Rethinking Wind's Impact on Emissions and Cycling Costs

Recent reports by the National Renewable Energy Laboratory and others suggest that the emissions-reducing benefits of renewable energy sources such as wind and solar may have been overstated and the cost of cycling fossil-fueled plants underestimated. These findings may change how utilities and policymakers weigh the costs and benefits of wind and solar energy.

By David Wagman

The American Wind Energy Association (AWEA) said in early January that 1,833 MW of wind power capacity had been installed during the third quarter of 2012. Those additions brought total installed wind capacity for the first three quarters of the year to 4,728 MW and pushed the total installed wind capacity in the U.S. to 51,630 MW, from more than 40,000 turbines. AWEA also reported that as of September 2012, more than 8,400 MW of capacity were under construction in 29 states and Puerto Rico. What's more, the wind industry has added more than 35% of all new U.S. generating capacity during the past five years, second only to natural gas.

All of that new wind capacity is aimed, at least in part, at displacing fossil-fueled generating sources and reducing atmospheric and greenhouse gas emissions such as nitrous oxide (NO_x), sulfur dioxide (SO_x), and the still-unregulated carbon dioxide (CO_2). Wind generation has inherent benefits: The turbines produce no emissions during their operating lifetimes and have no fuel cost. But some industry observers contend that adding intermittent resources such as wind and solar energy to the system actually increases rather than decreases greenhouse gas emissions.

Those observers point out that many power generators add fast-start gas-fired generating units (generally aeroderivative gas turbine and gas-fired engines) to back up renewable resources and generate power during the times when the sun doesn't shine or the wind doesn't blow. Those fossil-fueled resources are variously available as spinning reserves or as fast-start machines that can rapidly ramp to respond to changing output from renewable resources. Observers also contend that cycling or turndown operations at baseload coal and natural gas–fired plants to accommodate wind and solar also may increase air emissions because those fossil-fueled plants end up operating at less-than-optimal levels.

A fact sheet published by AWEA said that, on average, adding 3 MW of wind energy to the U.S. electric grid reduces emissions from fossil power plants by 1,200 pounds of CO_2 per hour. It said adding this amount of wind would "at most require anywhere from 0 to 0.01 MW of additional spinning reserves, and 0 to 0.07 MW of non-spinning reserves." AWEA said it is likely that those reserves would be provided by zero-emission hydroelectric resources, but even under a worst-case scenario in which a fossil fuel plant with an efficiency penalty of 1.5% must be used for reserves and all of the non-spinning reserves would be activated, the increase in emissions would "still be less than 1 pound of CO_2." Given that hydropower is always dispatched first and seldom cycled, and coal still provides around 40% of the electricity nationwide and is being cycled, this is a narrow and highly unlikely scenario (see sidebar).

AWEA said that although the wind may suddenly slow down at one location and cause the output from a single turbine to decrease, regions with high penetrations of wind energy may have hundreds or even thousands of turbines spread over hundreds of miles. As a result, it typically takes minutes or even hours for a region's total wind energy output to change significantly. Yet when the resource does unexpectedly drop, the amount of that reduction must be added immediately to the grid, first with spinning reserve capacity or with fast-start assets.

The unpredictability of the resource explains the large number of gas-fired assets built over the past several years. The trade group said that gas-fired units make it "relatively easy for utility system operators to accommodate these changes without relying on reserves." It said the task of accommodating variations in output can be made easier by using forecasting, which allows system operators to "predict changes in wind output hours or even days in advance with a high degree of accuracy."

Assessment Shortcomings

Despite the AWEA fact sheet, industry observers have found room to question the claimed environmental benefits of wind energy. For example, two researchers, Warren Katzenstein and Jay Apt of Carnegie Mellon University, wrote in 2009 that life-cycle assessments of renewable energy projects often failed to account for emissions from backup and cycling fossil-fired generation sources. The pair found that CO_2 emission reductions from a wind or solar photovoltaic (PV) system coupled with a natural gas system are likely to be 75% to 80% of those assumed by policymakers. Even for the best system they analyzed, NO_x reductions with 20% wind or solar PV penetration were 30% to 50% of those expected.

To estimate emissions from fossil-fueled generators that are called on to compensate for variable wind and solar power, the Carnegie Mellon authors modeled a combination of variable renewable power with a fast-ramping natural gas–fired turbine. They used a regression analysis of measured emissions and heat rate data taken at 1-minute resolution from two types of gas turbines to model emissions and heat rate as a function of power and ramp rate. They next determined the required gas turbine power and ramp rate to fill in the variations in 1-minute data from four wind farms and one large solar PV plant, and, finally, computed the emissions from the regression model.

The research team obtained 1-minute resolution emissions data for seven General Electric LM6000 natural gas combustion turbines (CTs) and two Siemens-Westinghouse 501FD natural gas combined cycle (NGCC) turbines. The LM6000 CTs had a nameplate power limit of 45 MW and utilized steam injection to mitigate NO_x emissions. A total of 145 days of LM6000 emissions data was used in the regression analysis. The Siemens-Westinghouse 501FD NGCC turbines had a nameplate power limit of 200 MW with GE's dry low-NO_x (DLN) system and an ammonia selective catalytic reduction (SCR) system for NO_x control.

Emissions data for 11 days was obtained for the 501FD combined cycle machine. The renewables data included 1-second, 10-second, and 1-minute resolution and was from four wind farms and one large solar PV facility in the Eastern Mid-Atlantic, Southern Great Plains, Central Great Plains, Northern Great Plains, and Southwest regions of the U.S.

Based on their analysis, the authors concluded that the conventional method used to calculate displaced emissions was inaccurate, particularly for NO_x emissions. They said that if system operators recognize the potential for ancillary emissions from gas generators used to fill in for variable renewable power, they can take steps to produce a greater displacement of emissions. They said that "by limiting generators with GE's DLN system to power levels of 50% or greater, ancillary emissions can be minimized." Operation of DLN controls with existing firing modes that reduce emissions when ramping may be practical. They also said that on a time scale compatible with renewable portfolio standard implementation, design and market introduction of generators that are more appropriate from an emissions viewpoint may be feasible to pair with variable renewable power plants.

Utility Perspective

Utilities that have relatively high and growing amounts of intermittent renewable resources on their systems also have analyzed renewable integration costs, paying particular attention to the cost of wear and tear on equipment and increased maintenance at existing conventional facilities.

For example, Public Service Company of Colorado (PSCo), a unit of Xcel Energy, prepared a report for state regulators in August 2011 that said the utility would add around 700 MW of wind power to its system by 2015, in line with its 2007 Colorado Resource Plan. That additional wind capacity meant PSCo would have around 1,934 MW of nameplate wind generation capacity on its system. One shortcoming of its planning process, however, was its failure to consider wind-induced cycling costs. With growing amounts of wind on its system, the utility said the cost impacts both of unit cycling and wind curtailments will increase, making it important to consider those costs as part of its future planning decisions. The importance of such calculations was highlighted for a single hour last spring when wind energy supplied 57% of the Colorado system's electricity.

"With an ever-larger wind portfolio, the depth and frequency of cyclical operation of baseload units will increase and affect more and more generators," the PSCo report said. "Coal-fired units that have historically been base loaded will be required to turn-down to their minimum capacity, or possibly turn off entirely. These cycling evolutions will be occurring more rapidly and more frequently with greater levels of wind generation."

The study said that any plant cycling causes component wear-and-tear costs. In particular, when a thermal generator is turned off and on, the boiler, steam lines, turbine, and auxiliary components endure large thermal and pressure stresses. Eventually, those stresses can cause component failures and drive up maintenance costs. During low-load operation, pressures and temperatures fluctuate in pipes and tubes, causing fatigue and, ultimately, early failure. Fatigue further erodes the designed stress tolerances of full-output operation, or creep tolerance. PSCo identified this creep-fatigue interaction as "one of the most important phenomena" contributing to component failure.

Wind-induced cycling costs among PSCo's coal-fired fleet pose an additional "hidden" cost of integrating wind generation onto the system, the report said. "It is appropriate to determine this additional wind integration cost and appropriately burden incremental wind power with this cost in future resource planning efforts." A sample of the cost findings is shown in Table 1.

The study evaluated two coal plant cycling protocols. The first (referred to as "curtail") involved cycling coal plants down to their economic minimum generation levels to accommodate wind and curtailing wind in excess of the level needed to meet system load. The second protocol (referred to as "deep cycle") involved cycling coal plants down to their lower emergency minimum levels to accommodate wind and curtailing wind in excess of the level needed to meet system load.

Although the analysis identified no significant difference in the cost of each protocol, the deep-cycle protocol was found to maximize wind output while minimizing coal burn and associated CO_2 emissions. PSCo said this protocol may result in reduced system reliability as a result of routinely operating baseload coal units down to their emergency minimum loading levels. It said such a condition would increase the wear and tear on these units and possibly lead to more coal unit outages. In contrast, the curtail protocol would result in slightly less wind generation than the deep-cycle protocol but would avoid deep cycling the coal units and the potential downside of reduced system reliability under a deep-cycle protocol.

PSCo chose deep cycling as the preferred operational protocol for its system in the near term, given that there was no distinct cost advantage to either protocol. However, it stopped short of considering some additional factors that it said could influence total costs. In particular, changes in SO_2 and NO_x emissions that may occur to accommodate wind due to reduced coal burn or coal units operating at suboptimal generating levels were not considered.

Reevaluating Impacts

The Carnegie Mellon and PSCo studies, among others, urge a systemwide approach to understanding wind and solar energy's effects on emissions. These studies helped lead researchers at the National Renewable Energy Laboratory (NREL) to acknowledge in 2012 that many efforts to assess the emissions benefits of wind had failed to account for ancillary emissions from generating units that cycle or ramp to compensate for the renewable resources' intermittent generation.

In a paper given at the IEEE Power and Energy Society General Meeting in San Diego last July, NREL researchers, along with analysts from Intertek-APTECH (IA), said that regional integration studies have shown that wind and solar may cause fossil-fueled generators to cycle on and off and ramp more frequently. They identified increased cycling, deeper load following, and rapid ramping as leading to potential wear and tear on fossil-fueled generators. They said this additional wear and tear can lead to higher capital and maintenance costs, higher equivalent forced outage rates, and degraded performance over time. What's more, they said that heat rates and emissions from fossil-fueled generators may be higher during cycling and ramping than during steady-state operation.

The conference paper concluded that "the impacts of generator cycling and part-loading

Table 1. PSCo scenario results from 2011 to 2025. The dollar values are shown as present value. *Source: "Wind Induced Coal Plant Cycling Costs and the Implications of Wind Curtailment for Public Service Company of Colorado," August 2011*

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2 GW	Curtail	3.60	1.20	4.82	0.77
2 GW	Deep cycle	5.10	0.10	5.21	0.83
3 GW	Curtail	5.00	3.30	8.30	1.03
3 GW	Deep cycle	8.20	0.60	8.75	1.08

can be significant; however, these impacts are modest compared with the overall benefits of replacing fossil-fueled generation with variable renewable generation."

The NREL/IA team along with GE Energy built on this initial work with a second, more comprehensive study using continuous emissions monitoring (CEM) data obtained from the Environmental Protection Agency to model ramping and cycling effects across the Western Interconnection based on a variety of scenarios of solar and wind penetration. The impacts of solar- and wind-induced cycling on emissions proved to be mixed, one of the report's authors told *POWER* in an interview.

"My conclusion regarding SO_2 is there is hardly any increase at all; since SO_2 is controlled by scrubbers," said Steve Lefton, director of power plant projects at IA. He said plant operators can control SO_2 emissions during ramping and cycling events by bringing more scrubber modules online sooner. Lefton said that analysis of hundreds of coal-fired units showed that SO_2 limits were exceeded only a few times and only for brief periods of time during startup or ramping.

NO_x emissions, by contrast, are a function of temperature, meaning their production likely will be higher until temperatures at the SCR inlet reach around 500F. He characterized the resulting increase in NO_x emissions as "minor" and said that it takes time to raise SCR inlet temperatures high enough to support efficient catalytic reduction.

Dr. Greg Brinkman, an NREL mechanical engineer and analyst, and report coauthor with Lefton, said that NO_x emission rates (in pounds per megawatt-hour) from a typical coal-fired unit would be 14% less when operated at part load compared to operating the unit at full load. For gas units, NO_x emissions are roughly 10% to 20% higher during part-load operation compared to full-load operation. NREL modeled the response of the electric power system to renewable penetration, considering part-load, startup, and ramping emission penalties. "Most emission rates at fossil-fueled generators changed by less than 2%," he said.

"CO_2 emissions rates from the average coal plant don't change; SO_2, and NO_x emissions rates from average coal, gas combined cycle, and gas combustion turbine plants increase or decrease by up to 2%, depending on plant type and the mix of wind and solar. SO_2 emissions rates from coal plants increased or decreased depending on the mix of wind and solar. Viewed from the perspective of avoided emissions, CO_2, SO_2, and NO_x benefits from wind and solar were all within 5% of what we expected based on the typical emission rates of the displaced generators," Brinkman said.

Effects on Maintenance Costs

Although any change in emissions appears to be relatively minor, the same cannot be said for maintenance costs due to ramping and cycling.

"From all reports, I'd say we've either been spot on or under-projecting cycling-related damage" that results from fossil-fueled units following intermittent renewable sources, said Lefton. "Yes, wind is a great thing, but it's not free."

Turbine blade damage and generator failures were linked to ramping. These findings came after Lefton and his team analyzed some 400 data sets that included long-term operating and maintenance costs and cycling data. The findings showed that even combustion turbines and reciprocating engines designed for quick starts, ramping, and cycling showed higher maintenance costs, elevated numbers of forced outages, and increasing numbers of generator failures.

"Generator failures used to be rare, but now they rank third in insurance claims filed for combined cycle machines," Lefton said. He noted higher incidences of heat recovery steam generator tube failures as well as more frequent turbine overhauls. Other maintenance issues linked to cycling include thermal barrier coatings that spall off, leaving the base metal exposed and vulnerable to cracking.

Dr. Debra Lew, an analyst with NREL and coauthor of the report, said while coal units cost the most to start up, gas-fired combustion turbines appear to be the most susceptible to higher maintenance costs as a result of ramping and cycling caused by wind and solar penetration because these units are started the most often. She said that wear and tear as a result of cycling to follow renewable energy may increase operations and maintenance costs for all types of fossil generation by $35 million to $157 million a year across the Western Interconnection, as shown in Table 2, for wind and solar penetrations up to 33%.

Last November, Lefton and several of his colleagues at IA presented a paper, "The Increased Cost of Cycling Operations at Combined Cycle Power Plants," at the International Conference on Cyclic Operation of Power Plants & CCGT. The paper reported that higher penetration of renewables on the North American grid is increasing the number of on-off and load-cycling operations, which the authors said will increase the need for spinning reserve megawatts, their costs, and the startup charges for putting combined cycle plants online.

The desire for faster online times increases the severity of damage during gas turbine starts and is increasing thermal transients with more rapid gas turbine acceleration and higher mass gas flows at higher exhaust temperatures that reach heat recovery steam generators (HRSGs). The paper said these factors affect the gas turbine and the HRSGs, as well as the balance of plant and water chemistry, ultimately reducing overall plant reliability. The average starts on these gas turbines/combined cycle units are increasing, and run times are generally decreasing. Though capacity factors may be decreasing, production costs will likely rise significantly due to cycling operations. The paper suggested that cost estimates made by industry often underestimate by a large margin the actual costs that cycling operations can incur, as shown in Table 3.

Wind Farm Life Expectancy

Wind farm life expectancy also may reduce calculated environmental benefits and increase the

Table 2. Renewables increase cycling and ramping costs. *Source: NREL*

[illegible]	[illegible]	[illegible]	[illegible]
No renewables	$271–$643 million	NA	NA
High wind	$321–$769 million	$50–$126 million	18%–20%
High mix	$306–$738 million	$35–$95 million	13%–15%
High solar	$324–$800 million	$53–$157 million	20%–24%

Table 3. Estimated cycling costs are often wrong. Costs provided in this table are per cycling event. *Source: Steve Lefton, et al.*

[illegible]	[illegible]	[illegible]
Small drum	$5,000	$3,000–$100,000
Large supercritical	$10,000	$15,000–$500,000
GT simple cycle	$100	$300–$80,000
GT combined cycle	$200	$15,000–$150,000

total investment needed to achieve environmental goals, particularly in the UK and Europe. A December 2012 report, published by the UK-based Renewable Energy Foundation and written by Gordon Hughes of the University of Edinburgh, scrutinized wind farm lifecycle emission benefits. The foundation in the past has criticized the UK government's Renewables Obligation policy, saying the subsidy distorts markets as well as the generation mix.

The Hughes study examined wind farm performance in the UK and Denmark and concluded that, after allowing for variations in wind speed and site characteristics, the average load factor of wind farms declines as they age, probably due to wear and tear. By 10 years of age, the contribution of an average UK wind farm to meeting electricity demand was said to have fallen by as much as one-third.

The report said this performance decline means that it is "rarely economic to operate wind farms for more than 12 to 15 years." Investors who expect a return on their investment over 20 to 25 years will be "disappointed," the report said. What's more, policymakers who expected wind farms built before 2010 to contribute toward CO_2 targets in 2020 or later should allow for the possibility that the total investment required to meet those targets will be much larger than previous forecasts suggested.

The study based its findings on data reflecting the monthly output of wind farms in the UK and Denmark. Normalized age-performance curves were estimated using statistical techniques that allowed for differences between sites and over time in wind resources, and other factors. The normalized load factor for UK onshore wind farms was found to decline from a peak of about 24% at age one to 15% at age 10 and 11% at age 15. The decline in the normalized load factor for Danish onshore wind farms showed a fall from a peak of 22% to 18% at age 15. For offshore Danish wind farms, the normalized load factor was shown to fall from 39% at the start of commercial operation to 15% at age 10.

Hughes said that the reasons for the observed declines in normalized load factors could not be fully assessed using the data available, but he speculated that "outages due to mechanical breakdowns" appeared to be a contributing factor.

Hughes said that analysis of site-specific performance showed that the average normalized load factor of new UK onshore wind farms at age one "declined significantly" between 2000 and 2011. In addition, he found that larger wind farms had worse performance than smaller wind farms. Adjusted for age and wind availability, the overall performance of wind farms in the UK has "deteriorated markedly" since the beginning of the century, he found.

According to Hughes, these findings have implications for policy toward wind generation in the UK. First, they suggest that the current government subsidy is "extremely generous" if investment in new wind farms remains profitable despite the decline in performance due to age and over time. Second, meeting the UK government's targets for wind generation will require a much higher level of wind capacity and capital investment than current projections imply. Third, the structure of contracts offered to wind generators may require modifications, because few wind farms will operate for more than 12 to 15 years.

In releasing the report, the Renewable Energy Foundation said that policymakers who were expecting wind farms built before 2010 to contribute toward CO_2 targets in 2020 or later "must allow for the likelihood that the total investment required to meet these targets will be much larger" than previous forecasts suggested. ■

—David Wagman is executive editor of POWER.

The Facts About Wind Energy's Pollution Reductions

Editor: The American Wind Energy Association (AWEA) recently contacted POWER to request an opportunity to respond to the editorial "Under Siege" published in the December 2012 issue. The following is AWEA's response to that editorial.

As wind energy's growth has continued, spurred by improving technology and declining costs, wind energy's role in reducing harmful pollution has become even clearer. Empirical data for the United States and Europe clearly indicates not only that wind energy results in the expected pollution reductions by directly offsetting the use of fossil fuels at power plants, but that by displacing the most expensive and therefore least efficient power plants first, wind energy results in even larger pollution savings than expected.

There is no dispute that every MWh of wind energy added to the power grid displaces a MWh that would have been produced by the most expensive power plant currently operating, which is typically the least efficient fossil-fired power plant. However, some have attempted to claim, without support, that adding wind energy to the power system can negatively affect the efficiency of other power plants, reducing the emissions savings produced by wind energy.

Fortunately, a large body of real-world data is now available to assess how wind energy affects the efficiency of other power plants, allowing one to approach the question from multiple angles. To start with, the U.S. Department of Energy collects detailed data on the amount of fossil fuels consumed at power plants, as well as the amount of electricity produced by those power plants. By comparing how the efficiency of power plants has changed in states that have added significant amounts of wind energy against how it has changed in states that have not, one can test the unsupported hypothesis that wind energy has a negative impact on the efficiency of fossil-fired power plants.

The data clearly shows that there is no such relationship, and in fact, states that use more wind energy have seen the efficiency of their fossil-fired power plants fare slightly better than states that use less wind energy. Specifically, coal plants in the 20 states that obtain the most electricity from wind saw their average efficiency decline by only 1.00% between 2005 and 2010, versus 2.65% in the other 30 states. Increases in the efficiency at natural gas power plants were virtually identical in the top 20 wind states and the other states, at 1.89% and 2.03% improvement respectively. The efficiency of fossil-fired power plants fared comparably well in the top 10 wind states (which obtain between 5% and 16% of their electricity from wind), with coal plant efficiency increasing by 0.51% in the top 10 wind-using states and declining by 2.65% in the other 40 states, while gas plant efficiency improved by 0.78% in the top 10 wind states and 2.17% in the other 40 states.

Similar results can be found in International Energy Agency data for Europe, which shows that the top 5 wind countries (which obtain between 7% and 23% of their electricity from wind) saw the average efficiency of their natural gas power plants increase by 11% as they ramped up their use of wind energy from 1999-2010, larger than the 7% increase in efficiency seen across all of OECD Europe. Over that time period, coal plant efficiency fell by 1% in the top 5 wind countries and remained unchanged across all OECD Europe countries.

Another method to assess whether wind energy is producing the expected emissions savings is to calculate whether increases in the use of wind energy are correlated with decreases in the amount of carbon dioxide emitted per MWh produced. A correlation coefficient of 0 would indicate that there is no statistical relationship between wind energy output and emissions intensity, a coefficient of -1 would indicate that wind output increases always coincided with increases in emissions, and the observed coefficients of nearly +1 indicate that increases in wind output nearly always coincided with major decreases in emissions. The correlation between increasing wind energy output and declining emissions intensity in the leading wind energy countries over the period 1999 to 2010 was extremely strong, with a correlation coefficient of .77 for Denmark, .82 for Germany, .86 for Portugal, .90 for Spain, and a whopping .96 for Ireland.

These correlation coefficients were far higher than for any other possible explanatory factors for the observed decreases in emissions intensity, such as increased use of hydroelectric or nuclear energy, increased use of natural gas instead of coal, changes in the efficiency of fossil-fired power plants, or changes in electricity imports or exports. If wind energy were causing large declines in the efficiency of fossil-fired power plants, zero or negative correlations would have been found, instead of correlations approaching 1.

These findings are further confirmed by the preliminary results of a new report from the National Renewable Energy Laboratory that uses empirical data from another source, EPA's network of power plant continuous emissions monitors, to evaluate the impact of wind energy on the efficiency of all fossil-fired power plants in the Western U.S. The in-depth, multi-year, and peer-reviewed analysis found that even in a scenario with wind providing 25% of all electricity in the Western U.S., wind's total impact on the efficiency of fossil-fired power plants would be "negligible," accounting for less than 0.2% of the emissions savings produced by wind energy. As a result, carbon dioxide emissions declined by 29–34% in the 25% renewable energy case. Moreover, the analysis found that adding wind energy to the grid actually slightly increases the average efficiency of coal and natural gas combined cycle power plants by offsetting the least efficient plants.

No matter how one approaches the question, the data is clear that wind energy greatly reduces fossil fuel use and pollution. Moreover, the results discussed above are in addition to a large body of independent grid operator, utility, and government analyses and data that have already examined how wind energy interacts with the power system and unanimously found that wind energy produces pollution savings that are as large or larger than expected.

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