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System-Wide Emissions Implications of Increased Wind Power Penetration

Lauren Valentino,[†,‡] Viviana Valenzuela,[†,§] Audun Botterud,[*,†] Zhi Zhou,[†] and Guenter Conzelmann[†]

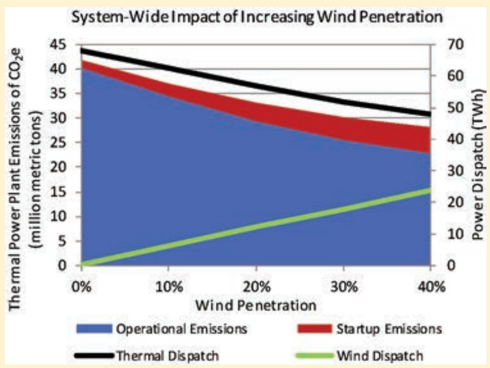
[†]Decision and Information Sciences Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, United States

[‡]University of Illinois, Champaign/Urbana, Illinois, United States

[§]Georgia Institute of Technology, Atlanta, Georgia, United States

Supporting Information

ABSTRACT: This paper discusses the environmental effects of incorporating wind energy into the electric power system. We present a detailed emissions analysis based on comprehensive modeling of power system operations with unit commitment and economic dispatch for different wind penetration levels. First, by minimizing cost, the unit commitment model decides which thermal power plants will be utilized based on a wind power forecast, and then, the economic dispatch model dictates the level of production for each unit as a function of the realized wind power generation. Finally, knowing the power production from each power plant, the emissions are calculated. The emissions model incorporates the effects of both cycling and start-ups of thermal power plants in analyzing emissions from an electric power system with increasing levels of wind power. Our results for the power system in the state of Illinois show significant emissions effects from increased cycling and particularly start-ups of thermal power plants. However, we conclude that as the wind power penetration increases, pollutant emissions decrease overall due to the replacement of fossil fuels.



INTRODUCTION

There has been a recent push by environmental agencies and policymakers alike to use alternative energy sources as a means to reduce harmful pollutant emissions from power plants. One scenario modeled in part by the U.S. Department of Energy examines the requirements and ramifications of wind power providing 20% of U.S. electricity by 2030.[1] Wind energy is advantageous because it does not exhaust the supply of natural resources like coal and oil, nor does it create any polluting or hazardous emissions. However, one of its drawbacks is that it is variable and uncertain. Although wind energy generation itself does not generate emissions, its variability and uncertainty may have negative effects on emissions from the rest of the power system. With increasing wind power penetration, fossil-fired power plants may be forced to adjust their output level, start up, or shut down to accommodate the variability in wind generation.[2] As wind energy becomes a bigger player in the electric power industry, it is expected that start-up and cycling events will occur more frequently. This analysis aims to quantify the total effect that wind energy has on pollutant emissions from the overall electric power system.

Denny and O'Malley[3] first analyzed the impact of wind generation on Ireland's power system using an economic dispatch model that incorporates wind power forecasts into the dispatch decisions. They found that wind generation alone could be used as a means to decrease carbon dioxide (CO_2) emissions, but it was not effective in reducing sulfur dioxide (SO_2) or nitrogen oxide (NO_x) emissions in Ireland. Katzenstein and Apt[4] assumed that natural gas turbines compensate for the variability in wind power and modeled emission rates as a function of power level and ramp rates using actual data from two gas turbines. They concluded that CO_2 emissions can be reduced by wind power but NO_x reductions are highly dependent on NO_x controls and dispatch decisions. Lu et al.[5] analyzed the additional costs and possible CO_2 savings incurred when integrating different levels of wind penetration into the ERCOT region of Texas in 2030. When the additional future demand is met by a combination of state-of-the-art coal-fired, gas combined cycle, combustion turbine, and wind power, they find that CO_2 emissions can be reduced by as much as 50.6% for 20% wind penetration due, in part, to the assumed replacement of coal for gas-fired generation. DOE's 20% by 2030 wind integration study estimated an annual carbon reduction of 825 million metric tons with a 20% wind power penetration in the United States.[1] Despite these predicted reductions in emissions, some authors argue that wind will actually increase overall system emissions due to cycling and start-up events. In particular, Bentek Energy[6] concluded that wind-induced cycling of coal plants drives heat

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rates up and operating efficiency down resulting in higher emissions. Previous emissions analyses[1,3,5] do not account for cycling effects, and recent wind integration studies in the United States[7,8] do not include the effect of start-up emissions. These are clearly omissions that require further investigation.

Some of the work concerning start-up emissions has been done under the pretense of developing emission rate limits for power generation units. Macak[9] studied emissions from natural gas-fired simple cycle units and found that emissions performance improves as load increases during the start-up period. Suess et al.[10] looked at start-up emissions from several natural gas-fired combined cycle units and presented a process that can be used by any facility seeking to implement new start-up or shutdown limits. In this study, we incorporate these findings[9,10] into a more detailed analysis of the environmental impact from increasing wind power penetration.

To our knowledge, we are the first to use a model that incorporates the effects of both cycling and start-ups in analyzing emissions from an electric power system with high wind penetrations. Our emissions analysis builds upon a detailed model of the operation of the power system, including unit commitment and economic dispatch under wind power uncertainty, as proposed by Wang et al. and Zhou et al.[11,12] Using heat rate curves to account for the cycling effect, the hourly power dispatch results are converted to fuel use and then power plant emissions. The method to assess start-up emissions is unique to each type of thermal generation unit: steam turbine, combined cycle unit, and combustion turbine.

This paper has the following outline: We first give an introduction to the wind power forecast and unit commitment/dispatch models used in the analysis. We then give a brief overview of power plant emissions and control technologies followed by an explanation of the emissions analysis methodology. Finally, we present emission results from the Illinois power system under different assumptions about wind power penetration.

METHODOLOGY AND DATA

Power System Operations. In this analysis, we use wind power forecasts[13] as input to the commitment and scheduling of the thermal power plants, considering the needs for both energy and operating reserves to maintain reliability in the power system. The uncertainty in the wind power forecast influences the amount of operating reserves required to handle forecasting errors in the power system, where supply and demand have to be balanced continuously.[14] We use probabilistic wind power forecasts based on kernel density estimation with a quantile copula estimator[15] to estimate the forecast uncertainty at the hour-ahead stage. The requirements for spinning and nonspinning reserves are derived from the probabilistic forecasts so that there is a 99% likelihood of meeting the demand for energy and operating reserve in real-time.[12] The required level of operating reserves increases as a function of the wind power capacity, as more wind power results in increasing levels of forecast uncertainty. This has implications for the efficiency and emissions from the thermal power plants, since more plants have to be committed and operate at reduced power generation levels to provide the required spinning reserves.

Our simulation of the power system considers scheduling and dispatch decisions in both day-ahead and real-time markets, using a detailed unit commitment and dispatch model. The objective of the model is to find the schedule for thermal power plants that minimizes the total operating cost of the power system for the next day, given the forecast or realized wind power generation and considering heat rate curves and the operational constraints of the thermal units. Transmission constraints are not considered in this analysis. We assume that base-load units, which have long start-up times, are committed in the day-ahead market based on a day-ahead forecast for wind power. The commitment of fast-starting units is reoptimized ahead of the real-time market based on a 1-h-ahead wind power forecast, which is more accurate than the day-ahead forecast. This simulation setup with day-ahead unit-commitment, recommitment of fast starting units, and real-time dispatch closely resembles operating procedures of most electricity markets in the United States today.

A detailed description of the algorithms for probabilistic wind power forecasting and power system operations is provided in the Supporting Information.

Emissions Analysis. Fossil-fired power plants are major emitters of many pollutant gases and particles. Emission estimates are important for developing emission control strategies, determining permitting requirements, and quantifying emissions from pollutant sources. Emission factors are often the best or only method available for estimating emissions, in spite of their limitations. For this analysis, we extract emissions factors from the EPA AP-42[16] for each individual power plant for the following pollutants: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x but mainly SO_2), and particulate matter (PM). The emissions factors represent averages of all available data of acceptable quality, according to the EPA.[16]

After the unit commitment and dispatch models are run, the dispatch results are used to calculate fuel input, and the emission levels are determined using the computed fuel consumptions and the emission factors given by the EPA AP-42. Emissions resulting from normal operational periods and start-up periods are calculated for CO_2, CH_4, N_2O, CO, NO_x, SO_x, and PM, as described below. A few exceptions to note are that natural gas as a fuel source results in negligible SO_x emissions because it naturally contains very little sulfur, nuclear has no conventional emissions during operation, and hydro-powered units are assumed to have zero emissions; that is, we ignore limited GHG emissions from reservoirs.

Operational Periods. During normal operational periods, emissions are calculated in a similar fashion for all types of electric power generation units. The hourly power generation, which is a result of the dispatch model, is converted into hourly fuel use through a fuel consumption function. We estimated a unique fuel consumption function for each individual unit based on four blocks of technology-specific heat rate data[17,18] and the respective unit sizes. The block-based heat rates are used as input to the unit commitment and dispatch model. A sample heat rate curve for a coal-fired steam turbine is illustrated in Figure 1. Heat rates are linked to cycling because, as power generation of a particular unit decreases, its heat rate increases meaning that more fuel is used per unit of electricity generation. Note that if more thermal units are forced to reduce their energy output to provide spinning reserves to accommodate wind power uncertainty, this will tend to increase the average heat rates and emissions from the respective units.

Control Technologies. In an effort to reduce harmful pollutant emissions, almost every thermal power unit has

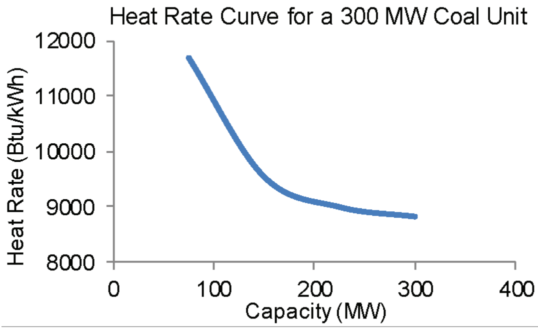

Figure 1. Sample heat rate curve for a coal-fired steam turbine unit.

control technologies and/or special firing techniques in place. Plant-specific information can be found in the EPA's eGRIDweb database,[19] and we account for these controls in this analysis. Specifically, we adjust the emission factors of each generator based on the control technology or firing technique it uses.

There are two types of controls: precombustion and postcombustion. During periods of normal operation, both types of controls are effective, provided there is no mechanical malfunction. However, during start-up periods, the postcombustion control techniques, which mainly apply to SO_x and NO_x, are not effective. Therefore, when calculating emissions during start-up periods, uncontrolled emission factors for SO_x are used. NO_x, along with CO, is emitted at higher rates during start-ups because NO_x formation is a function of firing temperature.[8] CO results from incomplete combustion of carbon, and there are four contributing factors: the oxygen concentration, flame temperature, gas residence time at high temperatures, and the combustion chamber turbulence.[20] Each of these contributing factors is different during start-up in comparison to normal operational periods resulting in higher emissions during a start-up than a normal operational period of the same time length.

Steam Turbine Unit Start-Up Periods. The emissions during start-up depend on how long the unit has been offline previously. The amount of fuel used to bring the unit online is a function of the downtime of the unit, and we estimate this nonlinear relationship based on available data.[21,22] With the fuel use per simulated start-up and AP-42 emissions factors, we calculate mass emissions for each pollutant.

As mentioned previously, postcombustion control technologies for coal-fired units are not effective until the unit has reached a certain temperature. We therefore apply uncontrolled emission factors for coal and fuel oil no. 6 for these calculations since many coal-fired steam turbines use a combination of coal and heavy fuel oil for start-up purposes.

Combustion Turbine Start-Up Periods. Unlike steam turbine units, the start-up time for combustion turbines is independent of the downtime. Leyzerovich[23] shows that despite significant differences in prior downtime, combustion turbines achieve their full capacity after 20 min.

Because the start-up time is independent of downtime, the fuel input during start-up is a function of the power to which the unit is ramped up. Time series for power output, heat rates, and NO_x emission rates from 16 separate start-ups were previously used in a study performed by Florida State University.[24] In general, the average heat input rate (MBtu/h) increases as the power to which a unit ramps up to increases. We estimate this as a linear relationship based on available data, and use the power output during the first hour of operation, the linear function, and the start-up time (20 min) to reach Pmin to calculate the fuel consumed per start-up of a combustion turbine unit. We convert the fuel to emissions using the EPA emissions factors. This method is used to calculate emissions for all pollutants, except for NO_x and CO since both are emitted at higher rates during start-ups.

The start-up time of a simple cycle gas turbine is approximately 20 min regardless of how long the unit has been inactive, as pointed out above.[23] On average, 34 pounds of NO_x are emitted,[8,24] and approximately 70 pounds of CO are emitted[8] during a 20 min start-up. In our model, we apply these mass emissions each time a combustion turbine unit start-up occurs.

Combined Cycle Unit Start-Up Periods. In a natural gas combined-cycle unit, a combustion turbine generates electricity in the same way that a simple cycle unit generates electricity. The addition of a steam turbine only enhances the efficiency of the natural-gas fired unit by utilizing the waste heat to produce additional electricity. The start-up of combined cycle units includes the start-up of both the gas turbine and the heat recovery steam generator (HRSG). We assume the gas turbine reaches its full capacity power output before the HRSG begins to heat up, as shown in Figure 2. Using the uncontrolled AP-42

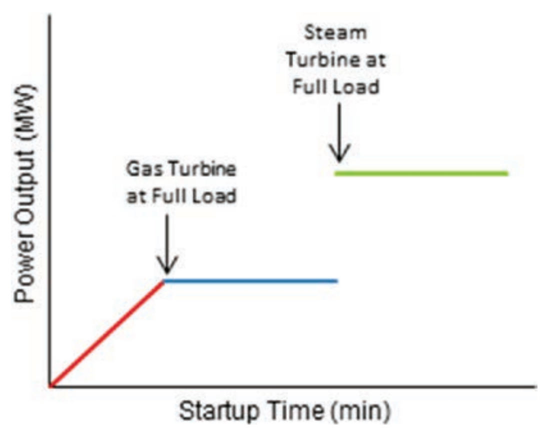

Figure 2. Start-up of a combined cycle unit can be broken into two stages: gas turbine start-up and heating of HRSG. The gas turbine takes approximately 20 min to reach its maximum output, and this is followed by the HRSG start-up.

emission factors, emissions are calculated for all pollutants, except for NO_x and CO, for the period up to the point the HRSG starts.

NO_x and CO emissions during start-up cannot be determined using the method presented above because both these compounds have higher emission rates during start-up than during periods of normal operation. Emissions for these two pollutants increase linearly as the start-up time increases.[10,25] Start-up times for combined cycle units, which are included in the operational constraints for each unit, are therefore used to determine the emissions of NO_x and CO.

We recognize that the limited data availability on start-up emissions adds uncertainty to the estimates outlined above. Better availability of data in the future will facilitate more accurate estimates of start-up emissions.

Case Study. In the case study, the Illinois power system is used to simulate the impact of several wind generation levels for a 4-month period based on data from July to October 2006.

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Loads and thermal generation correspond to the situation in Illinois in 2006. A fixed daily export schedule corresponding to the total export from Illinois over the year (i.e., 18.2% of total generation in 2006) was added to the in-state load. We assume that additional wind power is added to this system. The data for 2006 were based on Cirillo et al.[26] and updated based on more recent information. The system consisted of 210 thermal units (individual and aggregated) with a total capacity of 44 516 MW. The distribution of thermal generation capacity (i.e., not including wind or hydro power) is illustrated in Figure 3. The

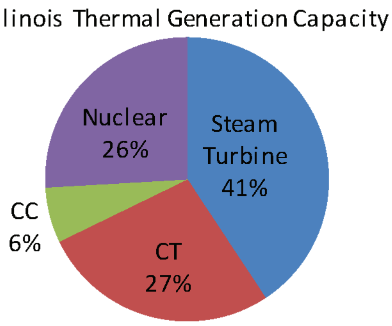

Figure 3. Thermal generation capacity by technology in Illinois, 2006. ST includes mainly coal-fired units, but also two residual fuel oil (no. 6) and three natural gas units. CT includes mainly natural gas-fired units, but also nine distillate fuel oil (no. 2 and jet fuel) units. CC units are natural-gas fired only.

thermal unit data serves as input to the unit commitment problem and consists of minimum and maximum output, initial state, minimum on/off hours, ramp rates, start-up costs, fuel costs, and heat rate curves. The heat rate curves were updated based on data from EPRI,[17,18] using the average reported heat rates for the different power plant categories. Table 1 summarizes the heat rate assumptions for the fossil-fired generation categories. The heat rates are higher for lower plant loading levels, resulting in a lower efficiency which is expressed as a part-load penalty in Table 1. Hence, if the variability and uncertainty in wind power forces the thermal power plants to cycle more frequently, they will operate at part-load more often with reduced efficiency and therefore higher emissions. The combustion turbines (CT) have the highest part-load penalties, whereas the part-load effect is lower for combined cycle (CC) and steam (ST) units. In the unit commitment and dispatch model, the heat rate curves were represented with up to four blocks for each thermal unit.

The hourly load profile corresponds to the historical data in the state of Illinois in 2006. We assumed that there is no uncertainty in the hourly loads in order to isolate the effects of wind power uncertainty from load uncertainty. The wind power data that we used consists of day-ahead wind power forecasts and realized wind power generation for 15 hypothetical locations in the state of Illinois in 2006. Time series of aggregate deterministic point forecasts (day-ahead and hour-ahead) and realized wind power generation for the 15 sites were obtained from the Eastern Wind Integration and Transmission Study.[7] The time series data has hourly time resolution. The accuracy of the wind power forecast varies from day to day. For the point forecasts, the normalized mean average error over the entire simulation period is 8.5% and 4.1% for day-ahead and hour-ahead forecasts, respectively. For the hour-ahead forecasts, we generated probabilistic forecasts and calculated operating reserve requirements accordingly, as described above. We trained the kernel density forecasting algorithm based on data from January to June 2006 and produced hourly probabilistic forecasts for the simulation period from July to October 2006. Note that a substantial amount of effort goes into data preparation and computations, and this prevented us from running a longer time period. However, the 4-month simulation period covers both the summer months with peaking loads and the shoulder months with intermediate and low loads and higher wind generation. Hence, the chosen period gives a good representation of the conditions of the power system over the course of a year.

RESULTS

Emission results for the 4-month simulation period are presented in Table 2 for each of the 7 pollutants studied in this analysis and the carbon dioxide equivalent (CO_2e). CO_2e emissions combine the greenhouse gases CO_2, CH_4, and N_2O into one measure using the individual gases' global warming potentials. Figure 4 shows that total emissions decrease with increasing wind power penetration. In each case, the wind power penetration is defined as percentage of total amount of wind energy produced (MWh) over the total electrical demand (MWh) in Illinois for the simulation period (excluding export). The bar charts in Figure 4 distinguish start-up emissions (red) from the operational emissions (blue).

Despite the omission of start-up emissions from previous wind integration studies, we did not expect start-up emissions

Table 2. Emission Reductions Relative to the Emission Levels at 0% Wind Penetration

	emission reduction							
wind	CO_2e	CO_2	N_2O	CH_4	CO	NO_x	SO_x	PM
10%	12%	12%	9%	12%	10%	13%	8%	11%
20%	21%	21%	11%	17%	15%	22%	17%	22%
30%	28%	28%	10%	21%	19%	29%	24%	32%
40%	33%	33%	4%	23%	20%	34%	30%	40%

Table 1. Average Heat Rates and Corresponding Part Load Penalties for Fossil Generation Technologies at Different Loading Levels[a]

	average heat rate [Btu/kWh]				part load penalty [%]			
load	coal (ST)	gas (CC)	gas (CT)	oil (CT)	coal (ST)	gas (CC)	gas (CT)	oil (CT)
25%	13152	10557	19529	24606	34.19	44.84	64.97	113.46
50%	10689	8250	13965	14618	9.06	13.20	17.97	26.82
75%	10021	7567	12402	12135	2.24	3.82	4.76	5.27
100%	9801	7288	11838	11527	0.00	0.00	0.00	0.00

[a]Blocking structure and minimum load levels are unit specific.

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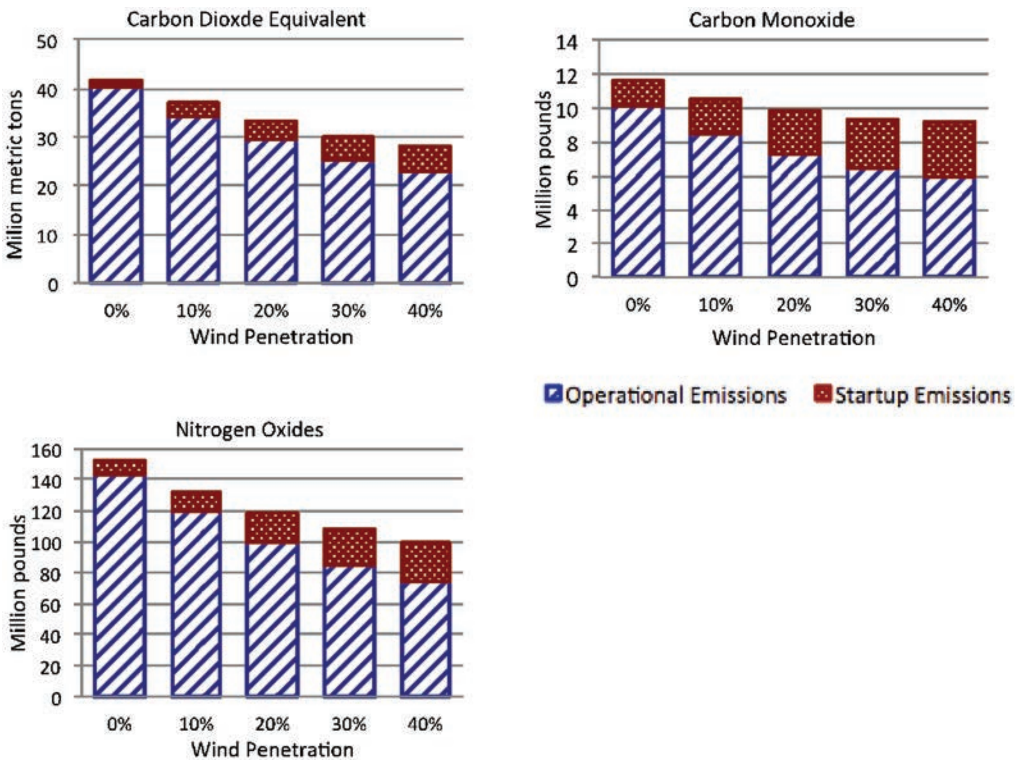

Figure 4. Total emissions results. The blue striped bars represent emissions resulting from normal operational periods, and the red dotted bars represent emissions resulting from start-ups. Carbon dioxide equivalent (CO_2e) includes CO_2, CH_4, and N_2O.

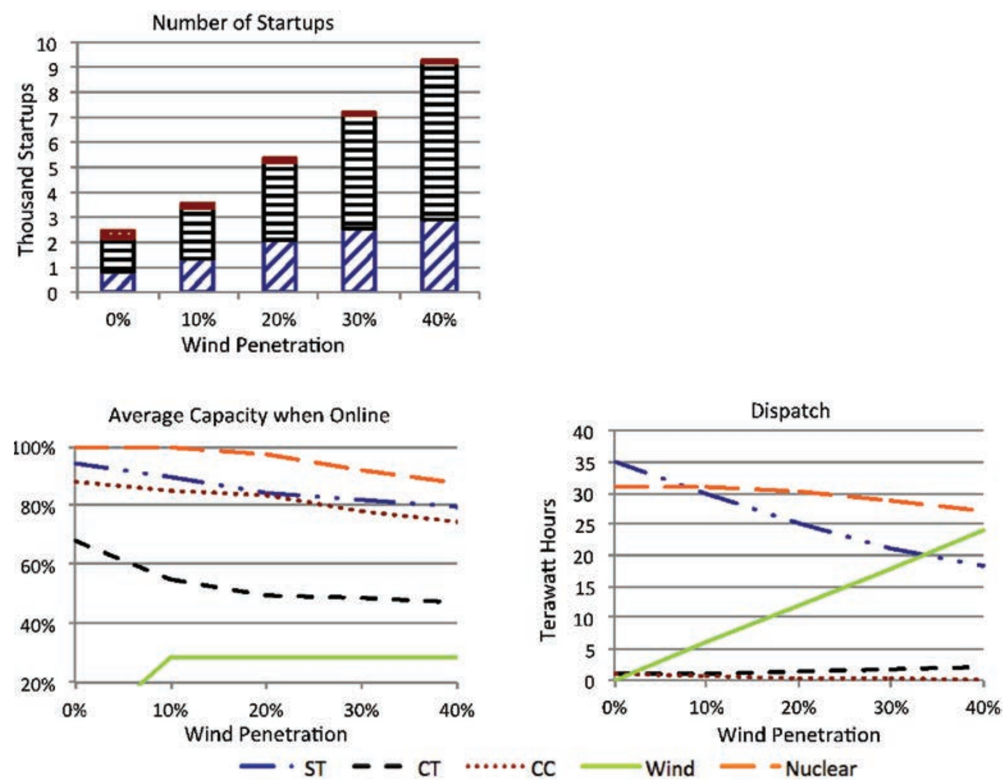

Figure 5. Dispatch results by unit type for various wind generation shares.

to be negligible. This is confirmed by our results, which show that start-up emissions contribute from 2.5% to as much as 35.7% of total emissions depending on the pollutant and level of wind penetration. Start-up emissions for all pollutants increase as the wind generation share increases. This is explained by the fact that the total number of start-ups increases as wind penetration increases (Figure 5). The results show that increasing levels of wind power require that both CT

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and ST units start up more frequently. ST start-ups lead to a drastic increase in pollutant emissions in comparison to a CT because of the longer start-up time. Despite all this, the reduction in emissions during operational periods is great enough that the trend of total emissions is clearly decreasing with increasing wind power penetration. However, from Table 2 we see that for most pollutants, the marginal emissions benefits are reduced for high wind power penetration levels, mainly driven by the higher start-up emissions (Figure 4).

Our results show that additional emissions from increased start-up and cycling effects are much smaller than the reduction in emissions due to displacement of fossil-fired generation. To better understand the underlying reasons for these results we investigate the simulated power system dispatch. Figure 5 shows the average generation of the different power plant categories when they are dispatched. As wind generation increases, all other types of units are operated at lower capacity when they are dispatched. Note that this is also the case with nuclear plants at high penetration levels. Figure 5 shows that at 30% and 40% wind penetration, some nuclear generation is replaced by wind power. This observation contributes to explain why the marginal emission reductions are lower for high amounts of wind power. The lower average online capacity corresponds to higher heat rates (Table 1) and therefore higher emission rates from the fossil-fired power plants. However, at the same time, there is a large decrease in generation from the ST category, which is mainly coal-fired, whereas there is a distinct increase in the generation from more flexible CTs, which are mainly natural-gas fired. Hence, increasing wind generation leads to a shift in dispatch from coal toward natural gas. The total implications for unit CO_2e emissions from fossil-fired generation are shown in Figure 6. We see that the start-up

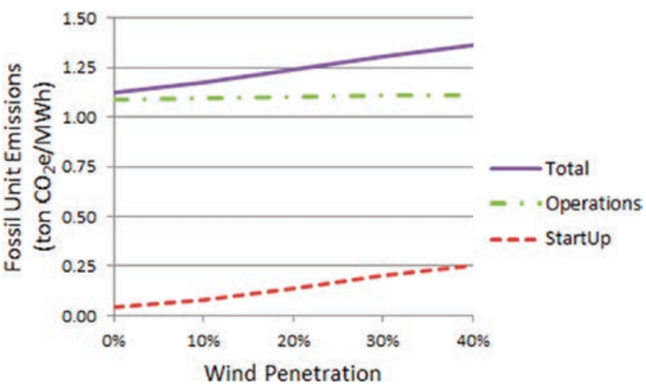

Figure 6. Unit emissions for total fossil-fired generation (steam, combined cycle, and combustion turbines) during start-up and operations for different wind generation shares.

emissions per MWh of fossil-fired electricity generation increase drastically. In contrast, the unit emissions during operation only see a minor increase. The more frequent cycling, which leads to more partial loading of thermal power plants, is to a large extent mitigated by the shift from coal to natural gas-fired generation. Hence, the increase in total unit emissions for fossil generation is mainly driven by higher start-up emissions.

■ DISCUSSION

Policymakers in many parts of the world turn to renewable energy as a means of reducing the environmental impacts from the electric power sector. It is therefore clearly of major importance to accurately estimate the emissions implications of a large-scale expansion of wind power and other renewable energy sources in the electric power grid. The modeling framework and analysis presented in this paper is a contribution toward this end, as it provides a better understanding of the system-wide emissions effects from a large-scale wind power expansion.

The main objective of power systems operators is to maintain a reliable power supply at the lowest possible cost. This becomes more challenging when a large portion of the energy supply is produced by a variable and sometimes unpredictable source. We simulate 4 months of system operations in the Illinois power system with a simulation setup that closely resembles the operating procedures of most current electricity markets in the United States. The uncertainty and variability from wind power is addressed through increased operating reserve requirements, which are derived from a probabilistic wind power forecast. Our emissions analysis is unique in the way that it incorporates the effects of both cycling and start-ups for all thermal units in the system. The results show that the increase in the number of start-ups has a higher impact on emissions than the increase in cycling and partial loading of thermal units. However, despite the increase in unit start-ups and cycling, the total amounts of CO_2, CH_4, CO, PM, NO_x, and SO_x emitted by thermal power units clearly decrease as the installed wind power capacity increases due to the overall displacement of fossil fuels.

We would like to emphasize that the accuracy of the results are limited by the assumptions used in the analysis. Limited data exist regarding the start-up emissions from thermal power plants. Within the past few years, however, many states have implemented policies mandating power generation facilities to record emissions during start-ups and shutdowns. Accurate records of emissions will give researchers a better idea of how emissions are affected when these events occur more frequently. With such data it will also be possible to estimate variable emission rates, contributing to further improving the accuracy of the emissions calculation. This analysis was also limited by the lack of available heat rate data for power plants. Our analysis used general heat rate data provided by EPRI,[17,18] but actual heat rate data for the power generation units in the system would clearly improve the analysis. It will be possible to formulate more precise models allowing for a more comprehensive understanding of the effects of incorporating a large amount of variable wind energy, if better data for start-up emissions and heat rates become available in the future.

In this study, we focus on the emissions implications from the operation of the power system, which is simulated with a high level of detail. However, one important limitation of our analysis is that we constrain the scope of the analysis to the power system in Illinois in 2006. We assume that additional wind power is added, but the number and type of thermal generation units are unchanged. In other words, we do not retire any thermal capacity as we increase the wind power. This may not be a realistic assumption as it is likely that older and more polluting units will be retired as the wind power penetration increases. At the same time, there is likely to be a shift toward faster and more flexible thermal generation, such as gas turbines, that can efficiently respond to changes in wind power output. This is an area for potential improvement in the analysis, and the consideration of expansion and retirements of thermal power plants is likely to lead to greater emissions reductions due to wind power.

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Finally, the analysis in this paper is limited to the state of Illinois, where the results show that wind power to a large extent replaces coal-fired generation with relatively high emissions. However, the analytical framework is general and could be applied to any region. The emissions implications of increased wind power penetration is to a large extent determined by the portfolio of other power plants. In our future work, we plant to repeat the analysis in regions with a different generation mix and to expand the geographical scope to consider the flow of power between regions with different resources.

■ ASSOCIATED CONTENT

Supporting Information

Additional details on the algorithms used for probabilistic wind power forecasting and power system operation. This information is available free of charge via the Internet at http://pubs.acs.org/.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: abotterud@anl.gov.

Notes

The authors declare no competing financial interest.

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