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The Impact of Distributed Wind on Bulk Power System Operations in ISO-NE

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***Abstract*—The work presented in this paper aims to study the impact of a range of penetration levels of distributed wind on the operation of the electric power system at the transmission level. This paper presents a case study on the power system in Independent System Operator New England. It is analyzed using PLEXOS, a commercial power system simulation tool. The results show that increasing the integration of distributed wind reduces total variable electricity generation costs, coal- and gas-fired electricity generation, electricity imports, and CO_2 emissions, and increases wind curtailment. The variability and uncertainty of wind power also increases the start-up and shutdown costs and ramping of most conventional power plants.**

Keywords-distributed wind; bulk power system operations; production-cost modeling

I. INTRODUCTION

Wind and solar are the most mature variable renewable energy technologies. Thus, considering the challenging goal to decarbonize the power system in the coming decades, the share of wind in the electricity generation mix is expected to increase significantly. Wind and solar are unique sources of electricity generation because of their variable and uncertain nature; thus, they have been the subject of several grid and market integration studies, each focusing on a different integration challenge as well as on different geographical locations to consider different energy mixes, market structures, and other inherent power system characteristics.

The National Renewable Energy Laboratory (NREL) has performed several renewable integration studies during the past years. For example, two phases of the Western Wind and Solar Integration Study have been completed thus far. The first phase focused on the benefits and challenges of integrating up to 35% wind and solar energy in the Western Interconnection in 2017 [1]; the second study's goal was to understand the impacts of wind and solar power on the fossil-fueled fleet in terms of wear-and-tear costs and emissions impacts of cycling [2]. In addition, the Eastern Wind Integration Transmission Study examined the operational impact of 20% to 30% wind energy penetration on the Eastern Interconnection [3], and the Eastern Renewable Generation Integration Study, which is still in progress, is evaluating the ability of greater interregional cooperation, geographic diversity, and sub-hourly scheduling to provide operational flexibility [4].

One reason wind integration in the U.S. power system is hindered is because the best wind resources are commonly located far from the main load centers. Developing new transmission lines to connect large wind power plants to load centers often requires difficult regulatory and legal hurdles as well as substantial financial investments. A potential alternative is to increase wind penetration in the power system by developing utility-scale wind turbines connected to existing distribution networks—or, in other words, by developing distributed wind.

Given the wind integration challenges described above, the work presented in this paper aims to study the impact of a range of penetration levels of distributed wind on the operation of the electric power system at the transmission level. This paper presents a case study on the power system in Independent System Operator New England (ISO-NE). Despite its present low wind penetration, "New England has multiple wind-rich areas ripe for development, making renewable energy an exciting possibility for the region's future" [5]. According to a study performed by GE Energy et al. [6], New England holds a theoretical potential to develop more than 215 GW of onshore and offshore wind generation.

The analysis uses PLEXOS, a commercial production-cost model, to analyze the operation of the ISO-NE power system for nine scenarios with increasing distributed wind penetration ranging from 0% to 21%. Comparisons among the nine simulation runs examine changes in the commitment and dispatch of generators, total production costs, electricity exchanges with neighboring regions, wind curtailment, and CO_2 emissions.

The paper is structured as follows: Section II describes the methodology, including a description of the ISO-NE PLEXOS model and the selection criteria for the distributed wind scenarios; Section III analyzes the results; and Section IV presents the conclusions and suggests opportunities for future work.

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II. Methodology

A. ISO-NE PLEXOS Model

The PLEXOS production-cost modeling software is used to simulate the operation of the ISO-NE power system to assess the transmission-level impacts of utility-scale (2-MW turbines) distributed wind in New England. The ISO-NE model has been designed to simulate the day-ahead (DA), 4-hour-ahead (4HA), and real-time (RT) markets. The DA and 4HA markets are modeled with 1-hour time-steps; the RT market is modeled with 5-minute time-steps.

The model includes a detailed representation of the ISO-NE transmission network in 2010 with 3,314 nodes, 2,485 transmission lines, and 1,830 transformers. The model is run nodally for voltage levels equal to or higher than 69 kV—in other words, the transmission line capacity limits are enforced only on lines with a voltage level of 69 kV or higher, which corresponds to 2,085 out of 2,485 lines. Moreover, the ISO-NE model represents electricity generation as it was in 2010, which included 468 generators with a total installed capacity of almost 36 GW, excluding wind and solar. Table I shows the installed capacity for each electricity generation source. Distributed wind turbines differ for each scenario, with varying distributed wind penetration levels, as described in the next section.

TABLE I. INSTALLED CAPACITY FOR DIFFERENT ELECTRICITY GENERATION SOURCES

Electricity Generation Source	Installed Capacity (MW)
Nuclear	4,878
Coal	3,740
Gas	17,101
Oil	5,691
Hydro	1,675
Pumped hydro	1,692
Biomass	844

The load and wind speed data included in the model corresponds to the year 2010. The total electricity system load in New England in 2010 was 131 TWh, with a peak system load of 27,102 MW [7]. In the DA and 4HA runs, DA and 4HA load and wind forecasts are considered. Details on wind data are provided in the next section. Nuclear, biomass, and coal-powered plants are committed in the DA run; whereas combined and steam turbines are committed in the 4HA run. All of these units may be redispatched within generator operating limits in the RT run. Hydropower plants are committed and dispatched in the DA run; whereas hydro-pumping plants are redispatched in the 4HA and RT runs.

The ISO-NE power system is interconnected to the neighboring regions of New Brunswick, Hydro Quebec, and the New York Independent System Operator (NYISO). To include realistic electricity flows to and from these regions, we constrain interregional flows using a method that accounts for 2010 hourly DA and RT locational marginal pricing in the neighboring regions and hourly electricity flows among ISO-NE and its neighboring regions. Electricity flows on the interconnectors among ISO-NE and the neighboring regions are subject to a \$3/MWh wheeling cost. This assumption avoids unrealistic cross-border flows when the electricity price differences among ISO-NE and its neighboring regions are less than \$3/MWh.

The ISO-NE model provisions contingency and regulation operating reserves in the three markets: DA, 4HA, and RT. The model considers only the spinning part of contingency reserves, which is a 10-minute product typically used to deal with unforeseen outages and which is defined to be half of 125% of the largest contingency in the system, or 824 MW. Non-spinning reserves are assumed to be always available; therefore, they are not included in the model. Instead, upward and downward regulation reserves are a 5-minute dynamic product and have load and wind components. Load and wind forecast errors are assumed to be uncorrelated; therefore, the regulation reserve requirements are equal to the square root of the sum of the squares of the two components. The load component is equal to 1% of the load (forecasted or actual). The wind component (different for each distributed wind scenario) is based on 10-minute persistence forecast errors—or, in other words, on 10-minute wind ramps. The wind component of the regulation reserves is calculated to ensure that 95% of the upward and downward wind ramps observed during the years from 2007 to 2009 are able to be covered by the reserve margin.

The ISO-NE model was validated by comparing its output to 2010 data published by ISO-NE. The validation shows that the model has very good agreement on the generation of each source by fuel type when compared to ISO-NE published data. In addition, the electricity price signals are very similar for most time periods. Therefore, the authors consider the ISO-NE model a valuable tool for studying the impacts of distributed wind on bulk system operations in the ISO-NE power system.

B. Distributed Wind Scenarios

Suitable locations for distributed wind power turbines depend both on geographical and network conditions. For example, distributed wind turbines are more likely to be connected to the distribution network in rural areas because of the difficult permitting issues in urban areas. Moreover, wind resource and some terrain features are important considerations when choosing a suitable site for a utility-scale wind turbine. With regard to network conditions, interconnecting multi-megawatt wind turbines to existing distribution lines is not always possible because of the need for significant line upgrades or the potential for decreases in system reliability and power quality. Even though studying the impact of wind power on the distribution network is not within the scope of this paper, the distributed wind generation scenarios analyzed in the study are designed to consider distribution constraints, including distance from the connecting node, voltage level at the connecting node, and the ratio of installed wind capacity to peak load at the connecting node.

The recent Wind Integration National Dataset (WIND) Toolkit [8], funded by the U.S. Department of Energy Wind Program, is the source of wind data for the distributed wind site-selection exercise as well as for the production-cost modeling. The WIND Toolkit data set includes wind data for the continental United States with an approximate 2-km by 2-km geographical resolution and a 5-minute temporal resolution including the years from 2007 to 2012. Several criteria were considered in the WIND Toolkit site-selection process (the goal was to select likely locations). For example, sites were excluded based on environmental and land-use conditions. For each suitable wind site, the data set includes actual wind power time series with a 5-minute resolution as well as hourly forecasts with different horizons.

The WIND Toolkit data set does not consider any constraints based on the location and characteristics of existing transmission and distribution networks; therefore, a method that considers network constraints is used to select suitable wind sites from the WIND Toolkit data set to be connected to the ISO-NE power system for several scenarios with varying penetration levels. The applied selection method considers the topology of the ISO-NE transmission network, and it constrains wind site locations based on network characteristics such as voltage level, feeder rating, and feeder length. The feeder rating is assumed to be equal to the peak load at each transmission node. Feeder length is assumed to be equal to or longer than the distance between a wind site and the transmission node to which it is connected.

Eight distributed wind scenarios with increasing distributed wind penetration levels have been designed. (One scenario was run without wind.) For each scenario, selected sites are only allowed to be connected to transmission nodes with a voltage level equal to or lower than 69 kV. The authors assume that 69 kV is the voltage level at which the transmission and the distribution networks intersect. In reality, this may not always be the case; but given the unavailability of distribution network data, it is assumed that anything equal to or lower than 69 kV is part of the distribution network to which distributed wind turbines can be connected to the grid.

The maximum distance between a wind site and the transmission node to which it is connected varies for each scenario to allow for different distributed wind penetration levels. Nodes that do not have any load are not allowed to be connected to any distributed wind site; therefore, distributed wind sites are constrained to locations in rural (but populated) areas. (Urban areas are already neglected in the site-selection methodology inherent in the WIND Toolkit data set.) The total capacity of the wind sites connected to the same transmission node is limited to the peak load on that node for the lowest five wind penetration scenarios. For the remaining three high-penetration scenarios, the total capacity of the wind sites connected to a single transmission node is limited to two, three, and four times the peak load on that node. These three high-penetration scenarios are designed to study higher distributed wind penetration levels while assuming that the distribution network below these nodes is designed to accommodate distributed generation with a capacity larger than the rated peak load. Successive scenarios include the wind sites of all lower penetration scenarios as well as the additional wind. Table II shows the different network constraints assumed for each scenario as well as the number of wind sites, the installed wind capacity, and the penetration levels. Constraint 1 is equal to the maximum distance between a wind site and the transmission node to which it is connected; Constraint 2 corresponds to the maximum ratio between the sum of the capacities of the wind sites connected to a node and the peak load at the node.

TABLE II. SCENARIO CHARACTERISTICS

Scenario	Constraint 1 (degrees lat-long)	Constraint 2	Number of wind sites	Installed wind capacity (MW)	Penetration level (%)
SC0	-	-	0	0	0
SC1	0.025	1	87	690	1.95
SC2	0.050	1	201	1,718	4.96
SC3	0.075	1	269	2,398	6.96
SC4	0.100	1	325	2,978	8.62
SC5	0.125	1	373	3,556	10.40
SC6	0.125	2	506	5,264	15.61
SC7	0.125	3	590	6,336	18.90
SC8	0.125	4	641	7,074	21.21

III. RESULTS AND DISCUSSION

As detailed in the previous section, to study the impact of distributed wind on bulk power system operations in ISO-NE, the ISO-NE model is run for nine scenarios: one scenario without wind (SC0) and eight scenarios with gradually increasing distributed wind penetration levels, from 1.95% to 21.2% (SC1 to SC8). The impact of distributed wind is analyzed with regard to several system variables.

Fig. 1 shows the electricity generation mix for the different distributed wind penetration levels. The first obvious difference that can be observed is the increasing share of wind in the electricity generation mix. The increasing wind penetration gradually decreases the share of other electricity generation sources. The two largest changes are observed for gas- and coal-fired electricity generation; gas is displaced the most. In the scenario with the highest wind penetration (SC8 - 21.2%), gas electricity generation is 34% lower than it is in the scenario without wind (from 61 TWh to 40 TWh).

However, with increasing wind penetration levels, power output does not decrease for all gas-fired electricity generation sources. The gas power plants are divided into four categories: combined-cycle (CC) turbines represent the largest category, with more than 90% of the share of gas-fired electricity generation; gas steam turbines (ST) represent the second largest category, with most of the remaining share; and gas turbines (GT) and internal combustion (IC) power plants represent only 0.05% of the share of gas-fired electricity generation in SC0. However, as shown in Fig. 2, unlike CCs and STs, GTs and ICs increase their electricity generation with higher wind penetration, reaching 1% of the share of gas-fired electricity generation in the scenario with 21.2% wind penetration (SC8). These two types of electricity generators have much higher variable electricity generation costs, but they can start and ramp much faster, which makes them better able to react to the variability and uncertainty of increased distributed wind. Oil-fired electricity generation, because of its similar characteristics—even though it represents the smallest share of the generation mix in every scenario—also increases its electricity output as a result of higher wind penetration, from 1 MWh in SC0 to 221 MWh in SC8, as shown in Fig. 3.

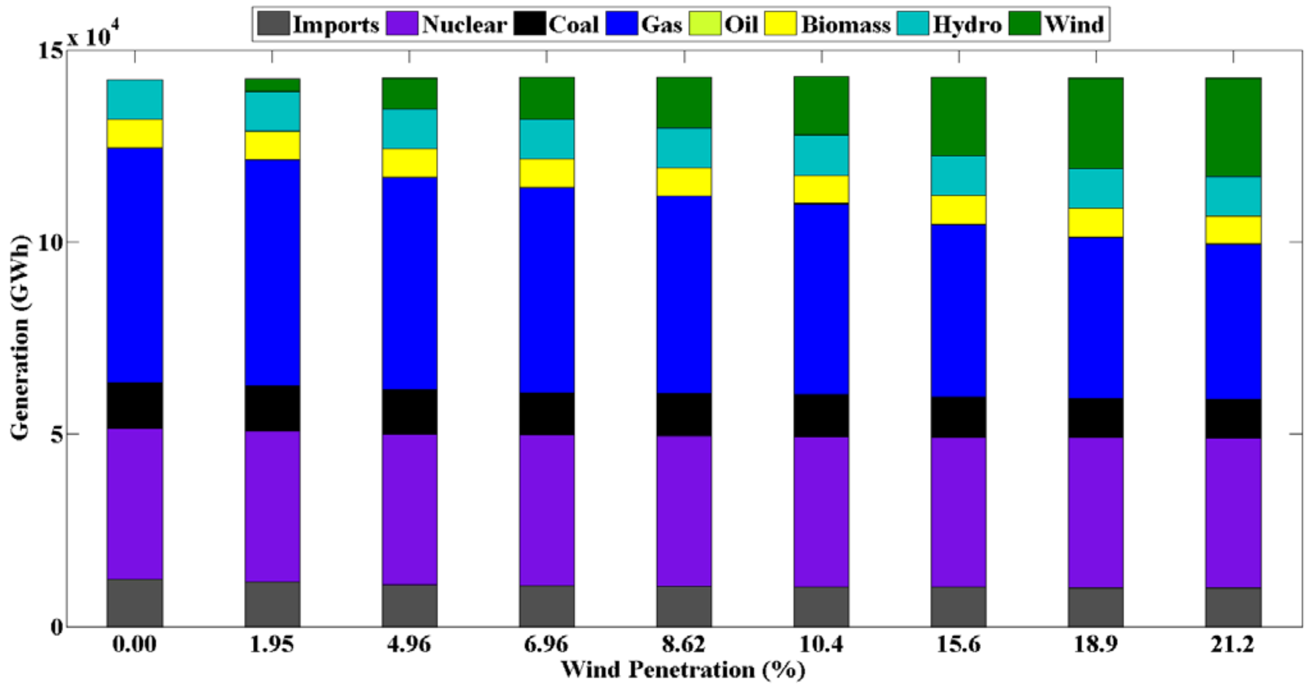

Figure 1. Generation mix for different wind penetration levels

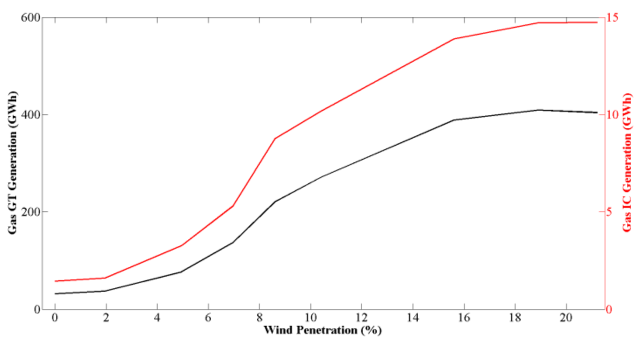

Figure 2. Gas GT and IC generation for different wind penetration levels

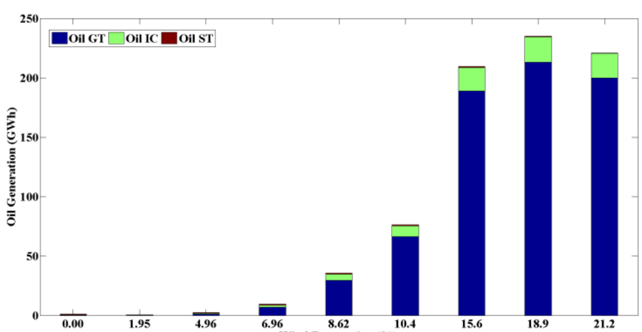

Figure 3. Oil-fired electricity generation for different wind penetration levels

On the other hand, coal electricity generation decreases by 17.5%, from 12 TWh to 9.9 TWh. Biomass electricity generation also decreases by 1.5%, from 7.37 TWh to 7.26 TWh. The shares of nuclear and hydro in the electricity generation mix are not affected by the increasing wind penetration levels and are practically the same in every scenario. Both nuclear and hydropower plants are committed in the DA market; in the case of hydro, it is assumed in the model that the generation level is set in the DA market and cannot be dispatched differently in the 4HA and RT simulations. Hydro pumping—included in the hydro category together with conventional hydropower as shown in Fig. 1—is also committed in the DA simulation, but it can be redispatched in the 4HA and RT simulations. Higher wind penetration levels do not significantly impact hydro pumping; only a very small increase is observed. Hydro pumping is 3.5% higher in the scenario with a wind penetration level of 21.2% (SC8) compared to the scenario without wind (SC0).

The share of electricity imports in the generation mix gradually decreases with the increasing share of distributed wind penetration. When wind penetration is higher than 8.62%, electricity imports decrease at a much lower rate with increasing wind penetration. Fig. 4 shows that although electricity imports decrease, electricity exports increase for wind penetration levels up to 8.62%. For higher wind penetration levels, electricity exports decrease at a very low rate. Net electricity imports decrease substantially, from 3.60 TWh in the scenario without wind to 0.9 TWh in the scenario with 10.4% distributed wind penetration. Net interchange is fairly stable at 0.9 TWh at distributed wind penetration levels higher than 10.4%. Electricity prices and their generation mixes in the neighboring regions are assumed to be the same as they were in 2010. If wind penetration levels also increased in the neighboring regions, electricity prices in the neighboring regions would be lower and the impact of distributed wind in ISO-NE on electricity exchanges would be different.

The integration of distributed wind increases the short-term variability and uncertainty in the system, which could potentially require faster responses from the rest of the generation fleet. This need is handled, among other operational changes, by oil-fired power plants and fast gas generators (GT and IC) that, as mentioned earlier, greatly increase their electricity output as distributed wind penetration grows. Their fast start times and ramping capabilities allow them to react faster to sudden changes caused by the variable and uncertain nature of wind.

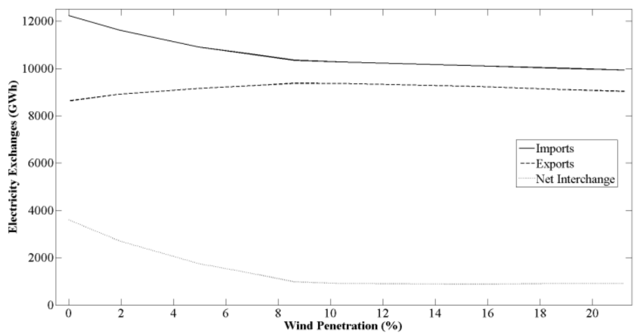

Figure 4. Electricity exchanges for different wind penetration levels

Other sources of electricity generation that decrease their generation as a result of higher distributed wind penetration do, however, increase their upward ramping relative to their generation, as shown in Fig. 5. Upward ramping is defined as the total megawatt ramping up of a generator during the year. Only upward ramping is presented, because downward ramping follows the same patterns. As may be expected, hydro-pumping plants vary their output more than other types of generators do; however, their ramping relative to their generation is not affected by a higher wind penetration level, as shown on the left of Fig. 5. The right portion of Fig. 5 shows a magnified view of the lower part of the left portion of the figure. Ramping per generation of nuclear, biomass, coal, and gas ST electricity generators increases as distributed wind penetration increases. On the other hand, ramping per generation of hydro and CC power plants remains constant as wind penetration increases. Hydro ramping is not affected by wind uncertainty, because hydropower plants are committed and dispatched in the DA simulation. Nuclear and biomass power plants experience the fewest ramping events. Biomass generators do, however, increase their ramping significantly with the presence of variable renewable generation. The ramping of nuclear power plants increases to a much smaller extent with higher distributed wind penetration because of their inflexibility. The ramping per generation of coal power plants and of gas STs is much higher, and they increase with higher distributed wind penetration levels as a result of the wind forecast errors that cause larger and more frequent generators to redispatch in RT.

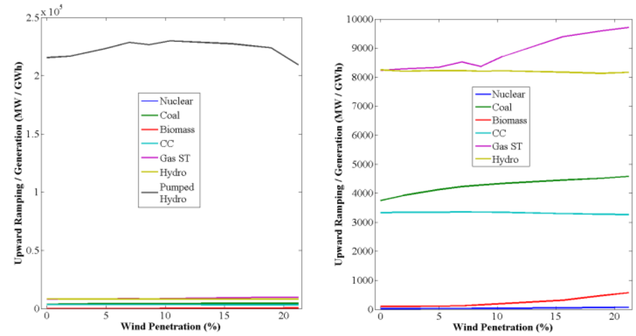

Figure 5. Ramping relative to generation for different wind penetration levels

Integrating distributed wind in the ISO-NE power system impacts the other electricity generation technologies as well as wind. Fig. 6 shows the amount of curtailed wind power for the different wind penetration scenarios. Wind power curtailment increases exponentially as wind penetration increases; however, even for the highest wind penetration scenario (SC8 – 21.2%) it is very small, below 0.7%.

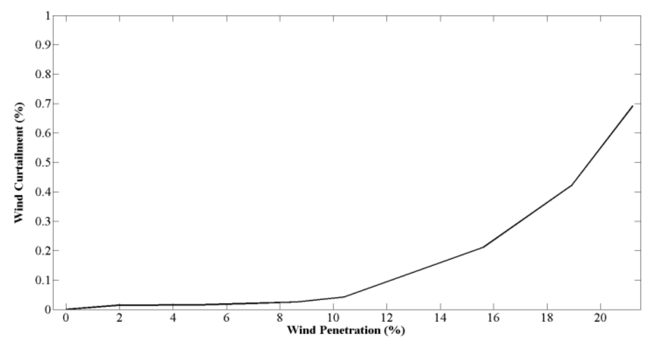

Figure 6. Wind power curtailment for different wind penetration levels

The impacts of distributed wind on electricity generation costs are shown in Fig. 7. When wind penetration increases, the total electricity generation cost (the sum of fuel costs, variable operation and maintenance costs, and start-up and shutdown costs) decreases. Fuel costs decrease; whereas start-up and shutdown costs increase. The integration of wind reduces the fuel consumption of other electricity generation technologies, which are operated differently with more frequent starts and shutdowns and have more frequent and larger ramping events. The reduction in fuel usage is larger than the additional ramping and start-up and shutdown cost driven by wind penetration.

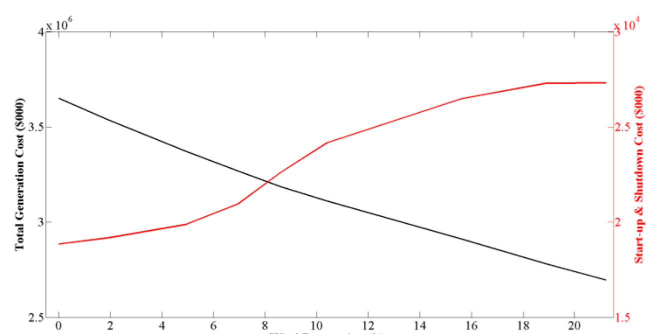

Figure 7. Electricity generation costs for different wind penetration levels

The fuel consumption reduction caused by the integration of distributed wind translates into a reduction of CO_2 emissions, as shown in Fig. 8.

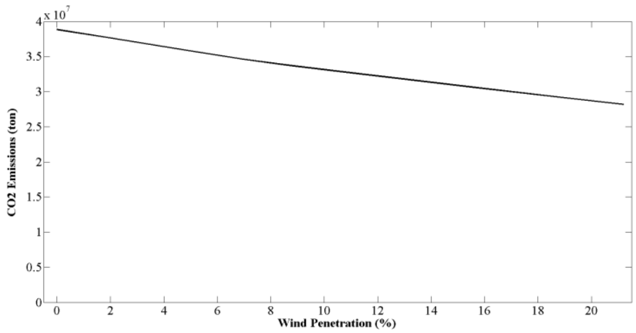

Figure 8. CO_2 emissions for different wind penetration levels

IV. Conclusions and Future Work

Results of the study presented in this paper show clear signs of the impact of distributed wind penetration on power system operations. Higher penetrations of distributed wind reduce total variable electricity generation costs, coal- and gas-fired electricity generation, electricity imports, and CO_2 emissions. The variability and uncertainty of wind power also increases the start-up and shutdown costs and ramping of most conventional power plants as well as wind curtailment. The impact on the capacity factor of coal- and gas-fired power plants and the costs associated with larger and more frequent ramping and starts of fossil-fueled generators may lead to different electricity market designs as well as changes in operational practices in regions with high levels of renewable energy sources.

The authors suggest that future work should analyze the impact of wind and load forecast errors on system reliability as well as the impact and cost of flexibility reserves. Finally, the model used for this study may be used in the future to study the impact of distributed wind on electricity prices, and therefore on generator valuation and revenues.

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