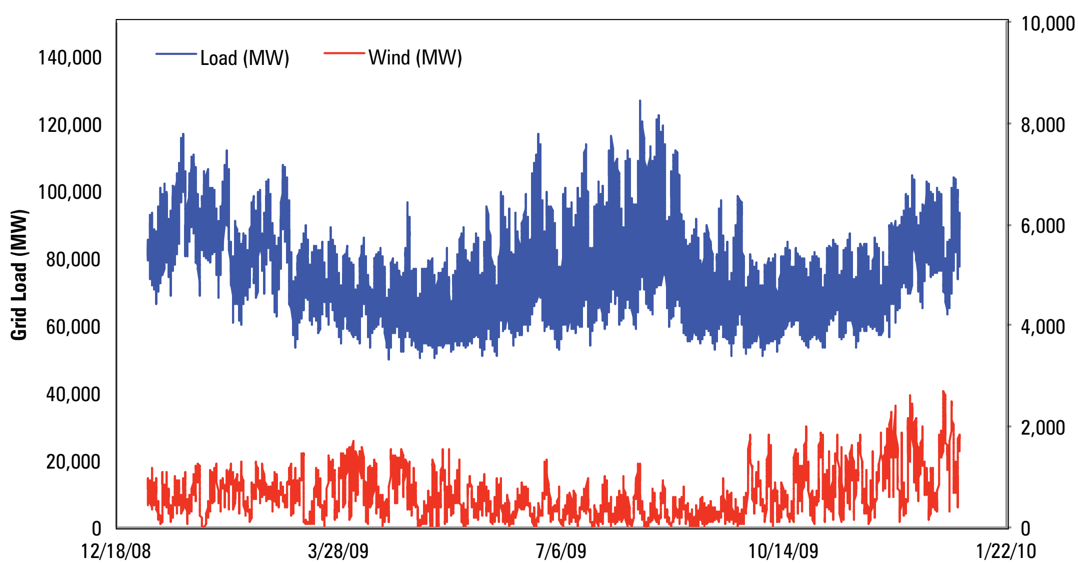
Part 2

Empirical Study

This section further explores the impacts of wind power on CO_2 emissions and system reliability. This analysis is based on actual grid demand and wind data as published by PJM.[27] PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia.

PJM detailed hourly data for the year 2009, which was used to calculate the effects of increasing wind penetration and storage on total grid CO_2 emissions, system reserves and wind dumping. The raw data appear in Figure 10, which shows that the total demand is around 80,000 MW, peaking in summer and winter, and at its lowest in spring and fall. Conversely, wind power peaks in winter and is at its lowest in summer.

Figure 10: PJM Hourly Load and Wind Data



Source: PJM, *Operational Analysis 2010*, Morristown, PA: PJM Interconnection.

A. Analysis Summary

Currently the wind penetration in the PJM service area is 0.8%. This analysis accounts for wind penetrations spanning the range from 0% to 100%, and power storage spanning the range from 0 weeks up to 18 weeks of total grid energy. Although 18 weeks of storage may seem excessive, large amounts of power storage are required in order to minimize wind dumping at high wind power penetrations.

The calculations below are based on the actual hourly PJM data for the year 2009, starting with existing wind generation and adding in hypothetical wind generating capacity. For each hour of the year, the calculations proceed as shown in the box below:

For this analysis, 150 simulations were run using different combinations of hypothetical wind penetration and storage. Table 8 shows a small example (one hour time slice) taken from three of the 150 simulation runs for the period starting January 10, 2009 at 23:00, chosen to show what happens when demand, wind power and storage vary. The column labeled "Scale up=1" uses the unchanged PJM data for wind. All of the available wind power goes to the grid to meet demand; there is no increase or decrease in storage; there is no dumping. The column labeled "Scale up=500" shows what might happen if there were 500 times the number of wind turbines available. In this case, there would be enough wind to meet all of the demand. There is also excess wind

Calculation Rules

- PJM Load (MW) is fixed. This is the grid demand.
- Specify wind "scale up factor." A scale up factor of 1 means that all of the current PJM wind power is available for use in meeting the demand. A scale up factor of 2 means that twice the current number of wind turbines have been made available to supply demand (e.g. more wind turbines have been built).
- The total available wind power (MW) is the current wind power from the PJM data multiplied by the wind scale up factor.
- Specify minimum and maximum allowable power storage in MWh.
- Send all available wind power to the grid to help meet the demands.
- If there is excess wind power, store it.
- If there is not enough power to meet demands, draw power from storage.
- Storage is not allowed to go below minimum.
- Storage is not allowed to go above maximum.
- If wind plus storage power are still not enough to meet the load, then run natural gas generators to make up the difference.
- If storage is full, and there is excess wind, then dump excess wind.
- Calculate CO_2 emissions per kilowatt-hour based on amount of natural gas generation needed.

power, which is stored. The column labeled “Scale up=1000” shows what might happen if there were 1,000 times the number of wind turbines available. Again, there is enough wind power to meet all demand, and there is excess wind power available, requiring the dumping of the excess wind because the storage is full.

Table 7: Sample Simulation Results

Variable	Units	Scale up=1	Scale up=500	Scale up =1000
Total demand (from PJM data)	MW	77,214	77,214	77,214
Total wind power (from PJM data)	MW	245	245	245
Wind scale up factor (1 is current # of PJM wind turbines)	-	1	500	1000
Wind power available after scaling up (more turbines)	MW	245	122,524	245,047
Wind power to grid	MW	245	77,214	77,214
Wind power to storage	MW	0	45,309	0
Wind power dumped	MW	0	0	167,833
Power from storage sent to grid	MW	0	0	0
Power from natural gas generation sent to grid	MW	76,969	0	0
CO_2eq generated by natural gas power	Tonne/h	38,484	0	0
Storage		Has room	Has room	Full

In analyzing 150 such simulations, a qualitative picture emerges. Table 8 shows that at low wind penetration levels, wind-dumping is small, while at high penetration levels wind-dumping, and therefore electricity cost, is large. Adding storage allows reduced CO_2 emissions, but storage costs increase with storage size. The sweet spot appears to be when wind penetration is below 20% and storage is small. The highlighted quadrant of Table 8 shows that adding wind decreases CO_2 emissions, without much storage cost or wind dumping.

Although CO_2 emissions are the focus of this work, other factors, including system reliability and cost (both due to dumping and storage) constrain the productive use of wind. This economic cutoff is below 20% of wind penetration.

Table 8: Overview of Wind Penetration (Based on PJM data)

		Power storage (weeks of power)	
		0	18
Wind Penetration (% of total Load)	>70%	Excessive dumping of wind Very high wind costs	Lowest CO_2 emissions Highest wind and storage costs
	20% - 70%	Begin to dump wind High wind costs	High storage cost
	0-20%	Sweet spot Reasonable cost	Storage allows decreased CO_2 High storage cost

B. Can Wind Power Provide 100% of a Grid's Load?

Is it possible to supply 100% of the grid load with wind? Figure 11 presents PJM data and shows what happens when we adjust average wind power to match the average grid demand over the year.

Notice that there are many periods when there is insufficient wind to satisfy the grid demand. Over 50% of the time, there is not enough wind to meet demand. There are many periods when there is no wind at all. This means that no matter how many wind turbines there are, there will be significant periods of time when wind cannot supply all of the power needed.

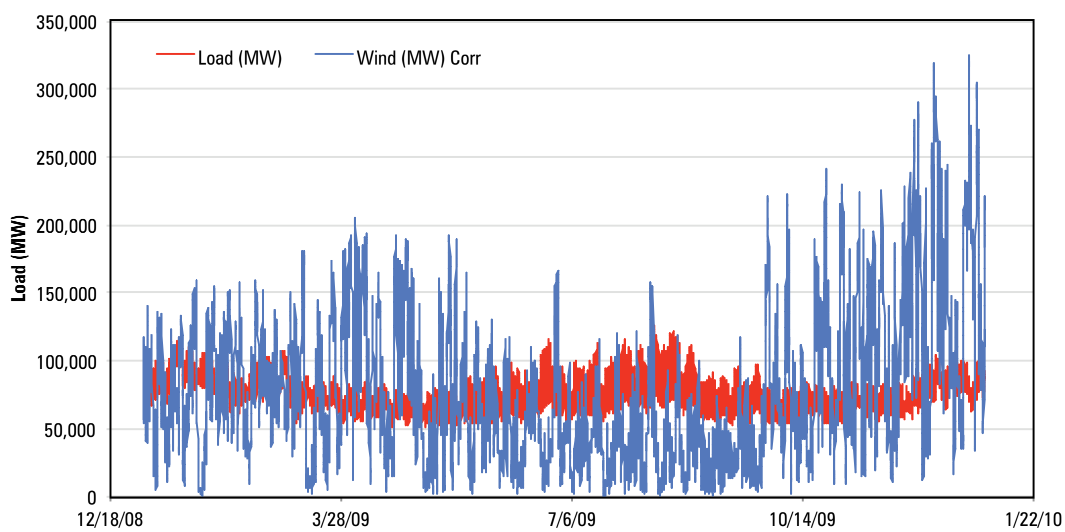
There are also times when there is too much wind for the demand. It is possible to store this wind power. When storage is full however, dumping the excess wind is necessary. Both storing and dumping are expensive.

Summarizing, Figure 11 shows a wind penetration of 100% (when averaged over a year). However, even at 100% wind penetration there will be long periods when it is impossible to meet demand using only wind. Furthermore, there will be long periods during which wind power must be stored or dumped.

C. Demand Matching

"Demand Matching" is a measure of how well the available wind power matches the demand pattern over time. In a perfect world, just enough wind power would be available to meet demand exactly, but as the data in Figure 11 show, this is unlikely to be the case. (There are geographical locations on earth with wind patterns that match demand patterns better than those shown in Figure 11. In these places, higher wind penetrations may be economically achievable. But these are rarities.)

Figure 11: Wind Power vs. Average Grid Load at 100% Wind Penetration



Source: PJM, *Operational Analysis 2010*, Morristown, PA: PJM Interconnection.

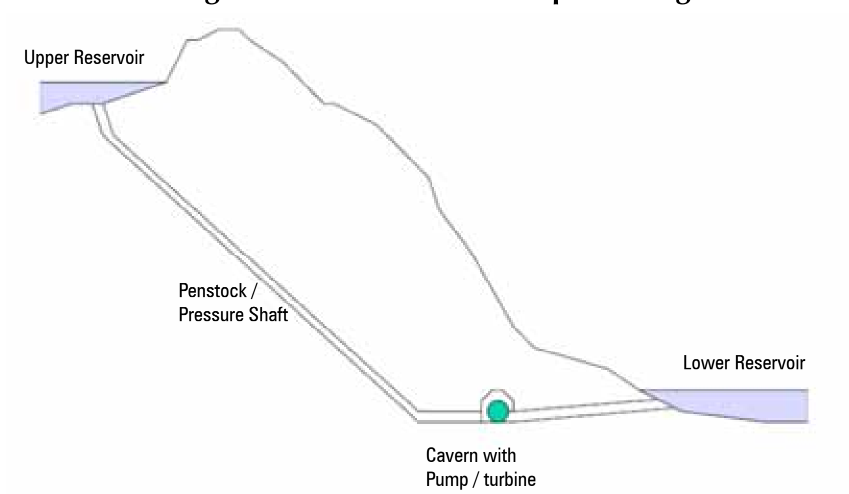
D. Wind Plus Storage

All forms of power can be stored. For example, wind power can be stored using batteries, compressed air and flywheels. Commonly however, existing grids have some hydroelectric power associated with them. The water levels in the hydroelectric reservoirs are manageable to allow some storage of wind power. Similarly some grids contain "Pumped Storage," which is a way to store power (e.g. from wind) by pumping water uphill when there is excess wind energy, and then running the water downhill through a turbine when wind energy is limited. Figure 12 shows a typical configuration for pumped storage. PJM's predicted pumped hydro storage capacity for 2010 is about 5000 MW.[28] Compared to the average hourly electrical demand in PJM's area of 77,800 MW, this amounts to about 2 hours of power storage (2 = 24 x 5,000/77,800). As Jessica Zhou notes in her undergraduate thesis, "Logically, pumped storage is unlikely to develop as quickly as wind energy. Building new dams and reservoirs for more storage capacity takes time, and each reservoir can only have so much extra capacity to pump into before the reservoir is full."[29]

The question arises, "How much pumped storage is enough so that a grid with the characteristics of PJM can supply its power demands using only wind power in combination with pumped storage?" Using the wind and load chacteristics shown in Figure 11, we estimate how much pumped storage is needed to smooth the fluctuations due to wind. Figure 13 shows that pumped storage inventory (depth) is increased in times when there is excess wind (winter), and is decreased when there is insufficient wind (summer) available to meet electricity demands.

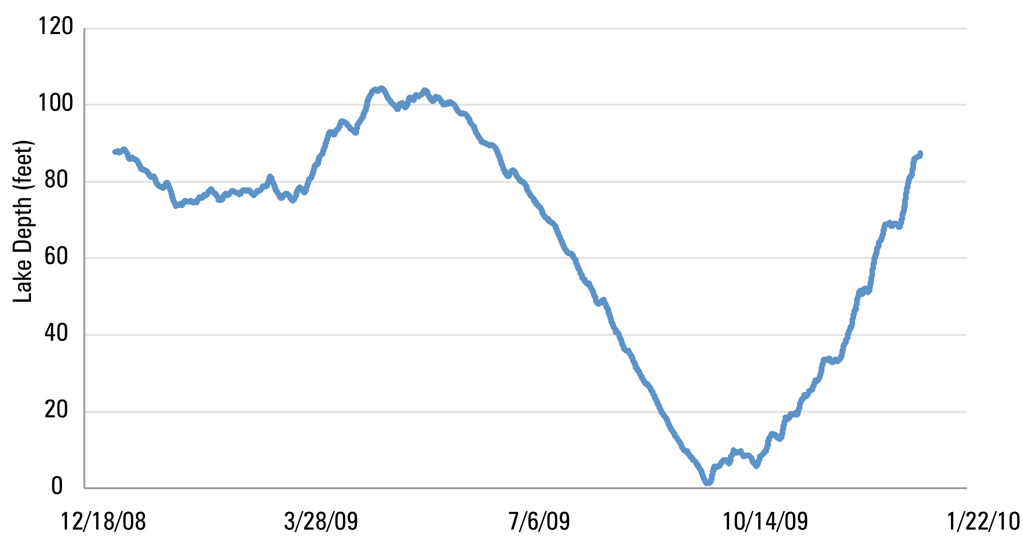
Using reasonable assumptions it is possible to calculate that the amount of water necessary to satisfy the pumped storage requirements is a body of water that is about 2,000 square miles by 100 feet deep. For reference, this is about the size of Lake of the Woods, which is located on the borders between Minnesota, Manitoba, Canada and Ontario, Canada (Figure 14).

Figure 12: Schematic of Pumped Storage



Source: Henrik Bindner, Power Control for Wind Turbines in Weak Grids: Concepts Development (Roskilde, Denmark: Risø National Laboratory, 1999) p. 12. Available at: http://130.226.56.153/rispubl/vea/veapdf/ris-r-1117.pdf, Accessed 03/22/2012

Figure 13: Pumped Storage Required to Make Wind Power Work at 100% Penetration

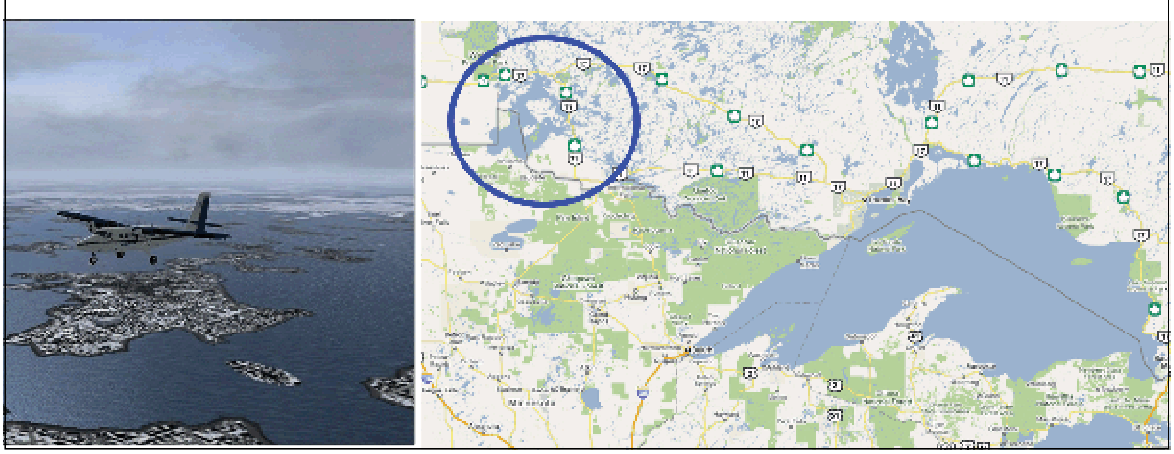


Source: Author's estimates based on PJM data.

Summarizing, storing excess wind power takes advantage of excess wind when it is available, and thus decreases CO_2 emissions from a power grid. This comes at a cost: building a pumped storage system the size of Lake of the Woods to serve a single electrical grid running on solely wind power is expensive in terms of both capital and environmental costs.

Both E.ON and Holttinen et al. came to similar conclusions. E.ON noted that "Adequate quantities of electrical energy cannot be commercially stored. This means that exactly the same amount of energy must be fed into the grid as is taken out. If the amount fed in differs from the amount removed, this can cause faults or even failure of the supply, as occurred in 2003 in the USA, Italy, Sweden and Denmark."[30] Holttinen et al. suggest that "For wind penetration levels of 10–20% of gross demand in power systems, the cost effectiveness of building new electricity storage is still low (excluding hydro power with large reservoirs or pumped hydro)."[31]

Figure 14: Lake of the Woods



E. Wind Plus Storage Plus Natural Gas

A more practical approach to increasing wind penetration is to recognize that it is not practical or cost-effective to use only wind in combination with storage. A better approach is to integrate wind into an existing grid, consisting of coal-fired, gas-fired, nuclear and other power generation facilities. The PJM data—along with simplifying assumptions that the grid consists only of wind, natural gas-fired generation and storage—illustrate this. This part of the analysis examines how these three variables interact as wind penetration into a grid increases. Figures 15 through 18 illustrate the analysis.

Figure 15 is the current situation where almost all of the grid's power comes from conventional hydrocarbon sources (i.e. coal and natural-gas fired). There is very little wind energy entering the grid and consequently very little need for wind dumping, storage or additional reserves. CO_2 emissions are high. Wind penetration is 0.8%. CO_2 generation is 500g CO_2eq/kWh. There is no wind dumping, and there is no need for storage.

Figure 16 shows what happens when wind penetration increases to 50%. Now more of the grid's power comes from wind, and less comes from natural gas. Storage is starting to come into play, and additional reserves are required due to the increased variability brought about by the wind. CO_2 emissions reduce to roughly 230g CO_2eq/kWh. There is still no wind dumping.

Figure 17 shows the case for wind penetration of 100%. When there is excess wind, storage is increased. When there is insufficient wind, and storage is available, the storage helps to generate power. When there is neither enough wind nor storage, natural gas generation starts to make up any remaining demand. CO_2 emissions are just under 200g CO_2eq/KWh. Wind dumping occurs in winter, when storage is full.

F. Wind Dumping

Figure 18 shows results from the perspective of wind dumping. Increasing wind penetration above 20% results in increasing amounts of wind dumping; this happens even when there are large amounts of available storage. A wind dumping number of 50% indicates that half of the available wind turbines are idle. In other words, the number of turbines installed is twice the amount required. Excessive wind dumping imposes an upper economic limit on wind power.

G. Spinning Reserves

The need for spinning reserves also increases with wind penetration. Figure 19 documents the trend from the study results. This has the effect of increasing wind power's inherently low CO_2 emissions, because additional natural gas and diesel reserves must be made constantly available to account for sudden wind drops, and because the amount of the reserve gets bigger as wind penetration increases. Below 20% wind penetration, storage requirements are minimal and spin-

Figure 15: Wind Penetration 0.8%

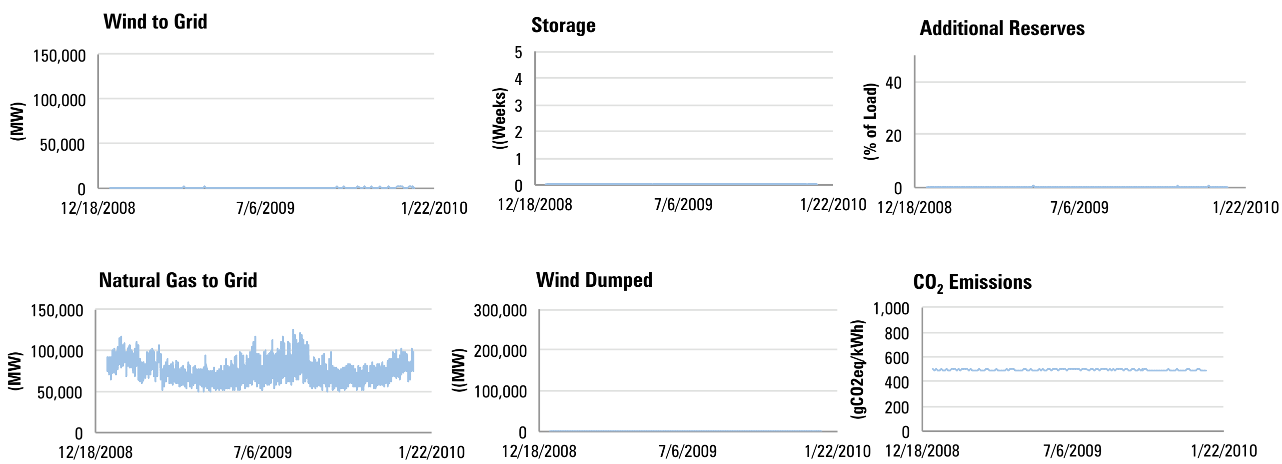


Figure 16: Wind Penetration 50%

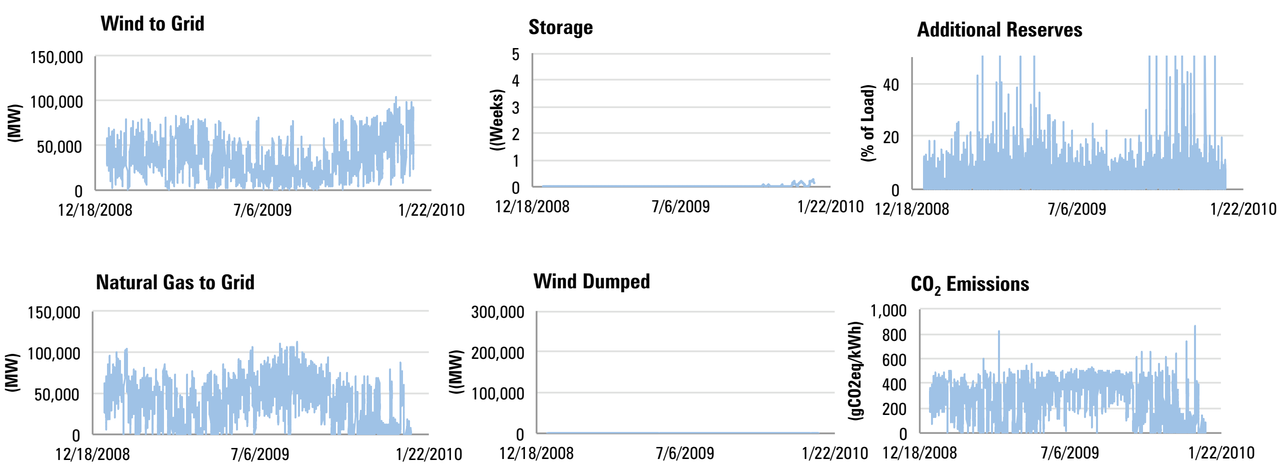
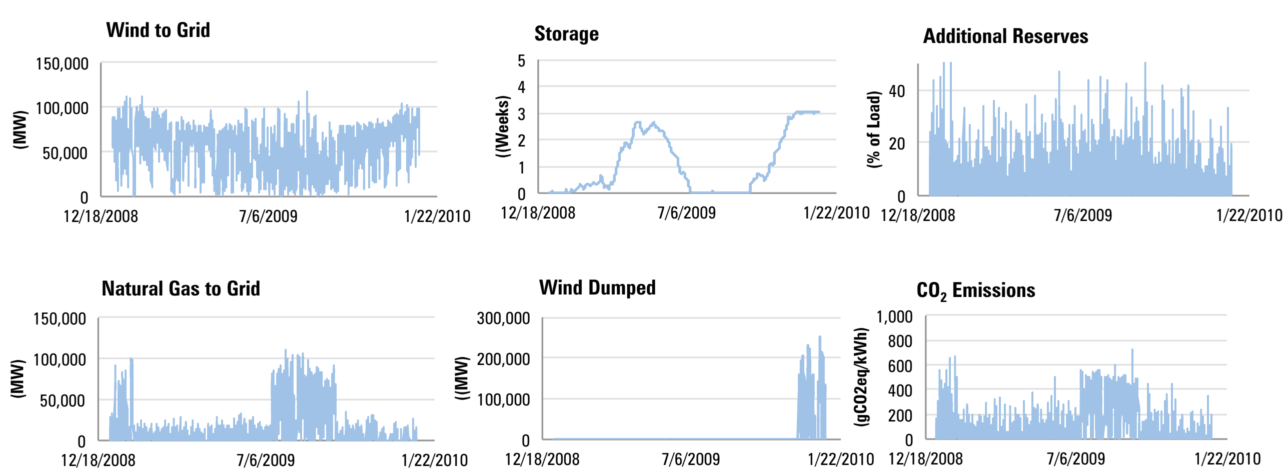


Figure 17: Wind Penetration 100%



ning reserve requirements are only 1–2% of total demand. Above 20% wind penetration, spinning reserve requirements increase significantly, even with large amounts of available storage (8 weeks in Figure 19).

Figure 18: Wind Dumped Increases with Wind Penetration

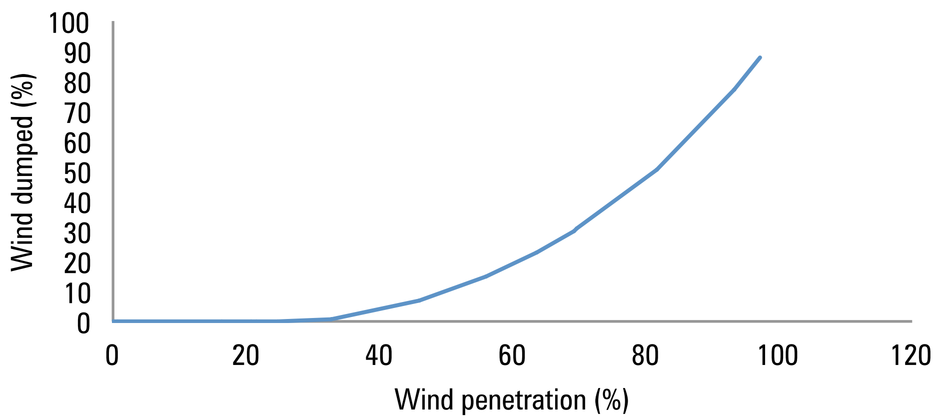
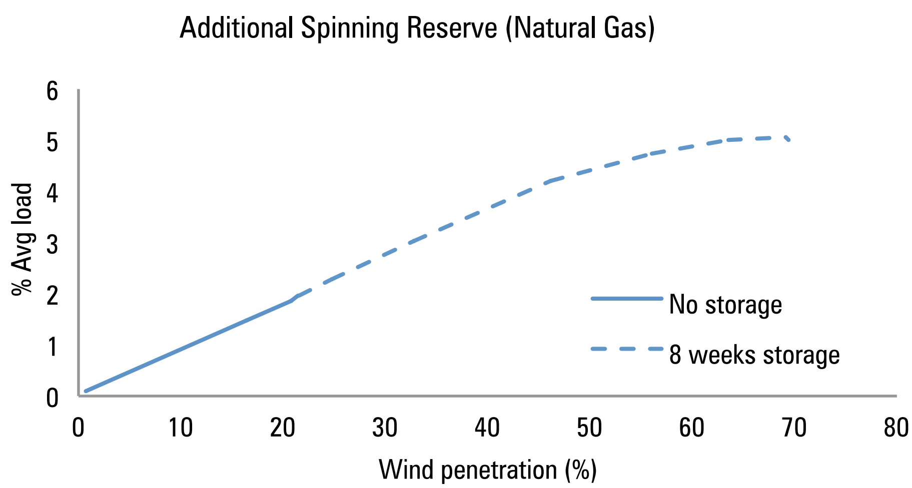


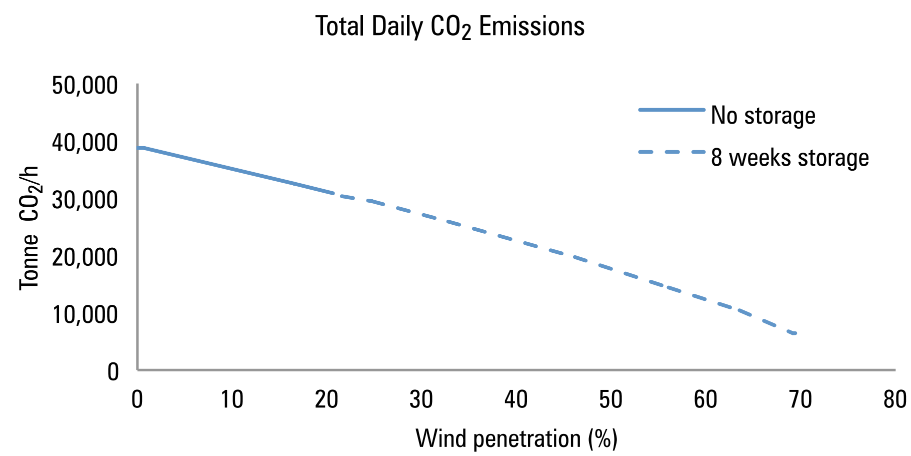
Figure 19: Spinning Reserves Increase with Wind Penetration



H. Wind CO_2 Analysis

Figure 20 documents the decrease in grid CO_2 emissions with increased wind penetration. Below 20% wind penetration, storage requirements, spinning reserves and wind dumping are minimal (see above discussion). Above wind penetrations of 20%, these factors impose increasingly severe economic and reliability constraints.

Figure 20: Total CO_2 Emissions/kWh



Part 3

Conclusions

It is commonly held that wind power has zero or nearly zero CO_2 emissions, with most of these emissions coming from manufacturing and installation of the wind turbines. Digging deeper, however, reveals that many other factors limit the amount of CO_2 emissions that can be avoided when wind power is added to the grid. Among these are factors related to wind's unpredictable nature, which in turn negatively affects grid reliability—requiring spinning reserves and storage, which also typically have other environmental impacts. For similar reasons, the costs of wind power increase dramatically with penetration.

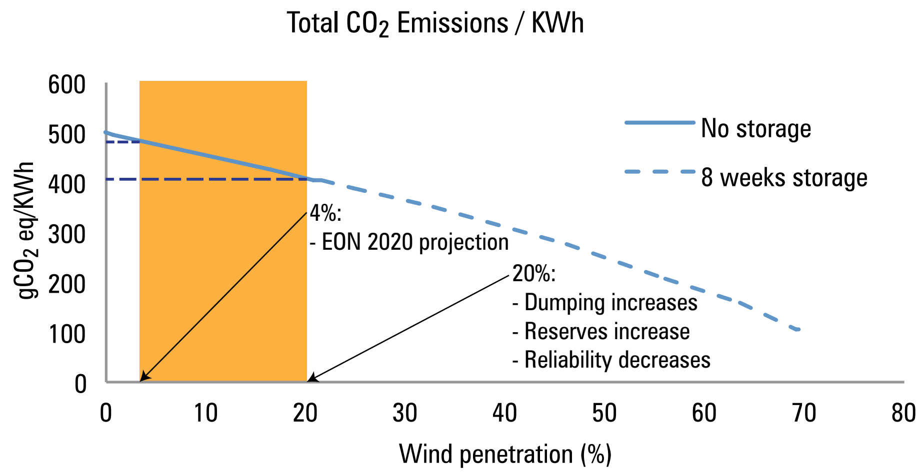
This analysis of PJM data shows that it is possible to build more wind turbines in order to increase wind penetration, thus satisfying more of a grid's demand using wind energy. In order to maintain grid reliability at high wind penetrations, it becomes necessary to build energy storage that fills when there is too much wind to supply demand, and empties when wind speed is too low to supply demand. Even with large amounts of available storage (18 weeks was the maximum in this study), there will be periods when storage is full and there is more wind than required to meet demands. During these periods, wind dumping occurs. Conversely, at low wind penetrations, there can be prolonged periods when wind is insufficient to meet demand, and there is no available storage left. During these periods, conventional power reserves (usually natural gas plants) supply power to meet demands. Since natural gas generation plants generate CO_2, their emissions are included in the accounting for wind power.

The analysis presented here demonstrates that there is a tradeoff. At low wind penetrations, there is very little impact on CO_2 emissions. As wind penetrations increase, the grid requires increasing amounts of spinning reserves to maintain reliability. At high wind penetrations, even large amounts of power storage cannot prevent significant (and expensive) wind dumping. The already high cost of wind power increases with the construction of storage facilities, and the cost to construct extra wind turbines, which will be dormant during periods of wind dumping.

Figure 21 summarizes these findings. The German company E.ON is basing its wind strategy for 2020 on an ultimate wind penetration of less than 4%. It has recognized the wind-induced reliability impacts on its grid. Using E.ON's conservative assumptions, the realizable CO_2 emissions reduction due to wind is about 18g of CO_2equivalent/kWh, or about 3.6% of total emissions. This analysis points to 20% as the extreme upper limit for wind penetration. At this point, the maximum realizable CO_2 emissions reduction due to wind is approximately 90g CO_2eq/kWh, or about 18% of total. However, it's more likely that 10% wind penetration is the upper limit, given the increased

storage costs, decreased grid reliability and increasing operating costs required to achieve this level. At this more realistic point, the maximum realizable CO_2 emissions reduction due to wind is approximately 45g CO_2eq/kWh, or about 9% of total.

Figure 21: Wind's Impact on CO_2 Emissions/KWh



Glossary

Term	Definition
Capacity Credit[32]	Capacity credit is a measure of the contribution that intermittent generation can make to reliability. It is usually expressed as a percentage of the installed capacity of the intermittent generators. Capacity credit as a percentage of installed intermittent capacity declines as the share of electricity supplied by intermittent sources increases.
Contingency Reserves[33]	These reserves mitigate a "contingency," which is defined as the unexpected failure or outage of a system component, such as a generator, a transmission line, a circuit breaker, a switch or another electrical element. In the formal NERC (North American Electric Reliability Corporation) definition, this term refers to the provision of capacity deployed by the balancing authority to meet the disturbance control standard (DCS) and other NERC and regional reliability organization contingency requirements.
Feathering	Wind turbine blades can be set so that the turbine stops turning, especially in high winds. This protects the machinery.
KWh	One kilowatt-hour. This is a measure of electrical energy equivalent to 10 100-watt light bulbs running for one hour.
Operating Reserves[34]	That capability above firm system demand required providing for regulation, load-forecasting error, forced and scheduled equipment outages and local area protection. This type of reserve consists of both generation synchronized to the grid and generation that can be synchronized and made capable of serving load within a specified period.
Regulating Reserves[35]	An amount of reserve that is responsive to automatic generation control (AGC) and is sufficient to provide normal regulating margin. Regulating reserves are the primary tool for maintaining the frequency of the bulk electric system at 60 Hz.
Spinning Reserves[36]	The portion of operating reserve consisting of (1) generation synchronized to the system and fully available to serve load within the disturbance recovery period that follows a contingency event; or (2) load fully removable from the system within the disturbance recovery period after a contingency event.
Tonne of CO_2eq/ KWh	This is a measure of CO_2 emissions. It is one metric ton of carbon dioxide "equivalent" per kWh. The designation "equivalent" means that other greenhouse gases, e.g. methane, are included in the measurement. A metric ton is 1,000 kg, or 2,200 lbs.
Wind Dumping	Sometimes not all available wind can be turned into useful power. This can happen at high wind speeds, when wind turbines must be feathered to prevent mechanical damage. It is also possible for wind dumping to occur if there is more wind energy being generated than can be absorbed by the consumers in the grid area for a period.
Wind Penetration	This is the percentage of the total power in a given electrical grid, which is provided by wind. For a 1 GW grid, which included 0.2 GW of wind power, the wind penetration is 20%.
Wind Spilling	See Wind Dumping

Endnotes

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15 Gross et al., *The Costs and Impacts of Intermittency*, Table 3.6.

16 E.ON Netz, *Wind Report 2005*, pg 8.

17 Ibid., p. 9.

18 Ibid.

19 Gross et al., *The Costs and Impacts of Intermittency*.

20 Ibid.

21 Ibid., Table 3.10

22 Ibid. p. 43

23 Ibid., Table 3.9.

24 Gross summarizes the results of six different studies, each estimating the relationship between wind penetration and energy spilled. Each point in Figure 9 represents a single point from Gross's Table 3.9, where a "point" is a pair (Wind Dumped, Wind Penetration).

25 The calculation is: ((7.4-4.6)/4.6)x100

26 The calculation is: ((7.4+5.0-4.6)/4.6x100)

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