Correspondence

Comment on "Air Emissions Due to Wind and Solar Power"

Katzenstein and Apt (*1*) investigate the important question of pollution emission reduction benefits from variable generation resources such as wind and solar. Their methodology, which couples an individual variable generator to a dedicated gas plant to produce a flat block of power is, however, inappropriate. For CO_2, the authors conclude that variable generators "achieve ~80% of the emission reductions expected if the power fluctuations caused no additional emissions." They find even lower NO_x emission reduction benefits with steam-injected gas turbines and a 2–4 times net *increase* in NO_x emissions for systems with dry NO_x control unless the ratio of energy from natural gas to variable plants is greater than 2:1. A more appropriate methodology, however, would find a significantly lower degradation of the emissions benefit than suggested by Katzenstein and Apt.

As has been known for many years, models of large power system operations must take into account variable demand and the unit commitment and economic dispatch functions that are practiced every day by system operators. It is also well-known that every change in wind or solar power output does *not* need to be countered by an equal and opposite change in a dispatchable resource (*2*). The authors recognize that several of their assumptions to the contrary are incorrect and that their estimates therefore provide at best an upper bound to the emissions degradation caused by fluctuating output. Yet they still present the strong conclusion: "Carbon dioxide emissions reductions... are likely to be 75–80% of those presently assumed by policy makers... We have shown that the conventional method used to calculate emissions is inaccurate, particularly for NO_x emissions."

The inherently problematic methodology used by the authors makes such strong conclusions suspect. Specifically, assuming that each variable plant requires a dedicated natural gas backup plant to create a flat block of power ignores the benefits of diversity. In real power systems, operators are required to balance only the net variations of all loads and all generators, not the output of individual loads or generators; doing otherwise would ensure an enormous amount of unnecessary investment and operating costs. As a result, detailed studies that aggregate the variability of all loads and generators to the system level find that the amount of operating reserves required to reliably integrate variable resources into the grid are on the order of 10% of the nameplate capacity of the variable generators, even when up to 25% of gross demand is being met by variable generation (*3*–*5*).

The authors' implicit assumption that incremental operating reserves must be 100% of the nameplate capacity of the variable generation, and be available at all times to directly counter that variability, excludes the option of decommitting conventional units when the load net of variable generation is low. In real power systems, generation response to wind variation can typically be met by a combination of committed units, each operating at a relatively efficient point of their fuel curves.

In the Supporting Information, we conceptually demonstrate that the CO_2 and NO_x efficiency penalty found by the authors can be significantly reduced by considering the unit commitment decision with just five plants. Real systems often have tens to hundreds of plants that can be committed and decommitted over various time frames. Ignoring the flexibility of the unit commitment decision therefore leads to unsupportable results.

A number of analyses of the fuel savings and CO_2 emission benefits (*6*) of variable generation have considered realistic operating reserve requirements and unit commitment decisions in models that include the reduction in part load efficiency of conventional plants (*3*). The efficiency penalty due to the variability of wind in four studies considered by Gross et al. is negligible to 7%, for up to a 20% wind penetration level (*7*). In short, for moderate wind penetration levels, "there is no evidence available to date to suggest that in aggregate efficiency reductions due to load following amount to more than a few percentage points" (*8*). As such, other studies using a more appropriate methodology have found a much smaller CO_2 penalty from variability than found by Katzenstein and Apt (*1*).

Less information is available on the NO_x emission penalty. Results from recent state-of-the-art integration studies in the United States indicate at the very least clear NO_x emission reduction benefits from variable generation. NO_x reductions estimated in these studies are discussed in more detail in the Supporting Information. Denny and O'Malley similarly find NO_x reduction benefits when forecasting is used in the unit commitment decision (*9*).

In summary, though Katzenstein and Apt consider part load efficiencies and emissions during ramping, they ignore several salient features of real power systems, particularly diversity and the unit commitment decision. Ignoring diversity leads the authors to implicitly assume 100% operating reserves, when detailed studies indicate that just 10% operating reserves may be required. Ignoring unit commitment leads the authors to potentially far overstate part load efficiency penalties and, therefore, to also overstate the CO_2 emission penalty associated with variable generation. Though the potential size of a NO_x emission penalty is not as well addressed in the extant literature, detailed integration studies in the United States at the very least indicate that wind and solar *decrease* NO_x emissions.

Acknowledgments

This work was funded by the Office of Energy Efficiency and Renewable Energy (Wind & Hydropower Technologies Program and Solar Energy Technologies Program) and by the Office of Electricity Delivery and Energy Reliability (Permitting, Siting, and Analysis Division) of the U.S. Department of Energy under Contract DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory and Contract DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

Supporting Information Available

Demonstration that the CO_2 and NO_x efficiency penalty for wind and solar presented by Katzenstein and Apt (*1*)can be reduced through consideration of the unit commitment decision, NO_x emission reduction results from recent integration studies, and clarification of CO_2 emissions reduction benefits of wind from ref *9*. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

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Published on Web 07/07/2009

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(6) Because CO_2 emissions are generally proportional to fuel consumption for a single plant, the CO_2 emissions penalty is similar to the fuel efficiency penalty.

(7) The interpretation of the CO_2 emission reduction benefits of wind in ref 9 by Katzenstein and Apt is incorrect and is clarified in the Supporting Information.

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Andrew Mills, and Ryan Wiser

Energy Analysis Department, Lawrence Berkeley National Laboratory, Berkeley, California 94720

Michael Milligan

National Renewable Energy Laboratory, Golden, Colorado 80401

Mark O'Malley

School of Electrical, Electronic and Mechanical Engineering, University College Dublin, Dublin 4, Ireland

ES900831B