The Impact of Wind Energy on Generator Dispatch Profiles and Carbon Dioxide Production

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Abstract

This paper considers the impact of wind energy and forecast uncertainty on two important factors associated with power systems and sustainability: generator dispatch patterns and CO2 emissions. The impact of wind forecasting error on both of these factors is investigated via an AC OPF model and Monte Carlo simulations using the 39-bus IEEE test system. Results of this analysis indicate that CO2 emissions reductions of 17% are achieved at 30% wind penetration, exceeding the 10% GHG reduction goal of the Regional Greenhouse Gas Initiative (RGGI). Results also demonstrate that the variability in dispatch levels of base load units increases with wind penetration, and this variability impacts the resulting carbon dioxide emissions from the system.

1. Introduction

In recent years, significant progress has been made toward understanding, and hopefully managing, the uncertainty associated with generation of electricity from wind on a large scale. The system impacts of high levels of penetration include increased need for regulation, higher price volatility, impacts on transmission congestion, voltage stability and unit cycling [1-3]

It is widely assumed that increasing the fraction of overall capacity from renewable resources will have a positive impact on pollutant emissions from the electric power sector. To date, there are few studies that seek to quantitatively test this hypothesis. [4] considers the impact of current and proposed policies to provide incentive for CO2 reduction in the industry. The incentives considered in [4] are cost- or cap-based, and do not explicitly include the impact of increased wind capacity on the system. In [5], emission pattern changes resulting from wind farm dispatch are estimated. However, the real time re-dispatch due to forecasting errors are not measured, overlooking the possibility that an increase in cycling of traditional generators, in response to wind forecast errors, is an important contributor to carbon dioxide emissions. In this paper the impact of increasing wind penetration, and associated forecast errors, on carbon dioxide emissions are considered. The simulation methodology is outlined in Section 2, results are provided in Section 3, and discussion and plans for further analysis are provided in Section 4.

2. Methodology

The model used in this project simulates the uncertainty in the forecast of wind farm output and its impact on system dispatch patterns and emissions. This is implemented through a multi-stage approach.

In the first stage, output from hypothetical wind farms is forecasted as an input to hour-ahead dispatch decisions. The simulated system includes five wind farms at various locations on the network (shown in Figure 2). The capacity of the wind farms are determined by the resource availability estimated by the NREL Eastern Wind Interconnection Study (NREL-EWITS) data set described in [6].

With the forecasted output at each wind farm, a “forecasted” economic dispatch is determined using an AC OPF [7]. In the third stage, a distribution of wind forecast errors is sampled to incorporate the uncertainty via Monte Carlo simulations.

The final stage of this approach is the re-dispatch of all generators on the system, with realized wind output. The new dispatch is also determined by the OPF, with traditional generators constrained to within specific ramp
limits of the previously determined dispatch point. Initial analysis of system production cost and reliability with this modeling approach are presented in [8].

An overview of the simulation framework is given in Figure 1, and specific aspects of this model are discussed in further detail in Sections 2.1-2.3.

2.1 Incorporating Wind Uncertainty

Wind farm locations are determined from the Eastern Wind Interconnection Study database from National Renewable Energy Laboratory [9]. This extensive database provides simulated wind speed and output data for potential wind generation sites across the Eastern Interconnect region. Sites are determined based on wind resource and land availability, with details available in [6].

For the purposes of this study, wind penetration levels of 10, 20 and 30% were selected. These levels of wind penetration were simulated using potential sites from the NREL dataset, and assuming a capacity factor of 30%. For example, in order for a particular wind farm to provide 100 MW of wind resource, it was assumed that nameplate capacity was ~333MW. To provide this capacity at each bus, adjacent sites were aggregated to provide the capacity required, or until capacity was exhausted at a particular location. The resulting breakdown of capacity by location (test system bus number) is summarized in Table 1.

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<thead>
<tr>
<th>Capacity (GW)</th>
<th>Bus Number</th>
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<tbody>
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<td>%</td>
<td>Req. Installed</td>
</tr>
<tr>
<td>10</td>
<td>0.64</td>
</tr>
<tr>
<td>20</td>
<td>1.28</td>
</tr>
<tr>
<td>30</td>
<td>1.92</td>
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</tbody>
</table>

Table 1: Location and Capacity of Simulated Wind Farms

2.2 System Generation Profile

In order to capture the response of different generating technologies (based on fuel and prime mover) to the variability of wind generation, the different generator types are assigned to buses according to an approximate historical distribution of generation and fuel types within the New England states. Wind is added to the technology mix for the analysis presented in this paper. The resulting test system is shown in Figure 2.

Figure 1: Simulation Model Structure

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Figure 2: 39 bus test system

Table 2 shows the historical breakdown of generating capacity in the New England states. For the simulations in this paper, biomass/wood was not included in the technology mix given its low percentage in the in regional mix.

<table>
<thead>
<tr>
<th>Coal</th>
<th>Fuel Oil</th>
<th>Peaker</th>
<th>NGas</th>
<th>Nuke</th>
<th>Hydro</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>1057</td>
<td>837</td>
<td>2611</td>
<td>434</td>
<td>801</td>
<td></td>
</tr>
<tr>
<td>NH</td>
<td>579</td>
<td>433</td>
<td>39</td>
<td>2465</td>
<td>2303</td>
<td>428</td>
</tr>
<tr>
<td>VT</td>
<td>1749</td>
<td>4412</td>
<td>1560</td>
<td>11709</td>
<td>4210</td>
<td>1778</td>
</tr>
<tr>
<td>MA</td>
<td>27</td>
<td>2349</td>
<td>2065</td>
<td>4304</td>
<td>2707</td>
<td>102</td>
</tr>
<tr>
<td>RI</td>
<td>77</td>
<td>2349</td>
<td>2065</td>
<td>4304</td>
<td>2707</td>
<td>102</td>
</tr>
</tbody>
</table>

Table 2: Historical generating capacity in MW for New England States [10]
In order to accommodate the low number of buses in the test system, this historical data was grouped into “north” (Maine, New Hampshire and Vermont), Massachusetts, and “south” (Rhode Island and Connecticut). Table 3 shows the distribution of generation and fuel type in MW capacity assigned to these regions for the 39 bus test system.

The test system represents approximately 14 percent of the total New England demand. The generating technologies modeled in the test system were therefore scaled from those shown in Table 2 to those shown in Table 3, specifying northern New England (Maine, New Hampshire, Vermont), Massachusetts, and southern New England (Connecticut and Rhode Island). The distribution of these generating technologies to the generator buses in the test system is indicated in Figure 2.

<table>
<thead>
<tr>
<th>Region</th>
<th>Coal</th>
<th>Fuel Oil</th>
<th>Peaker</th>
<th>N Gas</th>
<th>Nuke</th>
<th>Hydro</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>80</td>
<td>205</td>
<td>125</td>
<td>890</td>
<td>390</td>
<td>135</td>
</tr>
<tr>
<td>Mass</td>
<td>245</td>
<td>600</td>
<td>215</td>
<td>1600</td>
<td>575</td>
<td>250</td>
</tr>
<tr>
<td>South</td>
<td>90</td>
<td>410</td>
<td>280</td>
<td>910</td>
<td>370</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Generating capacity in MW for the 39 bus test system [10]

For simulating the system dispatch with the AC OPF and capturing the response of the different generator technologies, cost values obtained from the Energy Information Administration [11] were applied to each generator. The variable cost values are used as part of the dispatch, and the fixed cost values are used to determine the production cost for each scenario. These costs are shown in Table 4.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Variable Cost ($/MWh)</th>
<th>Levelized Fixed Cost ($/MWh)</th>
<th>Ramping Cost (% of VC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>24.30</td>
<td>69.20</td>
<td>15</td>
</tr>
<tr>
<td>CC, NGas</td>
<td>45.60</td>
<td>39.40</td>
<td>10</td>
</tr>
<tr>
<td>Hydro</td>
<td>6.30</td>
<td>78.30</td>
<td>5</td>
</tr>
<tr>
<td>Nuclear</td>
<td>11.70</td>
<td>101.20</td>
<td>15</td>
</tr>
<tr>
<td>Oil</td>
<td>115.00</td>
<td>24.60</td>
<td>10</td>
</tr>
<tr>
<td>Peaking, NGas</td>
<td>71.50</td>
<td>49.50</td>
<td>5</td>
</tr>
<tr>
<td>Wind</td>
<td>3.00</td>
<td>93.50</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 4: Generator costs [11]

2.3 Scenario Definitions

For the analysis of the effects of wind variability on power system performance, a broad set of scenarios has been defined. These scenarios differ in the level of wind installed, forecast wind generation, and forecast regional demand. The total installed capacity, other than wind, is held constant. Different demand levels are thus defined in terms of the percent that demand is below the generating capacity. Demand levels are thus modeled in terms of generation reserve margins. A low reserve margin represents a high load level.

The scenarios are defined as:
- Wind penetration level
  - 10% wind penetration (3 wind farms)
  - 20% wind penetration (4 wind farms)
  - 30% wind penetration (5 wind farms)
- Wind farm output forecast
  - Low, 25% output
  - Medium, 60% output
  - High, 100% output
- Load level
  - Low load, 30% reserve margin
  - Medium load, 15% reserve margin
  - High load, 10% reserve margin

Taken together, these attributes represent 351 base case power flow scenarios. Each of these scenarios is then processed through the Monte Carlo algorithm, drawing from the forecast error distributions (as discussed in Figure 1) in order to fully characterize the effect of the wind forecast uncertainty on power system operation. The results presented below are drawn from over 50,000 total AC OPF simulations.

3. Results

The objective of this work is the assessment of changes in carbon emissions and generator dispatch patterns, as a result of increased wind penetration. Carbon emission results are provided in Section 3.1 and dispatch patterns in Section 3.2.

3.1 Carbon Dioxide Emissions

The first metric for assessing the impact of wind variability on system performance is a comparison of average carbon dioxide emissions from all generation at each load and penetration level, summarized in Figure 3. Also included in Figure 3 are the overall CO₂ emissions from the system, while serving load without wind
The results provided in Figure 3 indicate that average CO₂ emission levels decrease with increased wind penetration. However, of particular interest is the fact that more significant reduction effects are seen at 10% wind penetration than at 20% and 30% penetration, when load levels are low. This is a result of the fact that at higher penetration and low load, the "real time" re-dispatch aspect of the simulation is causing wind output to be reduced for reliability purposes – a significant amount of the available wind energy is spilled for system reliability purposes. Conversely, at 10% wind penetration and low load levels, all wind energy is used to serve load.

Figure 3 – Average CO₂ Emissions with Wind Penetration and Reserve Levels.

Figure 4 summarizes the standard deviation of the CO₂ emissions across the simulations, for each load and penetration level. This figure shows that frequent spilling of available wind output at high wind penetration leads to lower carbon emissions variability at 20% and 30% wind penetrations. Conversely at 10% penetration and low load levels, variability in wind output is easily accommodated in the system and carbon emissions are similarly variable.

Figure 4 – Standard deviation of CO₂ emissions for load and wind penetration level.

### 3.2 Generator Dispatch Levels

As wind power is introduced into the technology mix, the existing generators are dispatched at lower levels. Figure 5 shows the changing dispatch levels for the fossil fuel generators (combined cycle, gas turbines, coal and oil-fired plants) when there is 10% penetration of wind into the system.

In the low demand case, the distribution of total fossil fuel dispatch amount is seen to range from approximately 3500MW to 5000MW. This bar chart represents the power system response to all possible combinations of high, medium and low output from the three wind farms, along with the realizations of the actual wind generation based on the distribution of wind forecast errors.

The brown and black bars, representing medium and high load levels, are seen to be somewhat similar to each other. This is due to the fact that at medium and high load levels, there is less excess capacity – most of the system resources are required to serve demand, while at the same time some available wind output is spilled in order to maintain system reliability.

Figures 6 and 7 show similar charts for 20% and 30% wind penetration.
These figures show only a slight decrease in the maximum aggregate dispatch for fossil fuel units with increased wind availability, as compared to the scenarios with 10% wind penetration. It is interesting to note that with high wind penetration levels combined with low system load (the light tan bars in figures 6 and 7), a significant amount of wind is spilled in order to allow for reliable system operation.

To compare the dispatch patterns across all scenarios, the average level of fossil fuel dispatch is shown in the pie charts of Figures 8, through 11. These charts show that conventional power plants are dispatched less as wind power is introduced into the technology mix. The most significant difference is seen when moving from the no-wind to the 10%-wind case. As wind penetration increases, the incremental effect on conventional generator dispatch levels is less dramatic.

Figure 8 shows the relative dispatch levels with no wind installed on the system, averaged across the three demand levels used in this analysis.

For Figures 9 through 11, each pie chart represents one wind penetration level, with generator dispatch values averaged across the different load levels and wind forecast/forecast error amounts. The labels for each pie section show the generator/fuel type, the average percent of the total demand served by that generating category, and the standard error for each category (shown in the parentheses).

For example, the large medium blue section for natural gas (combined cycle) in Figure 9 shows that the combined cycle plants serve, on average, 36% of the load when there is 10%
wind penetration. This pie section also shows that the aggregated combined cycle dispatch level varies by 10.9 percent, implying that these generators serve approximately 33% to 39% of load (+/- 10.9% of the 36% average amount).

An interesting point in these pie charts is that the assumed capacity factor for wind (used to determine the initial amount of wind to install in the test system for each set of scenarios) is higher than anticipated. Thus for the nominal “10% wind” scenarios, the installed wind farms are actually serving 16% of the load, on average. For the nominal 20% wind penetration scenarios, the wind farms are actually serving 25% of the load. At the highest wind penetration level, nominally 30%, that actually amount is in fact 31%, again demonstrating the need of the system to spill some wind power at high penetration levels, and without transmission system reinforcement.

An additional observation for Figures 9 through 11 is the increased levels of variability in dispatch of nuclear, coal-fired and hydroelectric plants as the wind penetration increases. At 10% wind penetration, the dispatch of the nuclear plants varies only 1.6% over all scenarios of changing load level, wind forecast and forecast errors. As wind penetration increases though, the variability in the dispatch level of the nuclear units increases to more than 10%.

In contrast to this pattern, the variability in the dispatch level of oil units decreases as wind penetration increases. At low wind penetration, the system has relative flexibility in selecting the least cost, baseload generators. As wind output increases though, the system becomes more constrained in which resources can be used to meet demand, balance wind variability and maintain system reliability. Therefore, even though the oil units have high variable costs, the system is forced to rely on them more consistently in order to maintain system reliability at the high penetration levels of wind output.
4.0 Conclusions

Results presented in the previous section indicate that significant carbon emission reductions can be achieved from the addition of wind energy resources, in this example system. The carbon emission reductions of 14% can be attained at 10% wind penetration, if this reduced system is used as a proxy for the behavior of the actual power system.

The generator dispatch patterns demonstrate that cheaper, baseload plants, such as nuclear and hydroelectric generators, are used instead of plants used to mitigate the variability in wind power output. Prior simulation results also show that the total production costs decrease as the wind penetration level increases [8]. However, these production cost values do not capture the costs of increased maintenance due to increased ramping response and cycling of the baseload generators.

Ongoing analysis with this project will investigate the effects of reinforcing the transmission system in order to facilitate transmission of the wind power to the load centers and so avoid spilling significant amounts of wind generation. In addition, costs of cycling conventional generators will be explicitly incorporated into the cost calculations.

5.0 References