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Thermal Plant Emissions Due to Intermittent Renewable Power Integration

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THERMAL PLANT EMISSIONS DUE TO INTERMITTENT RENEWABLE POWER INTEGRATION

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FINAL REPORT
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Carnegie Mellon University

Acknowledgments

LIST OF ACRONYMS AND ABBREVIATIONS

501FD	Siemens-Westinghouse 501FD Natural Gas Generator
Btu	British thermal unit
Btu/hr	British thermal unit per hour
Btu/kWh	British thermal unit per kilowatt hour
CAIR	Clean Air Interstate Rule
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CT	Combustion Turbine
DLN	Dry-low NOx System
GE	General Electric Company
kW	Kilowatt
kWh	Kilowatt hour
LM6000	General Electric LM6000 Natural Gas Generator
MW	Megawatt
MWh	Megawatt hour
NGCC	Natural Gas Combined Cycle
NO_x	Nitrogen Oxides
PV	Photovoltaic
RPS	Renewable Portfolio Standard
SCR	Selective Catalytic Reduction
SW	Siemens-Westinghouse Company

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1. Introduction

Twenty five U.S. states have enacted some form of renewables portfolio standards (RPS) for electricity generation and Congress is considering a national renewable electricity standard (RES). Wind power, the fastest-growing renewable energy source, exhibits significant output variability, as shown at the two time scales in Figures 1 and 2. The first shows variability for a single turbine at 1 second and slower, while the second shows that even in a large system with over a thousand wind turbines, the wind exhibits both short- and long-term variability. Solar power exhibits similar fluctuations.
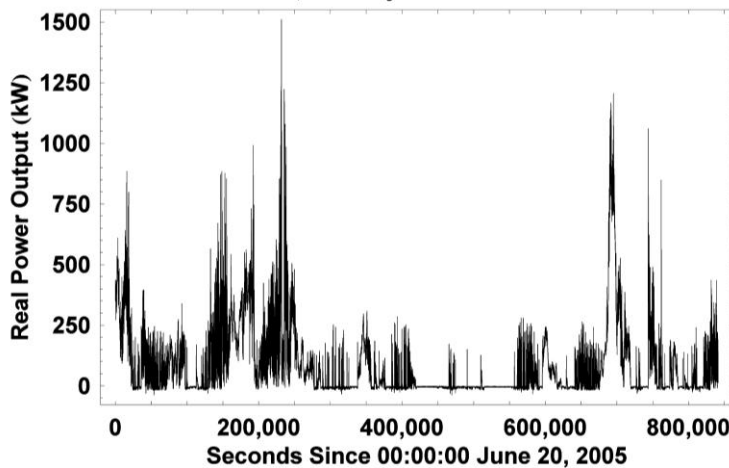
Figure 1 - One turbine, ten days at 1 second resolution.
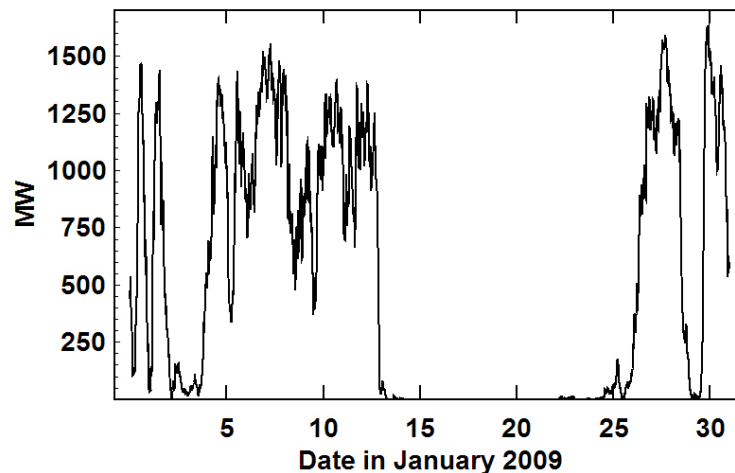
Figure 2 - BPA balancing authority total wind generation.

At the present low penetration of variable renewables (1.3% of U.S. net generation in 2008), these fluctuations can be largely ignored except in control areas where wind is a much larger fraction of generation than the national average. At the levels required by state RPS legislation (for example, 20% in California and 12% in New Jersey), the effects of variability and intermittency are no longer negligible. To provide a substantial portion of a state's electricity, wind power must be coupled with a firm power source to accommodate the fluctuations. Where significant hydro-electric storage is not available (or during drought years), combustion plants with fast ramping capabilities are likely to be used to ensure a steady and stable supply of electricity until cost breakthroughs are made in energy storage systems.

In order to estimate what effects wind and solar power variability may have on the air emissions of the electricity grid's conventional fossil fuel generators, a simplified base load plant was modeled by combining a wind farm or solar power station with one or more fast-ramping natural-gas turbines. Carnegie Mellon University (CMU) has used actual data from four wind farms and one large solar array and time-resolved measured emissions data from 9 natural-gas turbines of two different types. This model was used to answer the question of whether operating one or more natural-gas turbines in a manner that fills in variable wind or solar power results in increased NO_x and CO_2 emissions compared to full-power steady-state operation of natural-gas turbines. The common assumption is that wind fully displaces emissions from conventional fossil-fuel generators such that one MWh of wind energy would displace one MWh of a utility's portfolio emissions. If this were the case, then the expected output of the model is an emissions reduction equal to the penetration factor of the wind far, with the penetration factor defined as the amount of wind power produced divided by the total energy produced by the base load plant.

The results of CMU's analysis demonstrates that carbon dioxide emissions reductions from a wind (or solar PV) plus natural gas system are likely to be 75-80% of those presently assumed by policy makers. Nitrous oxide reduction from such a system depends strongly on the type of NO_x control and how it is dispatched. For the best system examined, NO_x reductions with 20% wind or solar PV penetration are 30-50% of those expected. For the worst, emissions are increased by 2-4 times the expected reductions with a 20% RPS using wind or solar PV.

The methodology and results contained within this report were developed by the Carnegie Mellon University, Carnegie Mellon Electricity Industry Center in Pittsburgh, PA. The work was funded by the Department of Energy, National Energy Technology Laboratory to address one of the critical questions in the U.S. electricity industry concerning environmental emissions profiles relating to integrating large volumes of intermittent renewable power supplies. NETL offers this report for publication to provide information, education and guidance on the topic.

2. EMISSIONS MODEL

2.1 *Emissions Model Approach*

In order to estimate what effects wind and solar power variability may have on the emission efficiencies of the electricity grid's conventional fossil fuel generators, a simplified base load plant was created by combining a wind farm or solar power station with one or more fast-ramping natural-gas turbines (Figure 3). Actual data were used from four wind farms and one large solar array and time-resolved measured emissions data from 9 natural-gas turbines of two different types. This model was then used to answer the following question: **Does operating one or more natural-gas turbines in a manner that fills in variable wind or solar power results in increased NO$_x$ and CO$_2$ emissions compared to full-power steady-state operation of natural-gas turbines?** The common assumption is that wind fully displaces emissions from conventional fossil-fuel generators such that one MWh of wind energy would displace one MWh of a utility's portfolio emissions. If this were the case, then the expected output of the model is an emissions reduction equal to the penetration factor of the wind farm, with the penetration factor defined as the amount of wind power produced divided by the total energy produced by the base load plant.
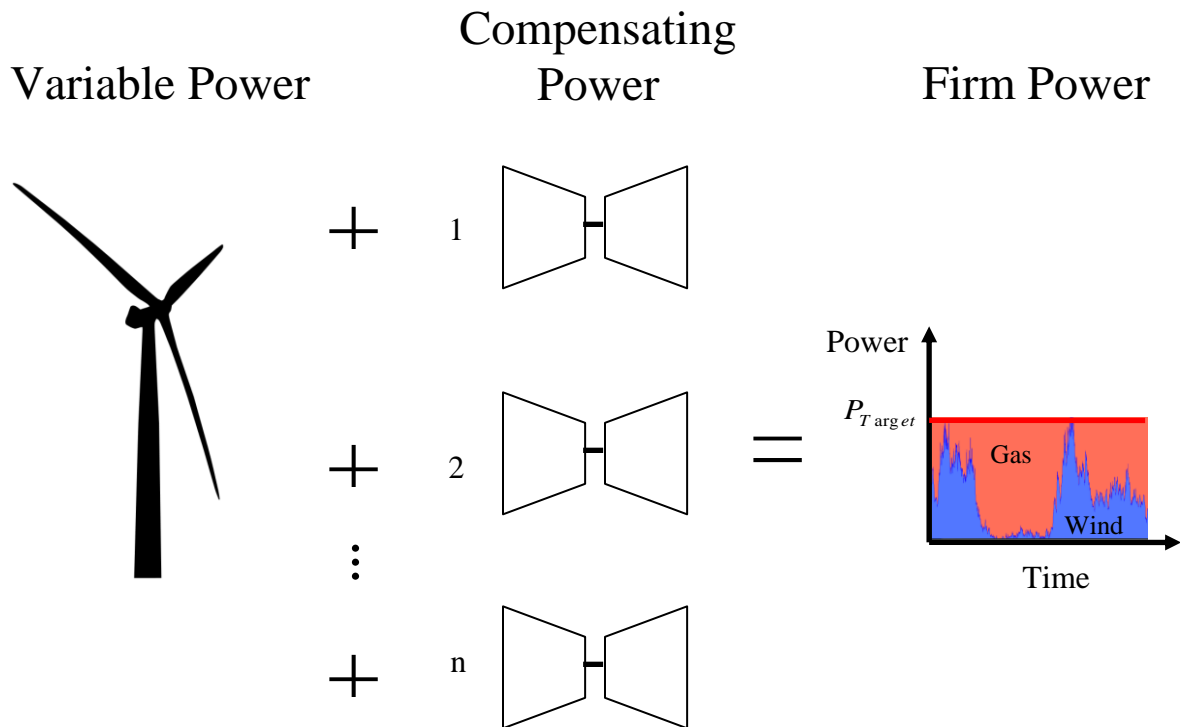
Figure 3 - Simplified drawing of the wind and natural gas turbine(s) model used. Initially, only one natural-gas turbine was paired with the wind farm. Further analysis examines how emissions were affected by pairing multiple turbines with the wind farm. Wind turbine clip art obtained from reference 1.

Initially, the base load plant output level was set to the nameplate capacity of the theoretical wind farm or solar station and the natural-gas turbine provides the compensating power, deemed fill-in power, when the wind farm or solar array deviates from the nameplate capacity (Figure 3). For further analysis, the number of natural-gas turbines that are paired with the wind farm was varied to determine what effects limiting the lower operating limit of the natural-gas turbines has upon emission reductions.

The objective for the base load plant is to maintain a constant power output by minimizing the error between the expected output and the actual output of the plant, shown in equation 4. This objective function is subject to the constraints shown in equations 6 - 9 and additional constraints introduced in equation 16 later in this model. No attempt was made at ensuring the stability of the electrical grid or to maximizing a generator's profits.

$$Min \, \varepsilon_{Total \, Power,i} = Min \left| P_{Total,i} - P_{\text{Target},i} - \varepsilon_{Total \, Power,i-1} \right| \tag{1}$$

where:

$$\varepsilon_{Total \, Power,i} \equiv Error \, in \, Power \, Plant \, Output$$

$$P_{\text{Target},i} \equiv Expected \, Power \, Plant \, Output \tag{2}$$

$$P_{Total,i} \equiv P_{Wind,i} + n \cdot P_{GasTurbine,i} \tag{3}$$

$$\equiv Total \, Power \, Generated$$

$$i \equiv time \, index \tag{4}$$

$$n \equiv Number \, of \, Gas \, Turbines$$

$$\dot{P}_{GasTurbine} \equiv \frac{dP_{GasTurbine}}{dt} \equiv Ramp \, rate \tag{5}$$

subject to:

$$P_{Total} = \text{Constant} \tag{6}$$

$$P_{Wind \, Max} = n \cdot P_{GasTurbine \, Max} \tag{7}$$

$$0 < P_{GasTurbine} \le P_{Max} \tag{8}$$

$$\dot{P}_{Min} \le \dot{P}_{GasTurbine} \le \dot{P}_{Max} \tag{9}$$

The model depends on accurately characterizing the emissions from the natural-gas turbine. For the purposes of this model, only nitrogen oxides (NO_x) and carbon dioxide (CO_2) were modeled as they are the primary pollutants emitted from a natural-gas turbine. NO_x contributes to the formation of ground-level ozone and will be increasingly regulated through EPA's Clean Air Interstate Rule [2]. CO_2 is of concern due to being the primary molecule contributing to climate change and the future projections of being a regulated emission. Power plant CO emissions account for less than one percent of CO emissions in the United States and are not considered in this analysis [3].

The two parameters most important to describing the operation of the natural-gas turbine are the power level needed to achieve a constant base load power output and the rate of change of the power level, ramp rate, needed from the natural-gas turbine to reach that power level. Thus, an ideal characterization of a natural-gas turbine's emission rates would be based on power level and ramp rate. The gas turbine model was based on a regression analysis of high-resolution emissions data from actual natural-gas turbines in operation.

Quantifying how much CO_2 a generator emits is relatively straightforward and depends on the heat rate of the generator and the type of fuel used. Assuming complete combustion, the heat rate is transformed to the CO_2 emission rate by multiplying by a conversion factor of 0.053 metric tons of CO_2 per MMBTU [4]. Although operating a turbine at low or medium power loads generally results in incomplete combustion, assuming complete combustion is a reasonable approximation for calculating CO_2 emissions, since most CO and hydrocarbon radicals are oxidized to CO_2 in the atmosphere. Thus, if the heat rate can be accurately modeled the CO_2 emission rate for the generator is accurately modeled. Modeling a natural-gas turbine's heat rate as a function of power level is a reasonable approach because the heat rate of a turbine directly translates to a power level. Modeling a natural-gas turbine's heat rate as a function of the ramp rate is also reasonable because it can capture the inertial energy and fuel inefficiencies inherent in the change from one power level to another (Figure 4).
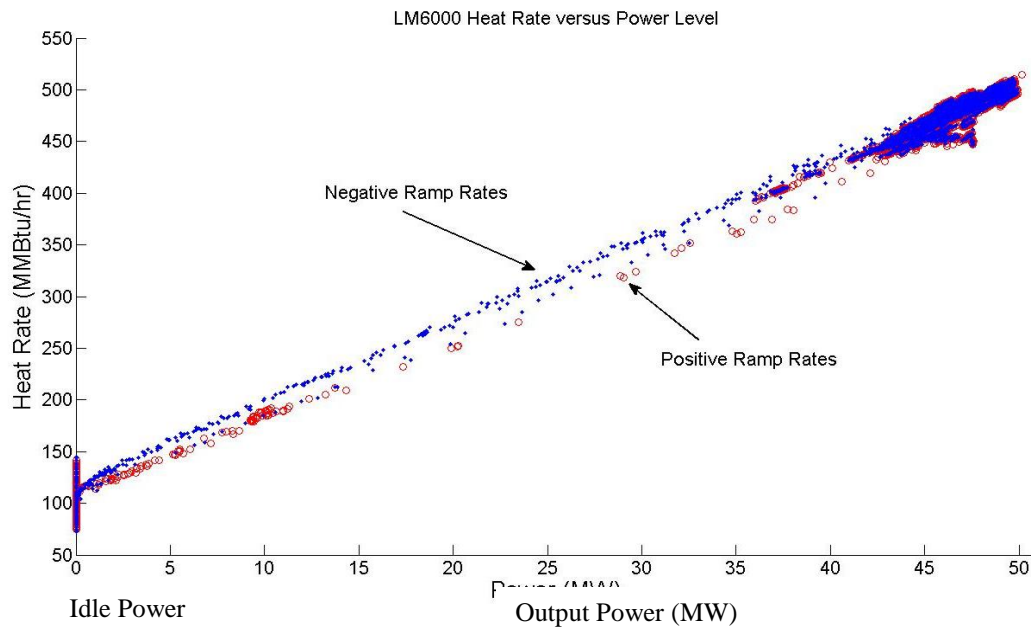
Figure 4 - Heat rate curve for an LM6000 turbine. The turbine is slightly more efficient ramping up to full power than it is ramping down from full power as seen in the difference in the heat rate over the power range of 2 to 43 MW.

Modeling a generator's NO_x emission rate is a more complicated matter, due to combustion and NO_x mitigation complexities. NO_x is a by-product of combustion and is formed from one of three pathways. The first and primary pathway is deemed thermal NO_x and it describes NO_x formed from molecular N_2 and O_2, the Zeldovich mechanism [5]. The second pathway is fuel NO_x (NO_x formed from nitrogen contained in the fuel). The third pathway is prompt NO_x (NO_x formed from molecular N_2 interacting with intermediate organic radicals formed during the early stages of combustion). While the modeling efforts do not depend on differentiating among the NO_x formation pathways, it is noted that thermal NO_x is the dominant mechanism for NO_x formation in natural-gas turbines [5].

NO_x became a regulated criteria pollutant under the Clean Air Act Amendments of 1970 and 1990 [6]. The two fundamental approaches to reducing NO_x emissions are to reduce the amount of NO_x formed during combustion or to remove NO_x through post-combustion exhaust stream clean-up. Thermal NO_x formation increases exponentially with flame temperature and linearly increases with increases in residence times [5, 7]. As a result, the technologies that reduce NO_x formation during combustion do so by reducing the flame temperature during combustion. The three prevalent methods to achieve this are water injection, steam injection, and dry control [5]. The primary methods utilized to remove NO_x from the exhaust stream are through selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) [9, 10, 11].

Water injection, whether it is liquid or steam, is the most common method to reduce NO_x emissions and involves injecting water into the turbine's combustion chamber to reduce the flame temperature and thus reduce NO_x [10]. Dry control involves staged, lean combustion and the principals behind General Electric's Dry-Low NO_x (DLN) technology, the most common dry control system used, will be described to understand how dry controls work [12]. GE's DLN technology relies on premixing fuel with air to create a fuel-lean mixture which is combusted in a two-stage process. The net effect is the reduction of flame temperatures and residence times. At full load, GE's DLN technology operates just above the flame blowout point of natural gas. As the load is reduced from its full load operating point, less fuel is fed to the combustion chamber resulting in lower flame temperatures. Eventually, the flame blowout point is reached where a flame cannot be sustained and GE's DLN system is forced to deviate away from the fuel-lean premixed firing mode to a diffusion flame where high flame temperatures are present. As a result, low NO_x emission rates are achieved in the power range of 50% to 100% of nameplate capacity and high NO_x emission rates, on the order of a magnitude greater, are achieved in the power range of 0% to 50% [11].

Using one-minute time resolution emissions data obtained for two types of gas turbines from an electric generation company, NO_x emission rates were characterized with power level and ramp rate. Appendix A contains detailed information on the methods used to characterize the NO_x emission rates of power plants. Due to the non-linear relationship between NO_x emissions and flame temperature and with flame temperatures dependent on the equivalence ratio between fuel and air, it is reasonable to expect that a turbine's power level and the rate at which it changes could capture the NO_x emission rates due to flame temperature. NO_x is also linearly dependent on the residence time of gases at the flame temperature. Residence times are dependent on the mass flow rate of the turbine as well as the flame size, which themselves are dependent on the power level of the turbine and reasonably the rate of change of the power level. Thus, a turbine's power level and ramp rate are used here to characterize its emissions rate per equation 10.

$$M_{Total} = \sum_{i=1}^{k} \frac{dM_i}{dt} \Delta t \qquad (10)$$

where:

$$M_{Total} = \text{Total Mass of Pollutant Emitted} \qquad (11)$$

$$\frac{dM_i}{dt} = f(P_{GasTurbine,i}, \dot{P}_{GasTurbine,i}) \qquad (12)$$

$$= \text{Mass Emission Rate of Gas Turbine for Time Period } i$$

$$\Delta t = \text{Time Interval of Data Set} \qquad (13)$$

$$k = \text{Time Length of Data Set} \qquad (14)$$

Once the gas turbine emissions had been modeled as a function of power and ramp rate, real one-second and 10-second time resolution wind data (down-sampled to one-minute resolution) and 1-minute resolution solar data were used to calculate how much of each pollutant was emitted, as well as how much of each pollutant was emitted if only the natural-gas turbine were used for the base-load plant. The amount each pollutant is reduced is calculated by subtracting the system's mass of emissions from the natural-gas turbine's base-load plant emissions and then dividing by the natural-gas plant's mass of emissions. The results were transformed into an expected reduction amount by dividing the amount each pollutant was reduced by the penetration factor of the wind farm. If no additional emissions from the gas turbine were caused by introducing variable renewable power, the expected emission reduction thus defined would be 100% for any renewable penetration level. That is, the expected emission reduction is 100% of the amount of wind in the system only if the variable renewable causes no additional emissions from the gas turbines.

$$Expected\,Emission\,Re\,duction = 100 * \left[\frac{M_{Total,NatrualGas} - M_{Total,Re\,newable+NaturalGas}}{M_{Total,NatrualGas} \cdot Wind\ Penetration} \right] \qquad (15)$$

2.2 *Data*

Instead of using emissions factor data as previous studies have done, real time-series emissions data for two series of turbines and one wind farm were obtained and used in this study. One-minute time resolution NO_x emissions data coupled with heat rate and load level over an eight-month period were obtained from an electric generation company for seven GE LM6000 gas turbines (CTs) and two Siemens-Westinghouse 501FD natural-gas turbines (NGCCs).

The LM6000 CTs are simple cycle turbines with a maximum power limit of 50 MW and employ steam injection systems to reduce NO_x emissions. A total of 573 days of emissions data was obtained of which, due to data filtering, only 145 days were used in the regression analysis. The Siemens-Westinghouse 501FD NGCCs are employed in a combined-cycle power plant with a maximum power limit of 200 MW. They combine GE's dry-low NO_x technology with an ammonium catalytic reduction system to achieve low NO_x emission levels. A total of 11 days of emissions data was obtained for the SW 501FD NGCCs and all 11 days were used in the

regression analysis. Over the eight-month period, the LM6000 CTs had a capacity factor of 6.4% and the 501FD NGCCs had a capacity factor of 0.4% with capacity factor being defined as the amount of energy produced by the generator divided by the amount of energy it could have produced over that time period if it was operating at maximum capacity.

The renewables data used includes 1-second, 10-second, and 1-minute resolution and is from four wind farms and one large solar photovoltaic facility located in the following regions in the United States: Eastern Mid-Atlantic, Southern Great Plains, Central Great Plains, Northern Great Plains, and Southwest The high time resolution wind data was down-sampled to create a one-minute resolution data set in order to pair it with the turbine emissions data sets.

2.3 *Model Parameters*

Using the emissions data obtained for each turbine, a multivariate regression analysis is performed for each pollutant.

LM6000 Combustion Turbine

The LM6000s were operated in a manner consistent with peaking units being ramped quickly up to full power, usually in the time span of two to three minutes, kept near their nameplate capacity for most of the duration and then ramped quickly down and shut off. Figure 5 is a plot of the ramp rates versus power levels. Three turbines were operated in a consistent manner while being brought up to full load.
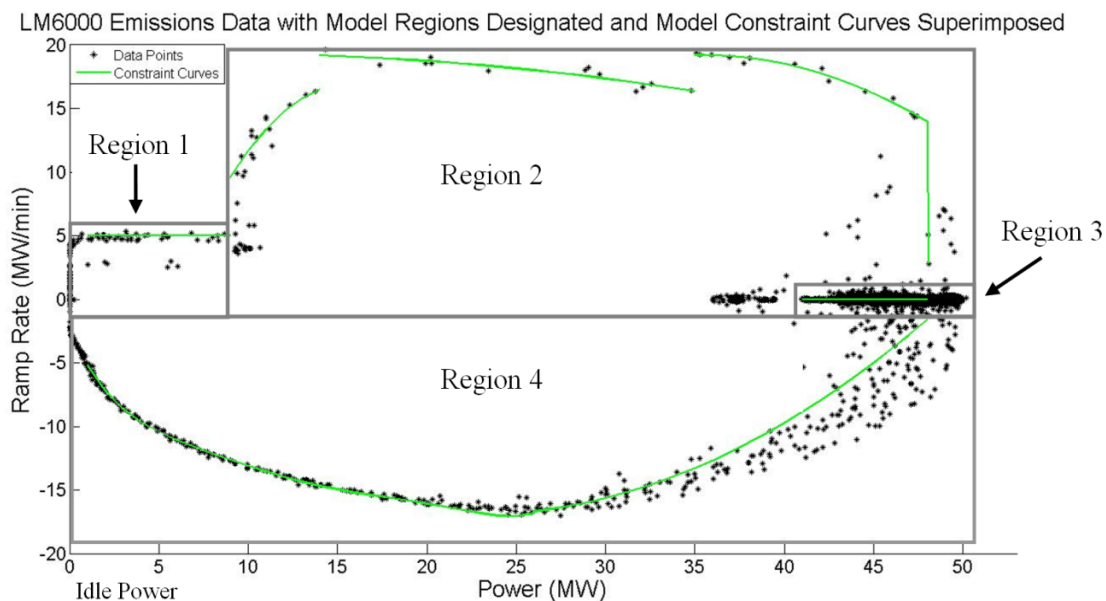
Figure 5 - Plot of LM6000 emissions data. The emissions data were divided into four regions which were modeled separately. The model regions are shown. The constraint curves imposed by the populated data curves are shown for each region.

The model characterization of the turbine is valid only along the populated regions and thus the populated regions serve as constraints and are plotted in Figure 5 and expressed formally in equation 16. The constraints result in an inability by the model to ideally fill-in the power needed to produce a firm power output. However, the data limitation is not a serious impediment to the model, as it means only that the model's gas turbine is not able to perfectly compensate for wind fluctuations; the maximum error even with the operation of the model constrained to the populated regions was 7.6% and the mean error was only 1.6%. A sensitivity analysis on the constraint curves can be found in Appendix B.

$$P_{Total,i} = P_{Wind,i} + n \cdot P_{GasTurbine,i} \qquad (3)$$

subject to:

$$\dot{P}_{GasTurbine,i} = f(P_{GasTurbine,i}) \qquad (16)$$

where:

$f(P_{GasTurbine,i})$ is dependent upon the region occupied

during time period i and $P_{GasTurbine}$

In order to model the emission rates for the LM6000 along the constraint curves, four separate regions were created and then the emissions data within each region was regressed using power and ramp rate as the independent variables. The delineation of the regions can be seen in Figure 5 and can be thought of as startup, ramping up to full power, steady-state full load, and ramping down to shut off; the regions are referred to numerically as regions 1, 2, 3, and 4 respectively. The regions were then characterized with the turbine's power levels and ramp rates. All data points where the power level was zero were eliminated from region 1 to eliminate the period when the turbine rotors are initially spun up to speed before the generator is connected to the drive shaft. As a result the model is constrained to regions of power levels greater than zero (equation 8).

The results for the NO_x emission rates for each region are presented in Table 1. All variables in each equation are significant at the 0.05 confidence level. The results for the CO_2 emissions rates for each region can be seen in Table 2. All variables in each equation are significant at the 0.05 confidence level.

Table 1 - LM6000 Region NO$_x$ Regression Results

Region 1

Equation
$$\frac{dM_{NOx,LM6000}}{dt} = 1.31x10^{-1} + 6.62x10^{-2}\,P_{LM6000} - 3.89x10^{-3}\,\dot{P}_{LM6000} \quad [kg/\min]$$

Regression Statistics

			Parameter Statistics				
Adjusted R^2	0.85		Intercept	Std. Error	6.99x10^{-3}		
# of Data Points	134			t-value	13.64	Prob > |t|	<0.0001
F-value	159.56		P_{LM6000}	Std. Error	1.6x10^{-3}		
Prob>F	<0.0001			t-value	11.77	Prob > |t|	<0.0001
Root MSE	5.26x10^{-2}		R_{LM6000}	Std. Error	2.48x10^{-3}		
				t-value	13.18	Prob > |t|	<0.0001

Region 2

Equation
$$\frac{dM_{NOx,LM6000}}{dt} = 6.76x10^{-1} - 2.27x10^{-2}\,P_{LM6000} + 3.27x10^{-4}\,P_{LM6000}^2 - 1.3x10^{-2}\,\dot{P}_{LM6000} + 6.53x10^{-4}\,\dot{P}_{LM6000}^2 \quad [kg/\min]$$

Regression Statistics

			Parameter Statistics				
Adjusted R^2	0.84		Intercept	Std. Error	3.96x10^{-2}		
# of Data Points	65			t-value	17.13	Prob > |t|	<0.0001
F-value	83.56		P_{LM6000}	Std. Error	2.74x10-3		
Prob>F	<0.0001			t-value	-8.27	Prob > |t|	<0.0001
Root MSE	2.95x10^{-2}		P_{LM6000}^2	Std. Error	4.81x10^{-5}		
				t-value	6.83	Prob > |t|	<0.0001
			R_{LM6000}	Std. Error	4.85x10^{-3}		
				t-value	-2.69	Prob > |t|	0.0094
			R_{LM6000}^2	Std. Error	2.18x10^{-4}		
				t-value	2.99	Prob > |t|	0.004

Region 3

Equation
$$\frac{dM_{NOx,LM6000}}{dt} = 2.68x10^{-1} \quad [kg/\min]$$

Mean Statistics

Standard Deviation		0.0222	# of Data Points	15,844

Region 4

Equation
$$\frac{dM_{NOx,LM6000}}{dt} = 8.35x10^{-2} + 7.53x10^{-4}\,P_{LM6000} - 3.85x10^{-3}\,P_{LM6000}^2 \quad [kg/\min]$$

Regression Statistics

			Parameter Statistics				
Adjusted R^2	0.94		Intercept	Std. Error	1.72x10^{-3}		
# of Data Points	447			t-value	50.2	Prob > |t|	<0.0001
F-value	3,486		P_{LM6000}	Std. Error	1.91e-4		
Prob>F	<0.0001			t-value	23.7	Prob > |t|	<0.0001
Root MSE	1.67x10^{-2}		P_{LM6000}^2	Std. Error	3.89e-6		
				t-value	-3.71	Prob > |t|	0.0002

Table 2 - LM6000 Region CO_2 Regression Results

Region 1

Equation $$\frac{dM_{CO2,LM6000}}{dt} = 2.68x10^{-2} + 1.77x10^{-3}P_{LM6000} \quad [tonnes/\min]$$

Regression Statistics			Parameter Statistics				
Adjusted R^2	0.85		Intercept	Std. Error	$2.84x10^{-4}$		
# of Data Points	134			t-value	4.34	Prob > |t|	<0.0001
F-value	731.81		P_{LM6000}	Std. Error	$6.54x10^{-5}$		
Prob>F	<0.0001			t-value	27.05	Prob > |t|	<0.0001
Root MSE	$2.63x10^{-3}$						

Region 2

Equation $$\frac{dM_{CO2,LM6000}}{dt} = 3.18x10^{-2} - 1.54x10^{-3}P_{LM6000} + 5.82x10^{-6}P^2_{LM6000} - 2.54x10^{-4}\dot{P}_{LM6000} \quad [tonnes/\min]$$

Regression Statistics			Parameter Statistics				
Adjusted R^2	0.999		Intercept	Std. Error	$5.53x10^{-4}$		
# of Data Points	65			t-value	57.54	Prob > |t|	<0.0001
F-value	21,893.8		P_{LM6000}	Std. Error	$7.29x10^{-5}$		
				t-value	21.15	Prob > |t|	<0.0001
Prob>F	<0.0001		P^2_{LM6000}	Std. Error	$1.3x10^{-6}$		
Root MSE	$9.22x10^{-4}$			t-value	4.48	Prob > |t|	<0.0001
			R_{LM6000}	Std. Error	$3.44x10^{-5}$		
				t-value	-7.38	Prob > |t|	<0.0001

Region 3

Equation $$\frac{dM_{CO2,LM6000}}{dt} = 3.6x10^{-1} + 1.26x10^{-3}P_{LM6000} + 9.27x10^{-6}P^2_{LM6000} \quad [tonnes/\min]$$

Regression Statistics			Parameter Statistics				
Adjusted R^2	0.864		Intercept	Std. Error	$3.6x10^{-3}$		
# of Data Points	15,845			t-value	9.99	Prob > |t|	<0.0001
F-value	50,487.5		P_{LM6000}	Std. Error	$1.58x10^{-4}$		
Prob>F	<0.0001			t-value	8.03	Prob > |t|	<0.0001
Root MSE	$1.64x10^{-3}$		P^2_{LM6000}	Std. Error	$1.72x10^{-6}$		
				t-value	5.39	Prob > |t|	<0.0001

Region 4

Equation $$\frac{dM_{CO2,LM6000}}{dt} = 2.72x10^{-2} + 1.88x10^{-3}P_{LM6000} - 9.207x10^{-6}\dot{P}_{LM6000} \quad [tonnes/\min]$$

Regression Statistics			Parameter Statistics				
Adjusted R^2	0.998		Intercept	Std. Error	$2.72x10^{-2}$		
# of Data Points	447			t-value	122.72	Prob > |t|	<0.0001
F-value	88,330.9		P_{LM6000}	Std. Error	$4.48x10^{-6}$		
Prob>F	<0.0001			t-value	420.07	Prob > |t|	<0.0001
Root MSE	$1.62x10^{-3}$		P^2_{LM6000}	Std. Error	$1.66x10^{-5}$		
				t-value	-5.52	Prob > |t|	<0.0001

501FD Combined-Cycle Turbines

The two Siemens-Westinghouse 501FD turbines for which we have data were cycled through more of their power range than the LM6000s and as a result data points populate the majority of the control map formed by the power levels and ramp rates, as seen in Figure 6. The constraints then imposed on the model by the SW 501FD turbines are the ramping limits that contain the populated region of the control map (99% of the data is contained within the limits of -5 MW/min and 5 MW/min). Initial investigations into the behavior of the emission rates of the 501FD indicated no significant dependence on ramp rate.
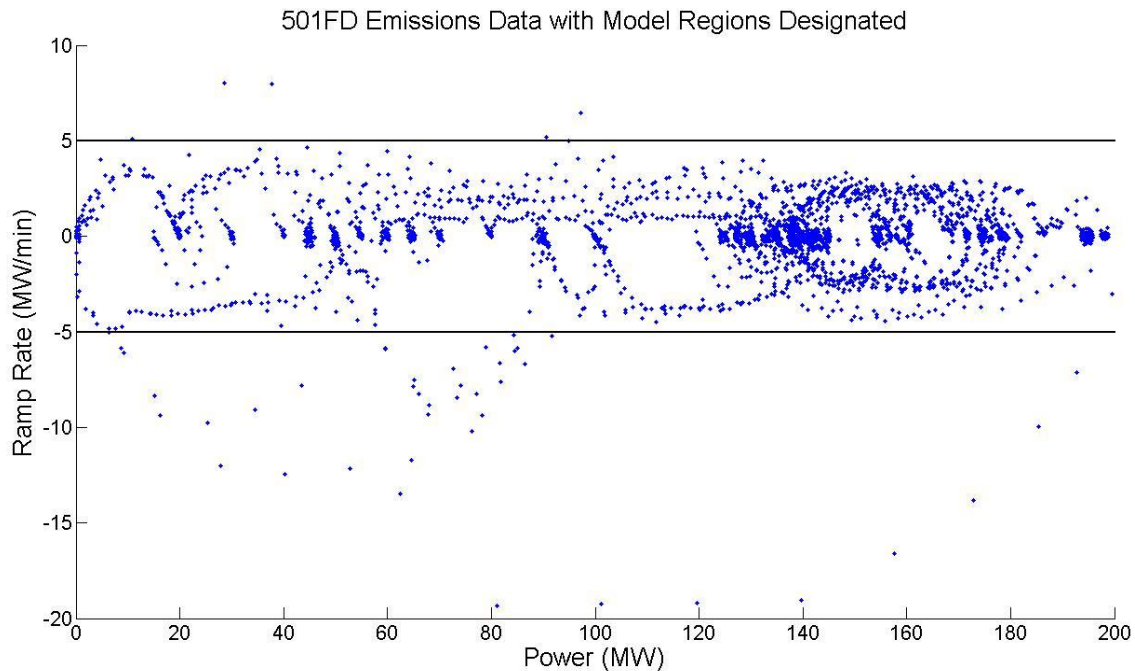
Figure 6 - Scatter plot of 501FD emissions data. The boundaries on the model's ramp rate, imposed by the populated data points in the control map, are shown. The 501FD was cycled through its control map significantly more than the LM6000 and as a result the 501FD model is able to operate with limited additional constraints.

In order to characterize the NO_x emission rates, three regions were defined (Figure 7). The three regions correspond to the different primary firing modes of GE's Dry Low NO_x system. There are additional firing modes used to transfer from one primary firing mode to another but due to GE's proprietary control algorithms the exact operation of the turbine could not be modeled. As a result, the turbines were characterized according to how GE describes their typical operation. An important characteristic of GE's DLN system, as seen in Figure 7 and fundamental to understanding the model results presented later, is NO_x emissions are an order of magnitude

greater at power levels below 50% capacity than emissions at power levels greater than 50% capacity. The results for the NO_x emission rates are listed in Table 3.
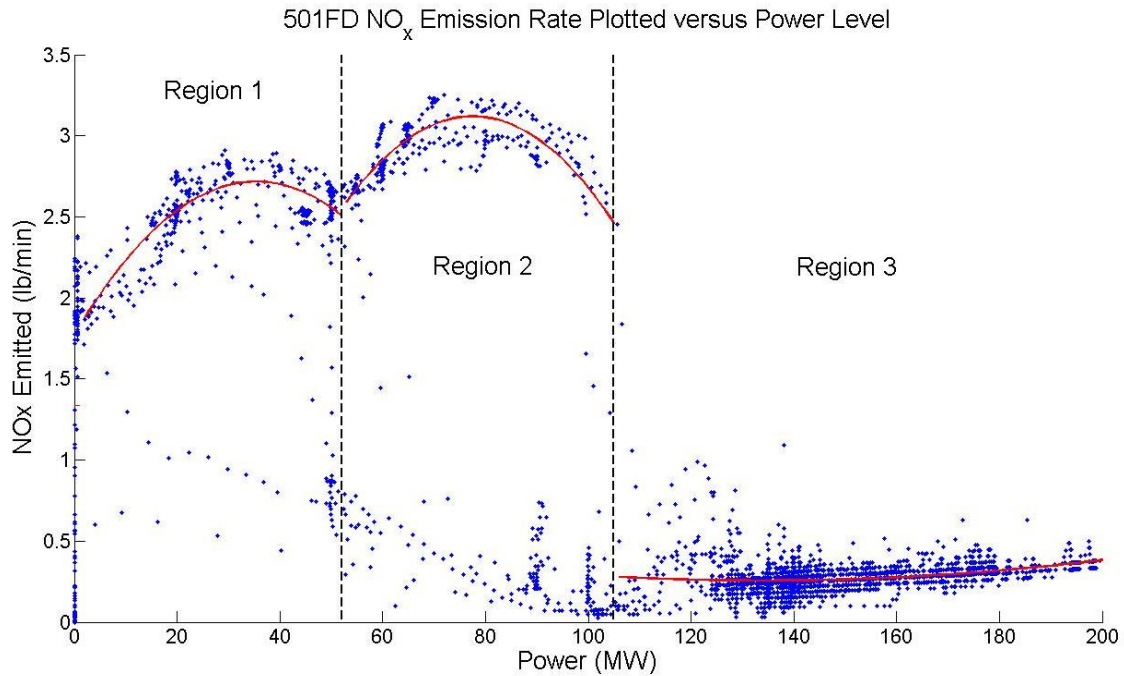
Figure 7 - Plot of 501FD emissions data. The emissions data was divided into three regions which were modeled independently of each other and are designated. This combined-cycle turbine is designed to produce low NOx only when operated at high power.

Table 3 - 501FD Region NO$_x$ Regression Results

Region 1

Equation $\dfrac{dM_{NOx,501FD}}{dt} = 8.03x10^{-1} + 2.45x10^{-2}\,P_{501FD} - 3.49x10^{-4}\,P^2_{501FD} \quad [kg\,/\min]$

Regression Statistics

			Parameter Statistics				
Adjusted R^2	0.72		Intercept	Std. Error	6.99x10^{-3}		
# of Data Points	463			t-value	124.45	Prob > |t|	<0.0001
F-value	723.12		P_{501FD}	Std. Error	6.44x10^{-4}		
Prob>F	<0.0001			t-value	30.03	Prob > |t|	<0.0001
Root MSE	6.99x10^{-2}		P^2_{501FD}	Std. Error	1.18x10^{-5}		
				t-value	-23.13	Prob > |t|	<0.0001

Region 2

Equation $\dfrac{dM_{NOx,501FD}}{dt} = -9.48x10^{-1} + 6.12x10^{-2}\,P_{501FD} - 3.95x10^{-4}\,P^2_{501FD} \quad [kg\,/\min]$

Regression Statistics

			Parameter Statistics				
Adjusted R^2	0.64		Intercept	Std. Error	7.26x10^{-2}		
# of Data Points	562			t-value	-12.98	Prob > |t|	<0.0001
F-value	489		P_{501FD}	Std. Error	2.0x10^{-3}		
Prob>F	<0.0001			t-value	30.47	Prob > |t|	<0.0001
Root MSE	4.58x10^{-2}		P^2_{501FD}	Std. Error	1.33x10^{-5}		
				t-value	-29.49	Prob > |t|	<0.0001

Region 3

Equation $\dfrac{dM_{NOx,501FD}}{dt} = 1.18x10^{-1} - 5.76x10^{-4}\,P_{501FD} + 4.1x10^{-6}\,P^2_{501FD} \quad [kg\,/\min]$

Regression Statistics

			Parameter Statistics				
Adjusted R^2	0.28		Intercept	Std. Error	1.96x10^{-2}		
# of Data Points	5,129			t-value	6.10	Prob > |t|	<0.0001
F-value	979.37		P_{501FD}	Std. Error	2.52x10^{-4}		
Prob>F	<0.0001			t-value	-2.39	Prob > |t|	<0.0001
Root MSE	1.02x10^{-2}		P^2_{501FD}	Std. Error	7.98x10^{-7}		
				t-value	5.24	Prob > |t|	0.0002

The heat rate for the 501FD turbines does not depend on the ramp rate and a linear regression is able to sufficiently model it. Figure 8 is a plot of the regression line overlaid on the CO_2 emissions rate data.
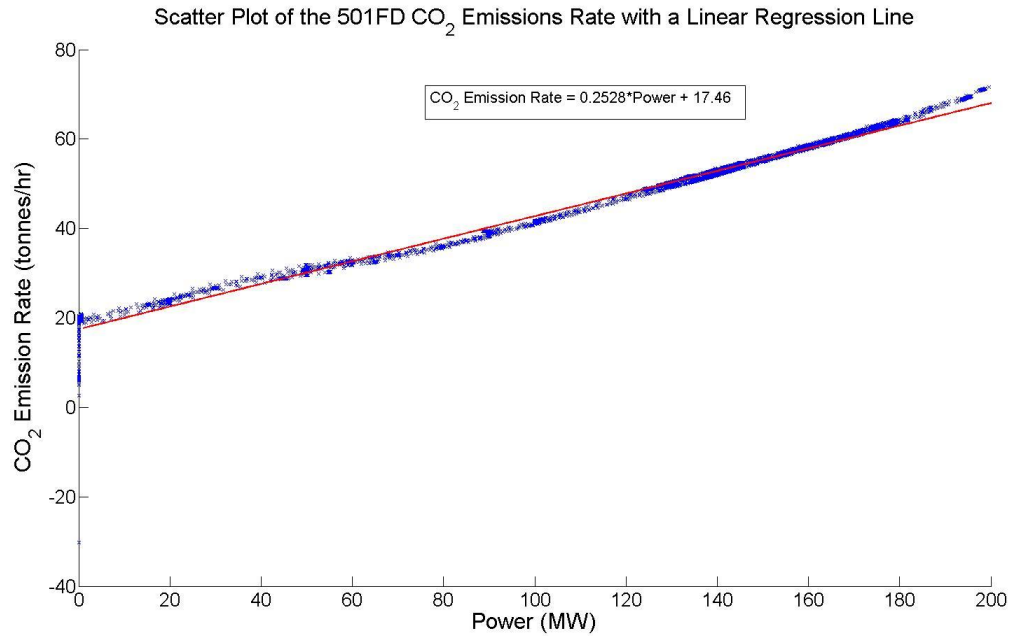
Figure 8 - CO_2 emissions rate for the 501FD turbines as a function of turbine output power (blue dots) and the linear regression model used to characterize the CO_2 emissions rate (red line). The linear regression equation is y = 0.2528x + 17.46 and has an adjusted R^2 value of 0.991.

2.4 *Emissions Results and Discussion*

Table 4 shows the results for a 10-day wind sample. All values are expressed in percentages of expected emissions displaced and include a 95% prediction interval. For the initial 1:1 pairing and a wind penetration factor of 7%, NO_x is reduced only 29% $\pm$ 4% of the expected emissions reduction when an LM6000 with steam injection is used and NO_x increases 240% $\pm$ 250% when an SW 501FD with DLN and SCR is used. For CO_2, emissions are reduced by 80% $\pm$ 1% when an LM6000 is used compared to a reduction of 76% $\pm$ 1% with the 501FD.

Table 4 – Baseload Power Plant Model Results for 10-Day Wind Data Set

	NO_x	*95% Prediction Interval*	CO_2	*95% Prediction Interval*
LM6000 – 45 MW				
Mass Emitted	8,280 lbs	(8,240 lbs, 8,320 lbs)	1,446 tonnes	(1444 tonnes, 1448 tonnes)
Expected Emissions Reduction	29%	(25%, 33%)	80%	(79%, 81%)
501FD – 200 MW				
Mass Emitted	6,400 lbs	(4,900 lbs, 7,800 lbs)	6,323 tonnes	(6319 tonnes, 6327 tonnes)
Expected Emissions Reduction	-240%	(-490%, 10%)	76%	(75%, 77%)

Sensitivity to Wind or Solar Capacity Factor

It is possible to have wind or solar power data sets that have identical capacity factors yet have significantly different time-series profiles. A simple example would be y = sin(x) compared to y = 0. Both have an average value of zero yet each has a distinct profile. In order to study the sensitivity of the results to the profile of the wind power over time, a sliding window composed of 1,000 minute segments was used on the wind and solar data and then fed into the model, producing 13,400 results. The 13,400 results were used to calculate an emissions factor for the wind or solar + gas baseload power plant (Figures 9 – 12). In Figure 10 and Figure 12 the mean emission factor and area encompassed by two standard deviations are plotted. Also plotted is the expected emission factor for the baseload plant if a conventional emissions displacement analysis is performed.
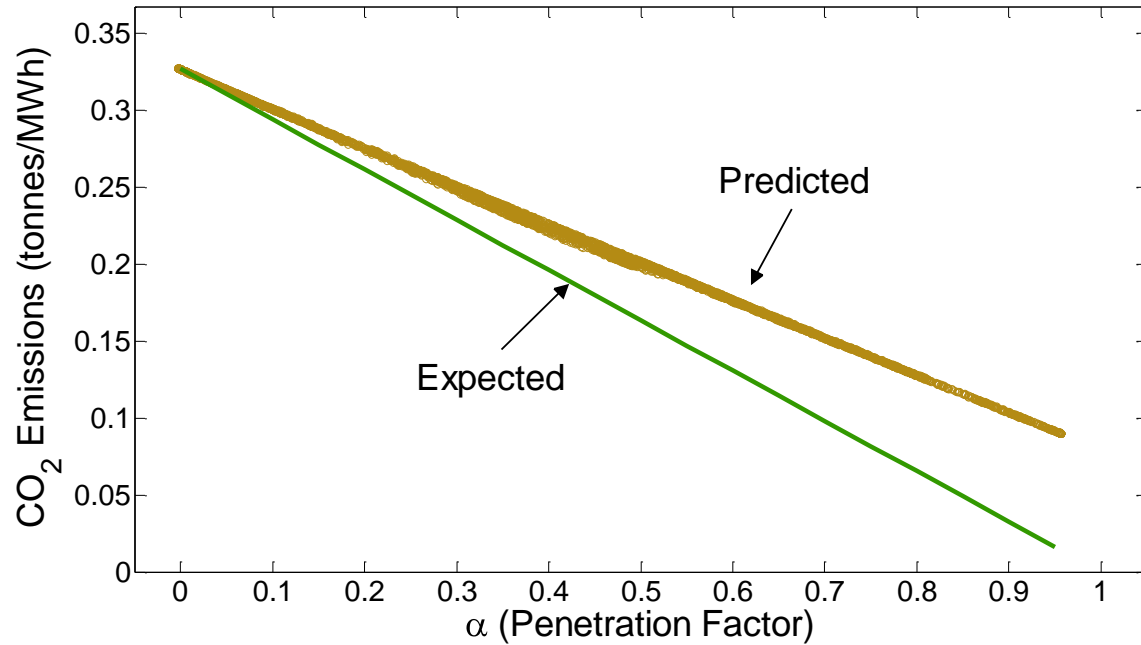
Figure 9 – LM6000 results. Renewable plus natural gas CO$_2$ emission factor vs. renewable energy penetration level (α) (brown area). The expected emissions factor (green, lower line) is shown for comparison.
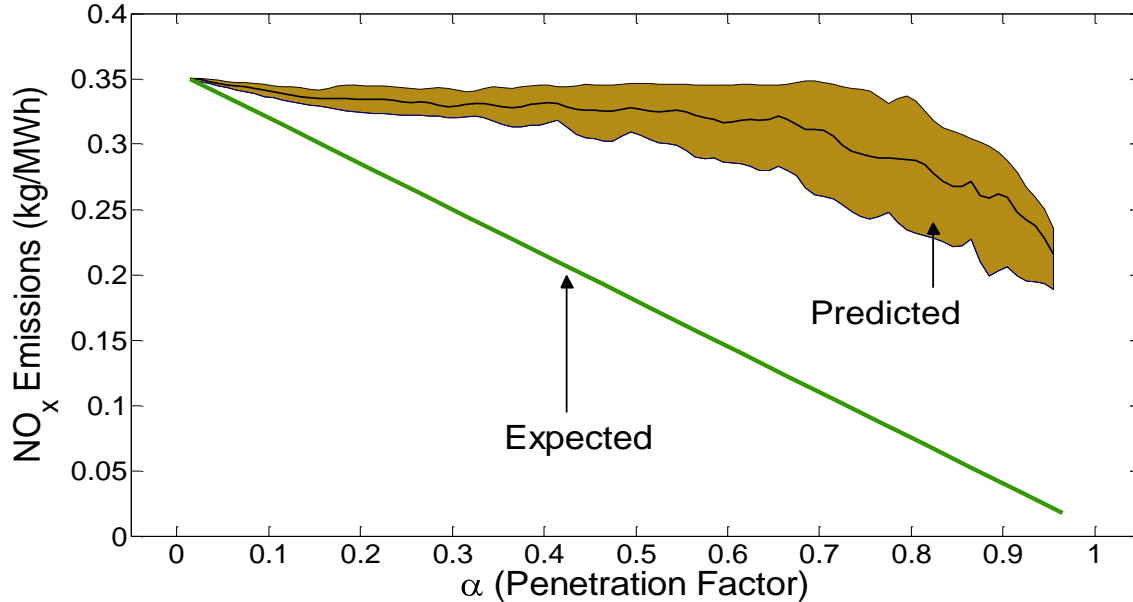
Figure 10 – LM6000 results. Mean renewable plus natural gas NO$_x$ emission factor vs. renewable energy penetration level (α) (black line); area shown represents 2 standard deviations of all five data sets (shaded brown area). The expected emissions factor (green, lower line) is shown for comparison.
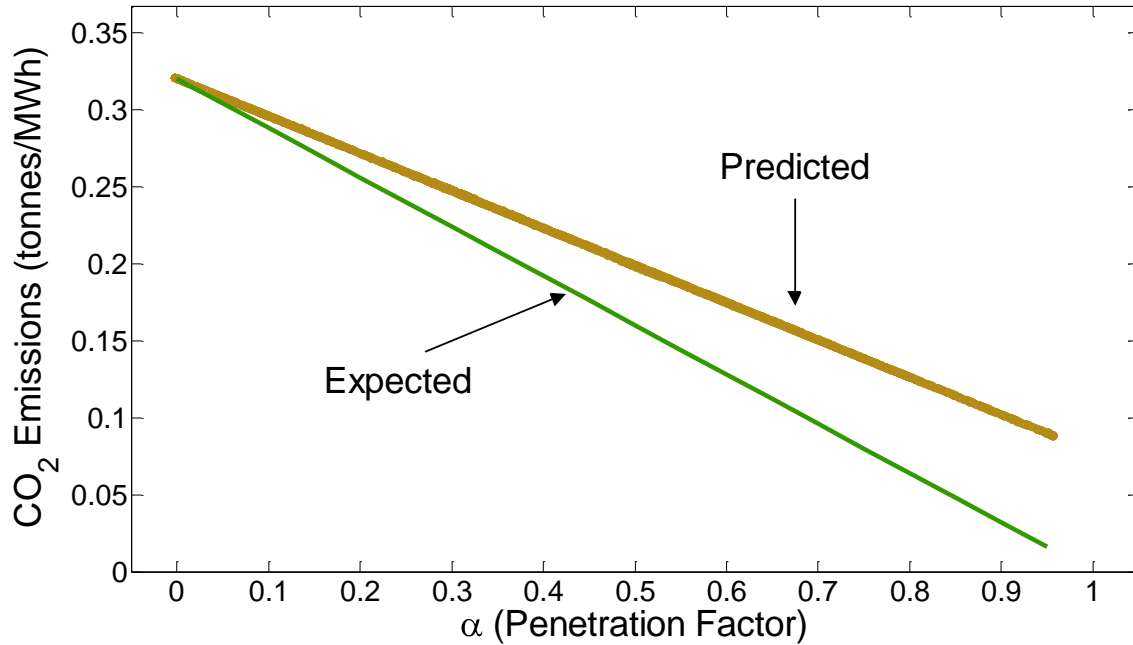
Figure 11 – 501FD results. Renewable plus natural gas CO_2 emission factor vs. renewable energy penetration level (α) (brown area). The expected emissions factor (green, lower line) is shown for comparison.
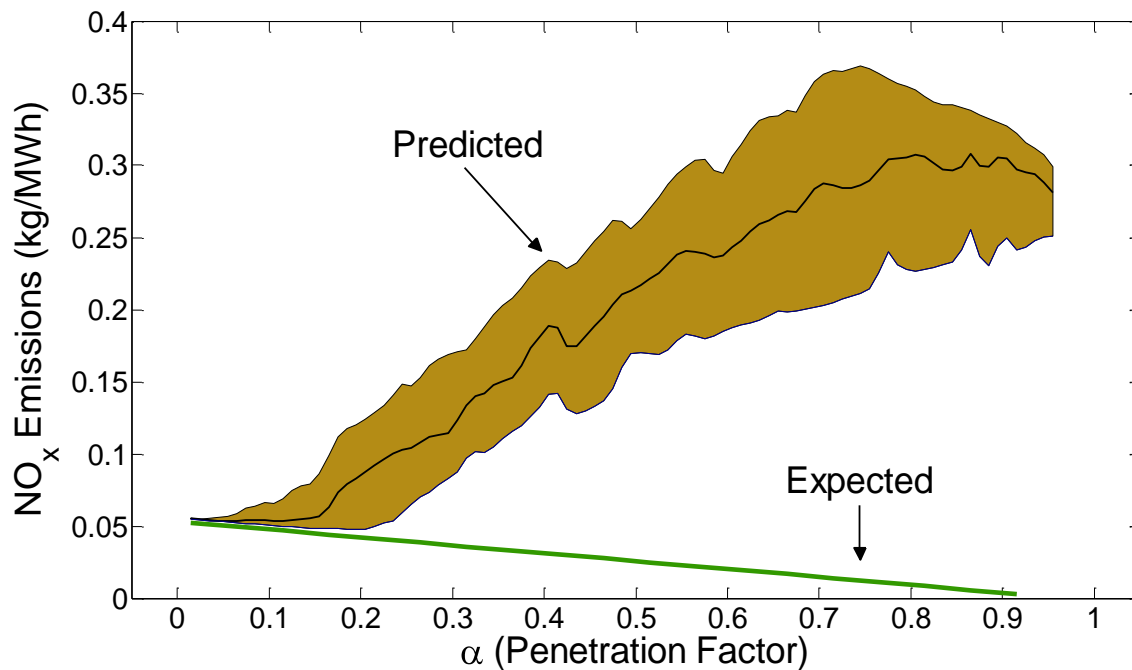
Figure 12 – 501FD results. Mean renewable plus natural gas NO_x emission factor vs. renewable energy penetration level (α) (black line); area shown represents 2 standard deviations of all five data sets (shaded brown area). The expected emissions factor (green, lower line) is shown for comparison.

All of the predicted emissions factors deviate from expectations based on an emissions displacement model. Compensating for wind's (or solar PV's) variability decreases the amount emissions are displaced. CO_2 emissions are predicted to be displaced linearly but at a slower rate than widely-used emissions displacement methods estimate for both an LM6000 and a 501FD. NO_x emissions for an LM6000 remain roughly constant for renewable penetrations below 65%. Only once penetration levels are above 65% does it appear NO_x emissions began to decrease. When a 501FD is providing compensating power for variable renewable energy, a threshold effect is observed. NO_x emissions are displaced according to expectations for penetration levels below 15%. For penetration levels above 15%, NO_x emissions increase rather than decrease because dry low NO_x systems are optimized for constant high power operation rather than cycling over the power range of a gas turbine.

2.5 *Multiple Generators*

CO_2 Emissions

CO_2 emissions are predicted to be displaced linearly for both the LM6000 case and the 501FD case. If the fraction of expected emissions reductions for CO_2 achieved is calculated according to Equation 17, η would be constant for all values of α. For the 501FD results, $\eta \sim 76\%$. For an LM6000, $\eta \sim 77\%$.

$$\eta = (M_{GT} - M_A) / (M_{GT} - \varphi) \qquad (17)$$

Mills et al. modeled the fuel use of multiple generators compensating for wind power and determined that multiple generators can increase the efficiency of a wind + gas plant [17]. They assumed that generators are turned on when needed and that there are no spinning reserves. This report adapted their model to calculate how η varies with wind penetration (α) and the number of generators in the system. The fundamental equation, assuming no spinning reserves, is

$$\eta = \frac{s\alpha + \frac{f_0}{P_{max}}\left(1 - \frac{\sum_{i=1}^{n}u_i}{n}\right)}{\left(\frac{f_0}{P_{max}} + s\right)\alpha}$$

where s is the slope of a generator's fuel consumption curve, f_0 is the generator's fuel consumption at zero load, n is the number of identical gas turbines, α is the penetration level of wind energy, P_{max} is the nameplate capacity of each generator, and u_i is the operating status of a each generator (1 if it is on, 0 if it is off). For the results displayed below, 501FD specific data was used. Specifically, $P_{max} = 200$ MW, $s = 0.035$ MBTU per MW-minute, and $f_0 = 2.23$ MBTU. The Southern Great Plains wind power data was used to determine what the mean value of η is for a variety of penetration levels. Figure 13 displays the results when 5 generators are used and Figure 14 displays the results when 20 generators are used. These results extend the results of [17] and show that a higher fraction of expected CO_2 emission reductions can be achieved with

multiple turbines to provide ancillary services, but that only ~85% of the expected CO_2 emission reductions are achieved for wind penetration of 20%.
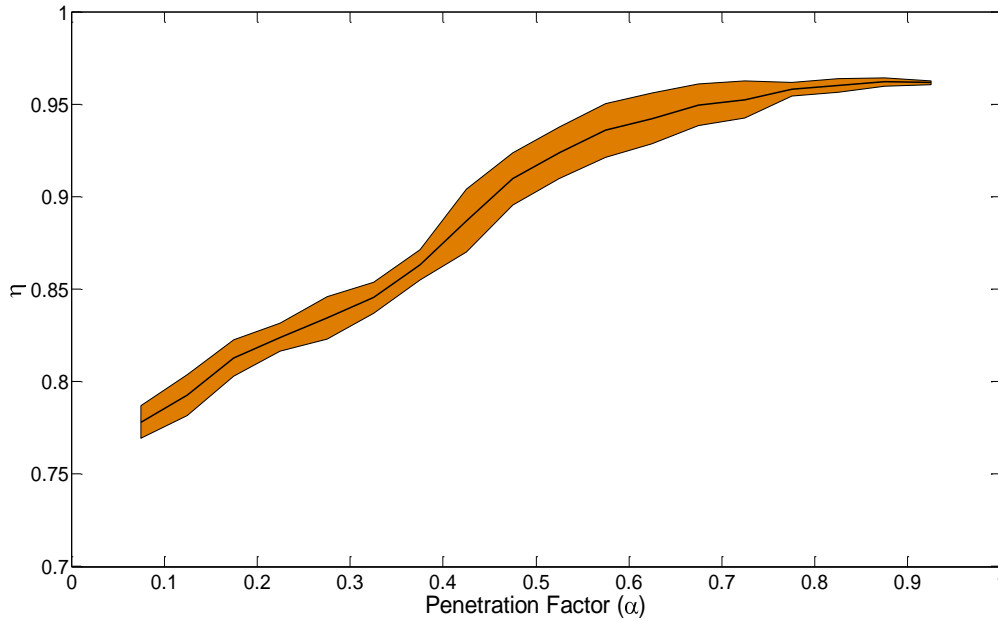
Figure 13 – Fraction of expected CO_2 emission reductions achieved (η) when 5 generators are used to compensate for wind's variability. No spinning reserves are used. The black line represents the mean η and the area shown (shaded brown area) represents one standard deviation from the mean when the Southern Great Plains wind data set is used.
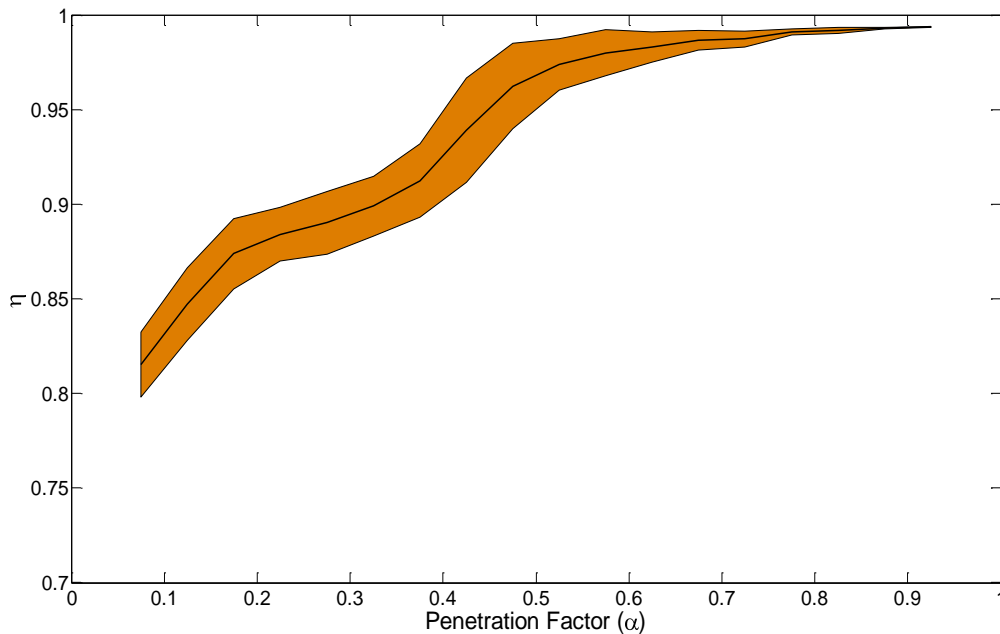
Figure 14 - Fraction of expected CO_2 emission reductions achieved (η) when 20 generators are used to compensate for wind's variability. No spinning reserves are used. The black line represents the mean η and the area shown (shaded brown area) represents one standard deviation from the mean when the Southern Great Plains wind data set is used.

Realistically, spinning reserves will be necessary to compensate for wind's variability and ensure a stable system. Figure 15 and Figure 16 display the results if one generator is used as a spinning reserve. Adding one spinning reserve generator reduces the system's CO_2 emission efficiency versus the wind penetration level. At 20% wind penetration, approximately 83% of expected CO_2 emission reductions are achieved when 20 generators are used to provide ancillary service, as opposed to 77% when 5 generators provide ancillary service.
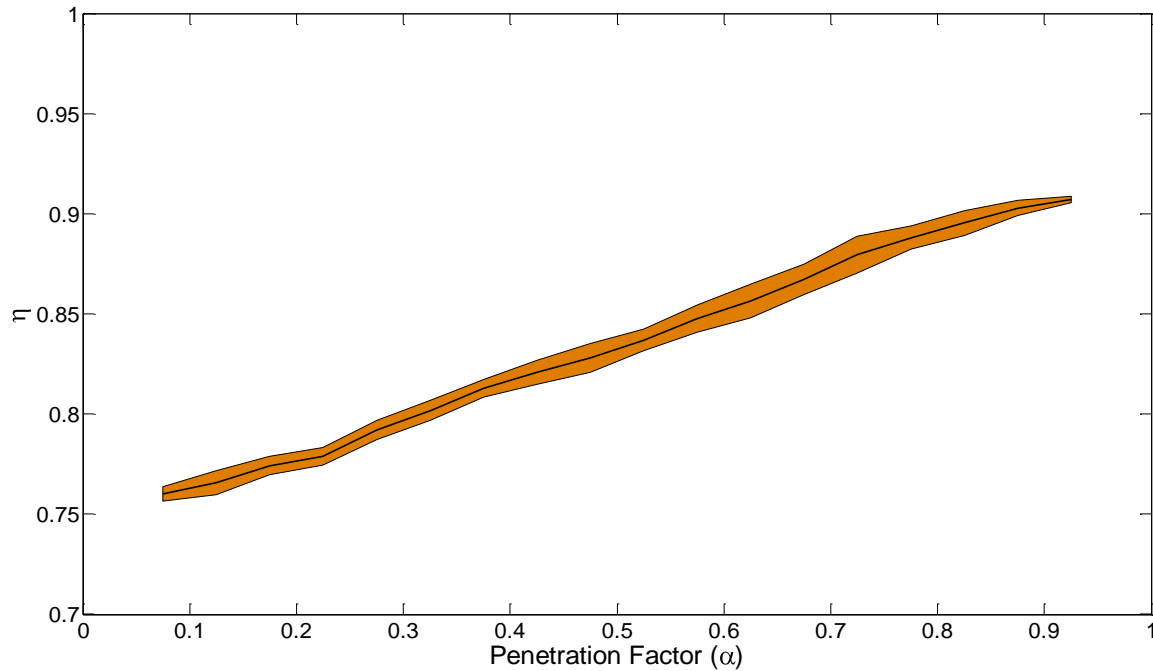
Figure 15 - Fraction of expected CO_2 emission reductions achieved (η) when 5 generators are used to compensate for wind's variability and one generator is used as a spinning reserve. The black line represents the mean η and the area shown (shaded brown area) represents one standard deviation from the mean when the Southern Great Plains wind data set is used.
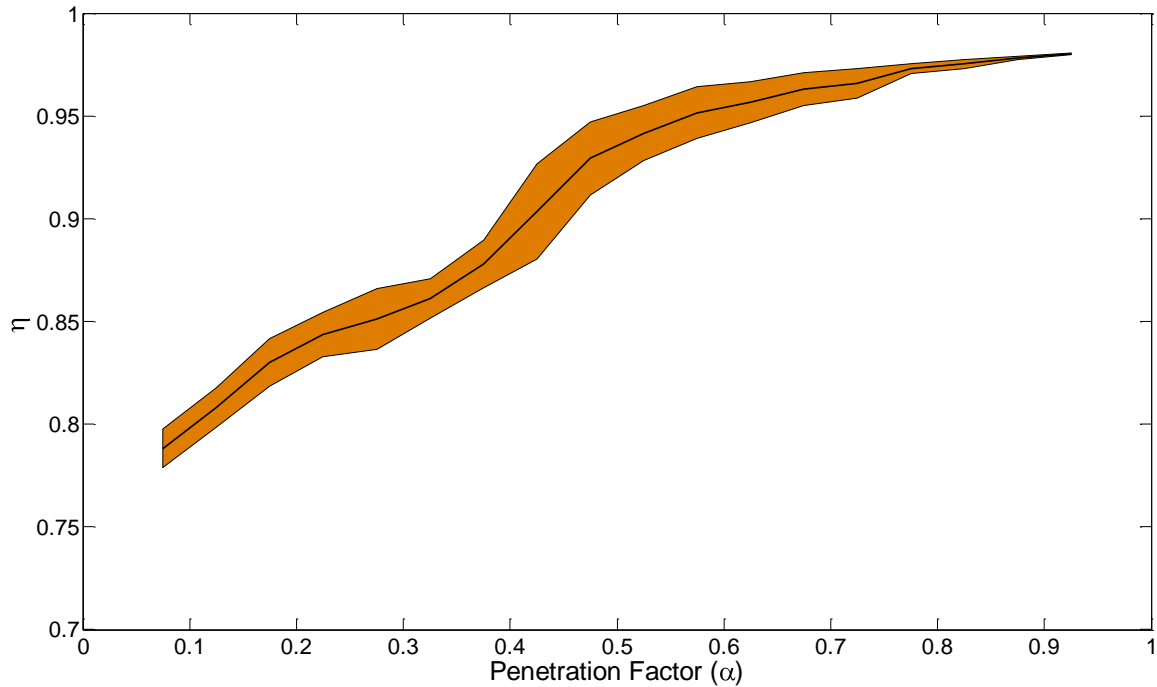
Figure 16 - Fraction of expected CO₂ emission reductions achieved (η) when 20 generators are used to compensate for wind's variability and one generator is used as a spinning reserve. The black line represents the mean η and the area shown (shaded brown area) represents one standard deviation from the mean when the Southern Great Plains wind data set is used.

NOₓ Emissions

Unlike CO_2 emissions, NO_x emissions are produced non-linearly as a function of the power level of a gas turbine. As a result, using multiple generators in the manner described for CO_2 emissions does not produce substantial improvements in η for an LM6000 (Figure 17). Improving η by using multiple 501FDs is possible but only if each turbine is operated at 50% of its nameplate capacity or greater (Figure 18). This limits the penetration of variable renewable power to 50% or less (even with a 20 or 25% RPS, this level could be exceeded at night when the wind blows strongly and load is low).
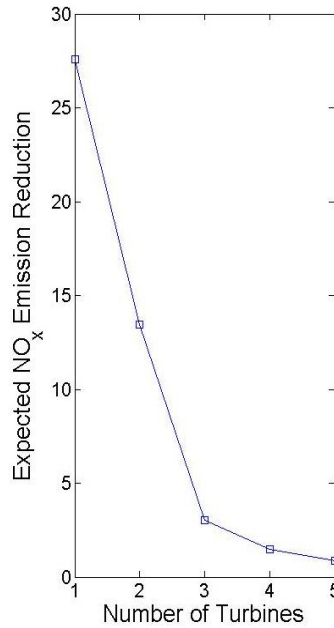
Figure 17 - NOx and CO$_2$ expected emission reductions when one to five LM6000 combustion turbines are paired with the wind farm. NOx emission reductions degrade as the lower operating limit of the turbines is increased while CO$_2$ expected emission reductions increase
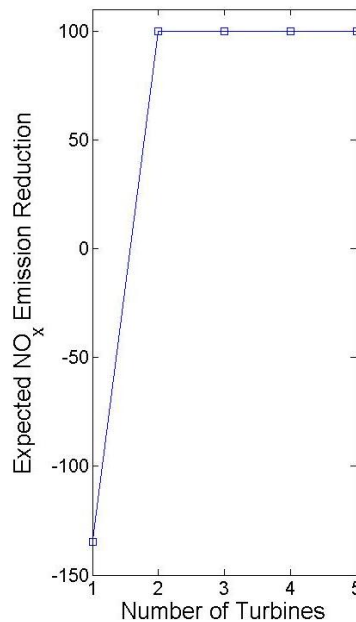
Figure 18 - NO$_x$ and CO$_2$ expected emission reductions when one to five 501FD combustion turbines are paired with the wind farm. There is significant improvement in NO$_x$ emission reductions when going from one turbine to two as a result of increasing the minimum power operating limit of the turbines from zero to 50% load.

Using two or more 501FD turbines result in expected emission reductions of 100% and is the result of relatively flat NO$_x$ emission rates for the 501FD with GE's Dry-Low NO$_x$ over power

ranges of 50% to 100%. CO_2 expected emission reductions do not change significantly as a result of the linear CO_2 model used.

3. INTEGRATION AND TRADEOFFS

3.1 *Coal+Wind Simulation and Results*

In order to conduct a preliminary investigation of the feasibility of operating coal and wind together to achieve approximately constant power, a mathematical simulation of such a system was constructed. Because NETL had requested that RDS perform a scoping study of coal+wind with a delivery time before our final report for this task was due, the results of the simulation described below was supplied to Mr. Patrick Findle of RDS/SAIC, the team lead for that study.

The objective function of the model is to maintain firm power, within a deadband (set to ½ % of the desired output power to prevent oscillation of the control loop). The system was sized so that the highest output power of the wind farm and of the coal generator are the same.
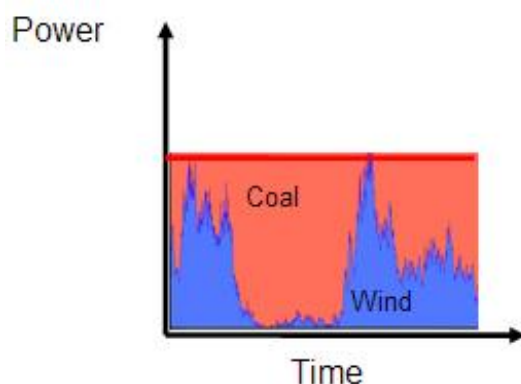
Figure 19 - The objective function of the coal + wind system is to maintain a set power level (the nameplate capacity of the wind farm) by ramping the coal generation to compensate for the wind's variability.

The model allows specification for the coal generation unit of a lower and upper operating limit and the ramp rate up and down (the model was constructed so that these may be specified separately, but for this preliminary study they were set to the same value). The low operating limit was set to zero for this study.
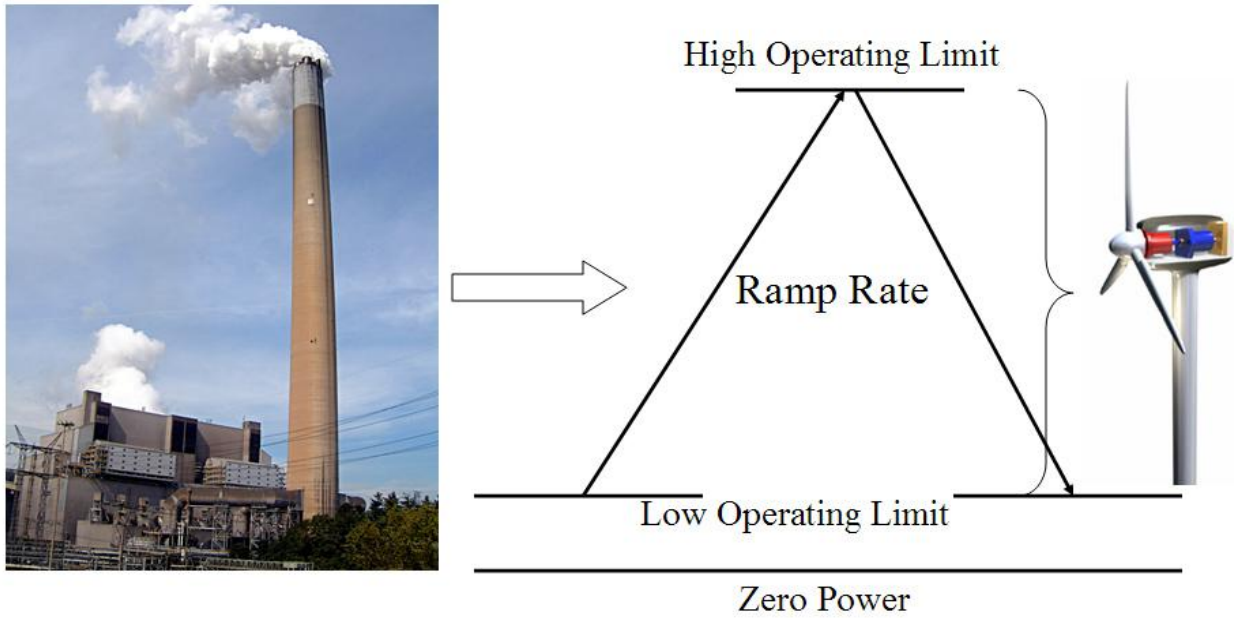
Figure 20 - Modeled characteristics of the coal generation unit.

A sample of 59 operating coal generators with high operating limits (HOL) from 98 MW to 1264 MW were examined. These units have ramp rates from 0.18 % of their high operating limit to 1.22% of their high operating limit per minute (Figure 21).
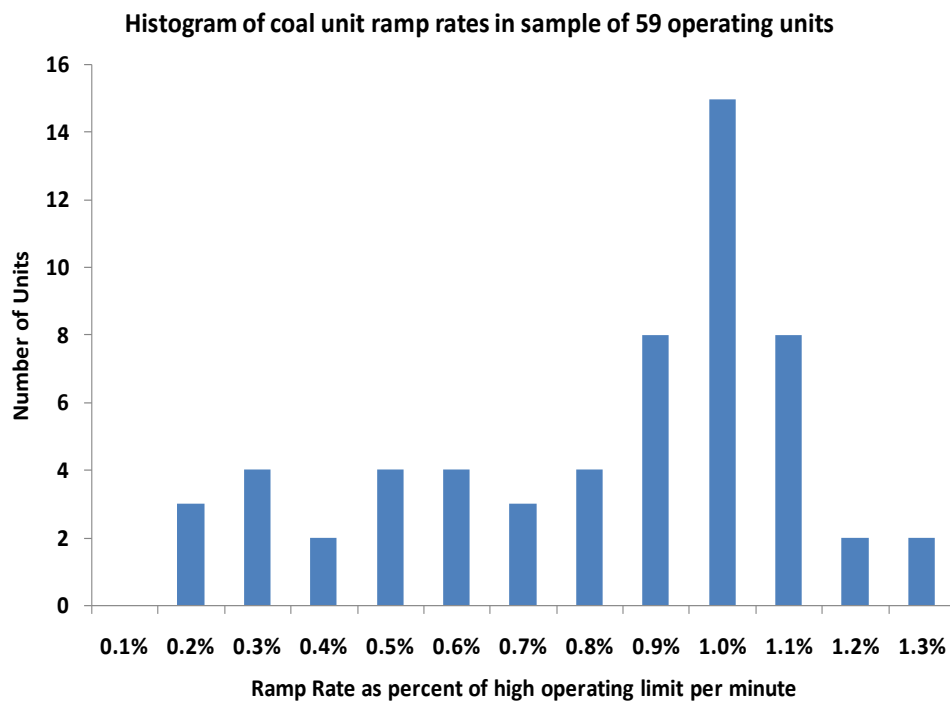
Figure 21 - Ramp rates of existing coal generation units for one representative utility.

For comparison, a sample of 9 operating gas/oil generators with high operating limits from 63 MW to 93 MW were examined. These units have ramp rates from 7.53 % of their high operating limit to 25.4% of their high operating limit per minute.

To drive the model, real power output data at one second time resolution was obtained for two wind farms over a continuous 10 day period.

For the model results presented below, a 12-hour period of the wind data was selected (43,200 seconds). The summed output power of the two wind farms was scaled to 1 GW.

Wind Power
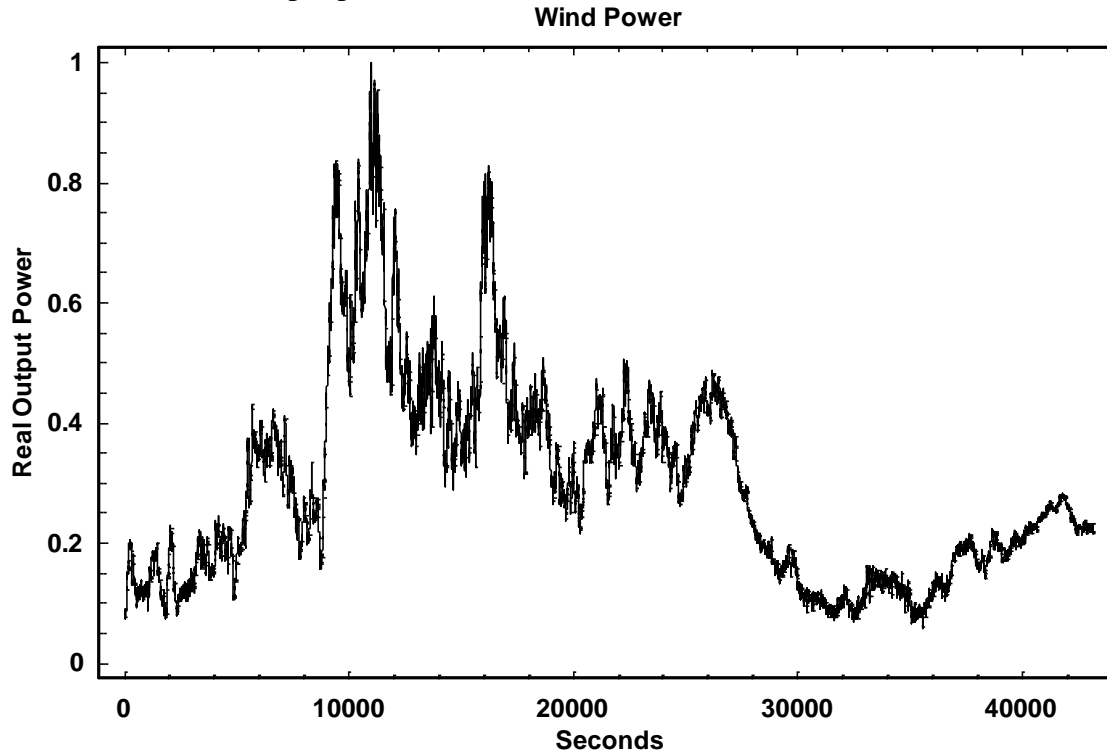
Figure 22 - Wind data used in the simulation, from the summed output of two wind farms for 12 hours, with time resolution of one second.

The capacity factor of the summed output from the two wind farms was 28% over the selected 12-hour period. This is a representative wind capacity factor; the average capacity factor for all US wind generation during this decade has been between 26.4% and 35%, depending on the year (Table 5).

Year	Capacity Factor for all US wind
2001	29.7%
2002	35.0%
2003	30.4%
2004	31.7%
2005	26.4%
2006	29.6%
2007	33.2%

Table 5. National average wind capacity factors, 2001-2007 (most recent available data). Source for wind generation, U.S. Energy Information Administration. Source for wind installed capacity, Ventyx Velocity Suite.

The model's time step is 0.1 second. The wind power was computed at each time step by linear interpolation of the 1 second wind data. At each time step, the ideal fill power was computed as the goal power (1 GW) less the wind power. The model ramped the coal unit power output up or down as at each time step in an attempt to reach the ideal fill power, at the ramp rate specified in that run of the model.

The match between coal units and the required fill power is illustrated in Figure 23 for ramp rates of 0.33%, 0.5%, 0.75%, 1%, and 1.25% per minute of the high operating limit (i.e. nameplate capacity) of the coal unit.

In order to provide a comparison with existing natural gas generators, or with future purpose-designed coal units with high ramp rates, the model was also run with ramp rates of 7.5% (typical of gas/oil generators of ~ 100 MW) and 25% per minute (achieved by three gas/oil generators of ~ 65 MW in the sample used).

The error between the ideal fill power and the ramp-rate-constrained coal unit power was computed at each time step. The maximum error:

(wind + achieved fill power - desired power) /desired power

during the 12 hours is shown in Figure 23 after the 1.25% per minute, 7.5% and 25% plots.

The simulation results quantify the advantage of higher ramp rates. Figure 24 shows the maximum error (defined as in the previous paragraph) as a function of ramp rate. The maximum error observed in the simulation can be well fit by a power law (the maximum error is reduced by roughly the inverse of the square root of ramp rate).

Figure 25 shows similar behavior for the integrated error during the 12 hour period (the sum of the absolute value of the error at each time step in the simulation). Again, the error is roughly proportional to the inverse of the square root of the ramp rate. That is, doubling the ramp rate decreases error by roughly a factor of 1.4.

Further research is required to investigate the ability of a wind + coal + gas system, with potential additions of fast devices, to reduce the system real power output error.

Required Fill Power (blue), Achieved Fill Power (red)

Fill Power Ramp Rate 0.33% per minute

Required Fill Power (blue), Achieved Fill Power (red)

Fill Power Ramp Rate 0.5% per minute

Required Fill Power (blue), Achieved Fill Power (red)

Fill Power Ramp Rate 0.75% per minute

Required Fill Power (blue), Achieved Fill Power (red)

Fill Power Ramp Rate 1% per minute

Required Fill Power (blue), Achieved Fill Power (red)

Fill Power Ramp Rate 1.25% per minute

Error

Fill Power Ramp Rate 1.25% per minute

Required Fill Power (blue), Achieved Fill Power (red)

Fill Power Ramp Rate 7.5% per minute

Error

Fill Power Ramp Rate 7.5% per minute

Figure 23 - Simulation results
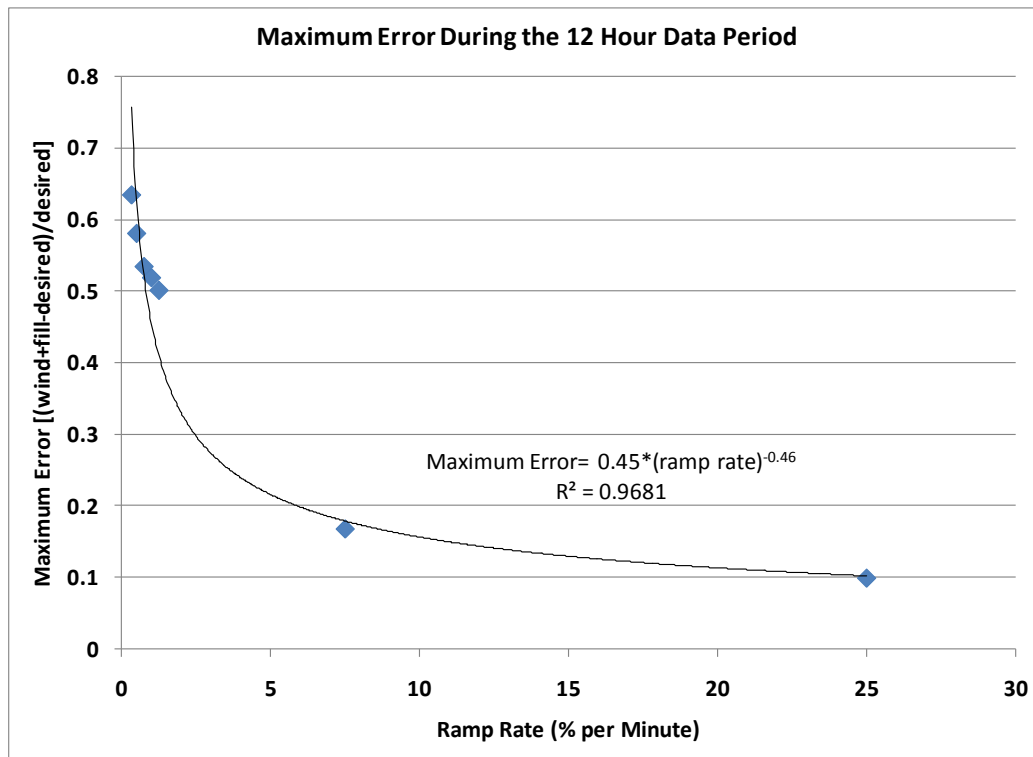
Figure 24 - Maximum error in real power from the wind + thermal system as a function of ramp rate.
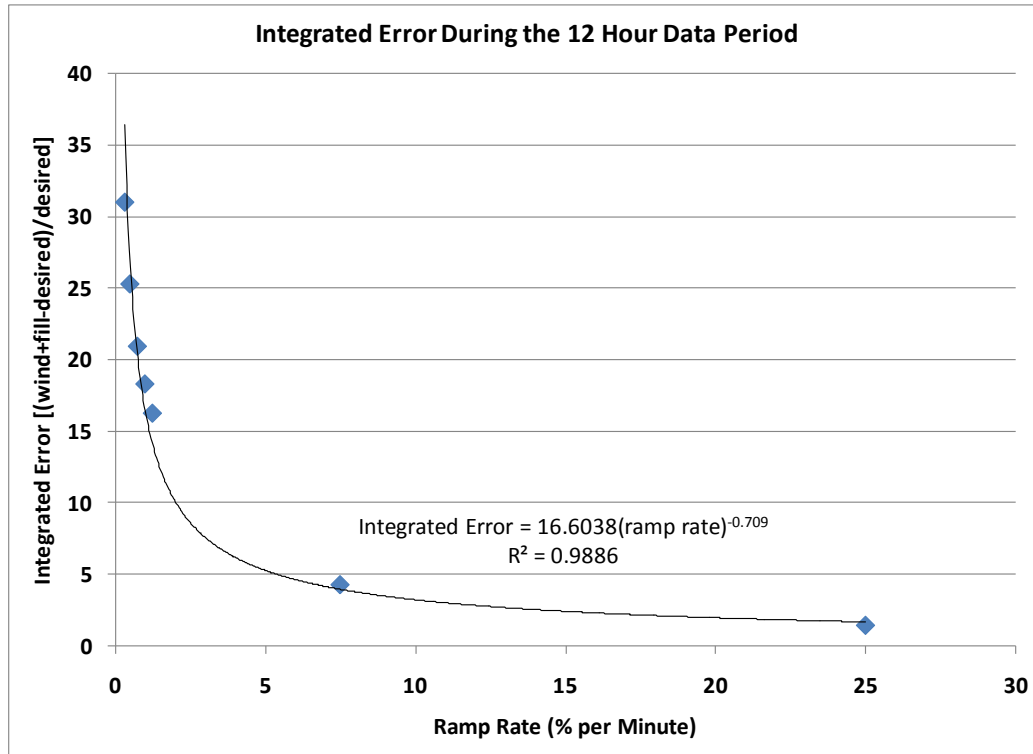
Figure 25 - Integrated error in real power from the wind + thermal system as a function of ramp rate.

3.2   *Remarks on System Design, Operation, Tradeoffs and Potential R&D*

3.2.1   **Wind and thermal plant system designs and operation**

There are two basic ways that real power systems can dispatch natural gas generators to compensate for the variable character of wind or solar PV power. In the first method, the operator dispatches a single natural gas generator that ramps up and down to cover the variability, then starts additional generators as required. In the second, the system operates all generators as spinning reserve. Both methods spread the ramping requirement equally over the running natural gas generators.

In either dispatch method, there are air emissions penalties to be paid. The first is the penalty associated with starting the generator (for example, see the upper branch of NO_x emissions in figures 5 and 7 above). The second is the penalty associated with operating at partial power (both methods can minimize this in multiple turbine operations). The third is the penalty that arises from keeping a generator operating at idle power so that it can quickly be ramped up when the wind or solar power falls off. The second method pays this penalty for all generators

operating as spinning reserve, while the first method pays a larger startup penalty than the second.

If system operators recognize the potential for ancillary emissions from gas generators used to fill in variable renewable power, they can take steps to produce a greater displacement of emissions. 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 (but rarely used) firing modes that reduce emissions when ramping may be practical.

3.2.2 **Tradeoffs in environmental releases and cost profile**

Carbon dioxide emissions reductions from a wind (or solar PV) plus natural gas system are likely to be 75-80% of those presently assumed by policy makers. Nitrous oxide reduction from such a system depends strongly on the type of NO_x control and how it is dispatched. For the best system examined, NO_x reductions with 20% wind or solar PV penetration are 30-50% of those expected. For the worst, emissions are increased by 2-4 times the expected reductions with a 20% RPS using wind or solar PV.

The implications of these results were examined by analyzing the potential interaction between state RPSs and the Clean Air Interstate Rule (CAIR). The District of Columbia Circuit Court of Appeals vacated CAIR in July 2008, but this section examines the interactions between an RPS and CAIR, under the assumption that a similar NO_x emission rule will come into force in the future. CAIR was designed to reduce annual NO_x emissions 60% by 2015. States with large RPSs may experience NO_x emissions from gas turbines used to fill in the variable renewable power that can make it more difficult to meet CAIR requirements. This section estimates the percentage these ancillary emissions could consume of a state's CAIR annual NO_x emissions allocation in 2020 (most RPSs are fully phased in by 2020; here we assume that the 2020 NO_x limits are the same as in 2015).

We assume all RPSs in CAIR states are fulfilled and that all RPS targets that can be met by wind are. RPSs that are specified by a percentage to MWh of wind generation in 2020 are converted by using EIA's 2001 assumption (used in the CAIR program) that load will grow linearly to 3% above 2008 load. All displaced and fill-in generators are assumed similar to either LM6000s or 501FDs. The expected emission reductions ($M_G - \varphi$) are estimated by using NO_x emission factors of 0.2 kg/MWh for LM6000s and 0.15 kg/MWh for 501FDs as obtained from EPA's AP-42 database. For each state, the study average the estimated η for the four wind farm data subsets and estimate M_A. Finally, the equations described above are used to derive the mass of NO_x emissions attributed to variability that are not currently included in most emissions displacement studies.

Table 6 summarizes the CAIR analysis. When LM6000 turbines are used, the potential emissions associated with variability are significant for Illinois, Minnesota, and New Jersey: countering wind's variability could consume 2 to 3% of each state's annual CAIR allocations. If 501FDs are used, 7 of the 12 states could have 2 to 8% of their annual CAIR allocations used to provide fill-in power for wind or PV power plants.

In states like New Jersey, careful selection of the NO_x controls used for wind compensation may be warranted to avoid upward pressure on NO_x allocation prices, similar to when the NO_x budget was first implemented. Using the emissions from Table 6 and assuming an annual NOx emission allocation price of \$2,800 per ton, the costs associated with degraded emissions performance can be as high as 0.24 cents per kWh of renewable energy for NO_x emissions. With a carbon price of \$50 per ton carbon dioxide, the added costs can be as high as 0.50 cents/kWh for CO_2 emissions. These costs do not include the additional maintenance costs that may arise from cycling the gas turbines to compensate for the renewables' variability.

As part of their NO_x control strategy, states may choose to award NO_x allowances to eligible renewable energy and energy efficiency projects. These awards range from a few percent of the NO_x allowances to as much as 15%. New Jersey's set-aside is 5%, and Minnesota has proposed a 15% renewable set-aside.

These results caution that annual average emissions factors may not be appropriate for the summer ozone control months, since the character of the variability of both wind and solar PV is dependent on the season. Note that the awards are based on the equivalent displacement assumption, and states that use gas generators to compensate for wind or solar PV variability may find that assumption is not warranted.

TABLE 6. Summary results of CAIR analysis for the 12 CAIR states with a renewables portfolio standard. The wind penetration fraction is the larger of the fraction of the state's 2020 RPS requirement that could be fulfilled by wind, or currently installed wind. The CAIR allowance is the 2015 allowance. Note: fractions may not match exactly due to rounding.

State	Wind penetration Fraction (α)	State's annual CAIR NO$_x$ allowance (thousand tonnes)	LM6000 with steam injection		501FD with DLN	
			M_V annual (tonnes)	% M_V of state's CAIR allowance	M_V annual (tonnes)	% M_V of state's CAIR allowance
Delaware	0.18	8.6	48	0.56	140	1.6
Illinois	0.18	60	1200	2.0	3400	5.8
Iowa	0.07	43	29	0.07	59	0.13
Maryland	0.075	11	40	0.37	260	2.4
Minnesota	0.25	34	730	2.2	2000	6.0
Missouri	0.11	60	250	0.42	220	0.37
New Jersey	0.16	12	350	3.0	910	7.7
New York	0.077	19	120	0.64	820	4.2
North Carolina	0.11	44	320	0.72	290	0.65
Pennsylvania	0.07	65	180	0.27	1000	1.6
Texas	0.033	150	590	0.04	120	0.08
Wisconsin	0.1	31	140	0.45	120	0.40

The calculations above assume that variability in renewable generation results in similar variability in the natural gas generators used to compensate. There are several reasons this may not be correct, including use of coal and oil generators for compensation and interaction between renewable variability and load variability, so the estimates in Table 6 are likely to provide an upper bound on estimates of the emissions increase associated with wind and solar generation's

variability. Storage systems other than pumped hydroelectric are presently not cost-effective, but may reduce the need for ramping generators should their costs fall.

3.2.3 Recommendations for potential research

On a time scale compatible with RPS implementation, design and market introduction of generators that are more appropriate from an emissions viewpoint to pair with variable renewable power plants may be feasible.

Both firing mode changes and reduction of the power level at which the dry low NOx system achieves low emissions of NOx are subjects for research and development.

It is possible that a systems operator tool might be developed to change the objective function of the dispatch optimization to include not only security-constrained optimum power flow but also emissions minimization as an objective for ancillary service dispatch.

Finally, methods to mitigate the effects of high-frequency wind power variability on electrical grid frequency at the wind farm should be investigated, and cost-effective electric smoothing devices may prove feasible with advances in materials science.

4. Literature Review

4.1   *Summary*

Existing literature on integrating variable renewable power (particularly wind) with fossil fuel generators considers four main themes.

1. Wind and solar power characteristics – understanding how wind and solar power vary with time.
2. Integration into the grid – anticipating problems and estimating how system dynamics will change.
3. Variability's affects on fossil generators – estimating how combustion systems may be affected by countering wind's variability.
4. Environmental consequences – estimating fossil fuel emissions that were displaced by wind energy.

For each, pertinent journal articles and studies are listed below with a synopsis and an explanation of relevance to this research.

4.2   *Wind and Solar Power Characteristics*

Integrating variable renewable power in an electricity system first requires an understanding of the nature of the variability that will be incorporated. Time domain analyses focus on

statistically quantifying how fast wind or solar vary. Frequency domain analyses examine the spectrum of wind or solar power.

4.2.1 **Wind power plant monitoring project**

Citation: Wan, Y.-H. Wind power plant monitoring project annual report. National Renewable Energy Laboratory. Document number NREL/TP-500-30032. 2001. Available: http://www.nrel.gov/docs/fy01osti/30032.pdf

Relevance: Wan's report details the time-domain characteristics of wind power. Wan examines wind power and ramp rates on a monthly, daily, hourly, 10-minute, minute, 10-second, and second basis. His work provides system operators and planners descriptive statistics of wind power that can aid in assessing system adequacy for incorporating wind variability.

Synopsis: "Over the past 13 months, more than 150 million data points have been collected and cataloged from two Midwest operating commercial wind power plants. Analysis of these data has provided useful insight on the behavior of wind power. Changes of wind speed rarely cause extreme power-level changes of a large wind power plant. The variations in wind power plant output as a result of natural wind speed variations are well within the capability of an interconnected power system. When step changes are used to gauge the wind power fluctuations, changes appear small in value and are within a very narrow range. On a second-by-second basis, the maximum step changes are 4.4 MW up and 7.6 MW down; however, the standard deviation value (σ) of all 1-second step changes is only 168 kW, with an average value of zero. On a minute-by-minute basis, given the knowledge of current power output at any level (e.g., at 40% of the total capacity) operators can expect that at least 92% of the time, the output power will remain at the same level in the next minute. For Lake Benton IL, with 138 turbines and 103.5 MW of total capacity, the maximum ramping-up rate during a 10-second period is 2.8 MW per second and the maximum ramping down rate is -2.5 MW per second. The corresponding average ramping rates are only 28 kW/s and -31 kW/s. In a 10-minute window, the maximum ramping-up rate is 6.9 MW per minute (115 kW/s) and the maximum ramping down rate is 6.6 MW per minute (110 kW/s). Over the 12-month period shows that 99% of the apparent power-changing rates are within ±220 kW/s. As expected, more wind turbines will tend to "smooth" the power output by reducing the variability of wind power. The data also indicate the predictability of wind power plant output. Correlation analysis of power outputs from Lake Benton II and Storm Lake wind power plants shows that output from one plant can be a very good indication of output from the other plant. This suggests that, with adequate information about wind speed and direction (and other meteorological data) from strategically located places, one can predict output from a wind power plant with a reasonable degree of accuracy."

4.2.2 **The spectrum of power from wind turbines**

Citation: Apt, J. The spectrum of power from wind turbines. *J. of Power Sources*. 2007, 169 (2), 369-374.

Relevance: Apt's paper examines the frequency characteristics of wind power. His major finding is wind power variability can be characterized as a Kolmogorov spectrum because wind power fluctuations are caused by atmospheric turbulence. As a consequence of the power spectrum's character, a portfolio of thermal power plants, storage and demand response, with a power spectrum similar to wind power's, is required to cost effectively compensate wind's variability a system.

Abstract: "The power spectral density of the output of wind turbines can provide information on the character of fluctuations in turbine output. Here both one second and one hour samples are used to estimate the power spectrum of several wind farms. The measured output power follows a Kolmogorov spectrum over more than four orders of magnitude, from 30 seconds to 2.6 days. The spectrum constrains the character of fill-in power which must be provided to compensate for wind's fluctuations when wind is deployed at large scale. Installing enough linear ramp rate generation to fill in fast fluctuations with amplitudes of 1% of the maximum fluctuation would oversize the fill-in generation capacity by a factor of two for slower fluctuations. A more efficient solution is feasible."

4.2.3 **The character of power output from utility-scale photovoltaic systems**

Citation: Curtright, A.; Apt, J. The character of power output from utility-scale photovoltaic systems. *Progress in Photovoltaics*. 2008. 16 (3), 241-247.

Relevance: Curtright and Apt's paper examines the frequency characteristics of solar power. Counter intuitively, their major finding is that at high frequencies solar power has relatively more variability than wind power when measured using power spectral density.

Abstract: "The power spectral density of the output of utility-scale wind farms and solar photovoltaic (PV) arrays is examined to provide information on the character of fluctuations in real power output; the power spectrum constrains the character of fill-in power. Both one second and one hour samples from several wind farms and ten second and one minute resolution data from four solar PV arrays are analyzed. The measured output power for wind follows a Kolmogorov spectrum over more than four orders of magnitude, from 30 seconds to 2.6 days. That for PV is significantly flatter; thus fluctuations at short time scales are larger relative to those at long time scales for PV than for wind. While wind's capacity factor varies from 32% at the sites examined to 40% at excellent sites, the capacity factor for a 4.6 MW PV array in Arizona is determined to be 19% over two years."

4.3 *Integration Into the Grid*

Integrating wind into a system is a significant concern for system operators, and system planners, researchers, and consultants have produced a significant amount of work to anticipate any problems. Research efforts have focused on how variability can and should be handled in electricity systems and how the system dynamics may change. Finally, integration studies have examined electricity markets for resource adequacy and system stability

4.3.1 **Dealing with intermittency**

4.3.1.1 **The impact of large scale wind power production on the Nordic electricity system**

Citation: Holttinen, H. The impact of large scale wind power production on the Nordic electricity system. VTT Technical Research Centre of Finland. Publication 554. Julkaisija-Utgivare: 2004. Available: http://www.uwig.org/P554.pdf

Relevance: A comprehensive thesis analyzing the impact of large amounts of wind power in the Nordic electricity system. The applicability of Holttinen's thesis (see http://lib.tkk.fi/Diss/2004/isbn9513864278/) to US systems is limited because the Nordic electricity system contains a significant amount of hydropower and is strongly interconnected with neighboring electricity systems. Areas such as the Pacific Northwest can benefit from Holttinen's findings but regions heavily dependent on fossil power plants, such as the Southeast or Texas, cannot.

Abstract: "This thesis studies the impact of large amounts of wind power on the Nordic electricity system. The impact on both the technical operation of the power system and the electricity market are investigated. The variability of wind power is reduced when looking at a large interconnected system with geographically dispersed wind power production. In the Nordic countries, the aggregated wind power production will stay between 1-90% of the installed capacity and the hourly step changes will be within ±5% of the installed capacity for most of the time. The reserve requirement for the system, due to wind power, is determined by combining the variations with varying electricity consumption. The increase in reserve requirement is mostly seen on the 15 minutes to 1 hour time scale. The operating reserves in the Nordic countries should be increased by an amount corresponding to about 2% of wind power capacity when wind power produces 10% of yearly gross demand. The increased cost of regulation is of the order of 1 €/MWh at 10% penetration and 2 €/MWh at 20% penetration. This cost is halved if the investment costs for new reserve capacity are omitted and only the increased use of reserves is taken into account. In addition, prediction errors in wind power day ahead will appear in the regulating power market to an extent which depends on how much they affect the system net balance and how much the balance responsible players will correct the deviations before the actual operating hour. Simulations of increasing wind power in the Nordic electricity system show that wind power would mainly replace coal fired production and increase transmission between the areas within the Nordic countries and from Nordic countries to Central Europe. The CO_2 emissions decrease from an initial 700 gCO_2/kWh to 620 gCO_2/kWh at 12% penetration. High penetrations of wind power will lower the Nordpool spot market prices by about 2 €/MWh per 10TWh/a added wind production (10 TWh/a is 3% of gross demand)."

4.3.1.2   The viability of balancing wind generation with storage

Citation: Feeley, C., A.G. Bryans, B. Nyamdash, E. Denny, M. O'Malley. "The viability of balancing wind generation with storage." IEEE PES 2008.

Relevance: Feeley et al. analyze the effect of variable renewable power on the optimal dispatch of a portfolio of thermal generating assets. As more wind is added to a system, the amount of energy provided by base-load plants, such as coal or nuclear plants, decreases while the energy provided by peaking plants, such as natural gas turbines, increases. For systems minimizing cost by dispatching energy based on power plant marginal costs, increasing the amount of wind in a system will increase the cost of electricity for consumers because thermal peaking plants have the highest marginal costs and base-load plants have the lowest.

Abstract: "This paper studies the impact of balancing wind generation with storage on the thermal plant mix and load for different levels of installed wind and storage, and under different operational strategies. Moreover, the optimal time frame to be used for the optimization of the system operation is studied and the possible revenue that can be generated by the system with wind and storage is calculated for different scenarios. It is shown that the introduction of intermittent energy resources reduces the participation of the base-load plants and increases the peaking plants, and the increasing storage dramatically increases the participation of the midmerit plants. Furthermore, the mid-merit strategy and 24 hours time frame resulted in the best use of the system with wind and storage."

4.3.1.3   Supplying baseload power and reducing transmission requirements by interconnecting wind farms

Citation: Archer, Cristina L. and Mark Z. Jacobson. "Supplying baseload power and reducing transmission requirements by interconnecting wind farms." *J. of Appl. Meteorology and Climatology*. 46 (2007): 1701 - 1717.

Relevance: If wind's variability can be reduced it could be used to provide baseload power. Archer and Jacobson examine if the power from interconnected, spatially separated wind power plants would be less variable than power from an individual wind power plant. They use hourly and daily NOAA wind speed data as a proxy for actual wind plant power data. They estimate the correlation between the power output of interconnected wind plants, estimated by wind speed data, decreased as more wind plants were interconnected. Archer and Jacobson's results are valid only for time periods of an hour or longer and are important for system planning. But their results cannot be used to assess whether the variability of wind power is reduced for shorter time scales where system stability is important. Further work using data at finer time resolution is required to determine the applicability of these results to real power systems.

Abstract: "Wind is the world's fastest growing electric energy source. Because it is intermittent, though, wind is not used to supply baseload electric power today. Interconnecting wind farms through the transmission grid is a simple and effective way of reducing deliverable wind power swings caused by wind intermittency. As more farms are interconnected in an array, wind speed correlation among sites decreases and so does the probability that all sites experience the same wind regime at the same time. The array consequently behaves more and more similarly to a single farm with steady wind speed and thus steady deliverable wind power. In this study, benefits of interconnecting wind farms were evaluated for 19 sites, located in the Midwestern United States, with annual average wind speeds at 80 m above ground, the hub height of modern wind turbines, greater than 6.9 m s-1 (class 3 or greater). It was found that an average of 33% and a maximum of 47% of yearly averaged wind power from interconnected farms can be used as reliable, baseload electric power. Equally significant, interconnecting multiple wind farms to a common point and then connecting that point to a far-away city can allow the long-distance portion of transmission capacity to be reduced, for example, by 20% with only a 1.6% loss of energy. Although most parameters, such as intermittency, improved less than linearly as the number of interconnected sites increased, no saturation of the benefits was found. Thus, the benefits of interconnection continue to increase with more and more interconnected sites."

4.3.2 **System operation**

4.3.2.1   **Wind generation, power system operation, and emissions reduction**

Citation: Denny, Eleanor and Mark O'Malley. Wind generation, power system operation, and emissions reduction. IEEE Transactions on Power Systems. Vol. 21, issue 1. February 2006: 341-347.

Relevance: Denny and O'Malley modeled the emissions reductions of significant penetrations of wind power by simulating the operation of Ireland's power system with up to 30% wind. In estimating the emissions displaced by wind power, Denny and O'Malley utilize emission factors (mass or concentration of pollutant emitted per energy produced) that vary over a turbine's power range instead of the traditional method of using emission factors that were taken at full-power steady-state conditions. With a more accurate model, they found wind power is able to significantly displace CO_2 emissions but had a negligible effect on NOx and SO_2 emissions. Denny and O'Malley modeled emissions reductions from wind power penetration using an economic dispatch model for Ireland and an emissions factor that varies with turbine power for a natural gas combined-cycle turbine (NGCC) and a simple-cycle natural gas combustion turbine (CT), concluding that CO_2 would be reduced 9% for a wind penetration factor of 11% (82% of the expected reduction for that penetration of wind) and NOx emission reductions would be 90% of the expected reductions. Their model uses hourly data sets that are not able to capture a portion of the rapid fluctuations of wind and does not depend on ramp rate; they did not examine the effects of different NOx mitigation methods.

Abstract: "With increasing concern over global climate change, policy makers are promoting renewable energy sources, predominantly wind generation, as a means of meeting emissions

reduction targets. Although wind generation does not itself produce any harmful emissions, its effect on power system operation can actually cause an increase in the emissions of conventional plants. A dispatch model was developed that analyzes the impact that wind generation has on the operation of conventional plants and the resulting emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2), and oxides of nitrogen (NOx). The analysis concentrates on a "forecasted" approach that incorporates wind generation forecasts in the dispatch decisions. It was found that wind generation could be used as a tool for reducing CO_2 emissions but alone, it was not effective in curbing SO_2 and NOx emissions."

4.3.2.2   Coal and wind power plant integration

Citation: Ihle, Jack. "Coal and wind power plant integration." Platts research and consulting. Presentation: Tuesday, October 21, 2003.

Relevance: Ihle, through an analysis of coal plant ramp rates and wind power variability, estimated 8 MW of coal capacity for each MW of wind power capacity are needed if coal plants are to compensate for 100% of wind's variability. This suggests in systems solely dependent on coal power, the maximum penetration of wind power with 100% reliability is approximately 5%.

4.3.2.3   Power system modeling of 20% wind-generated electricity by 2030

Citation: Hand, M., N. Blair, M. Bolinger, R. Wiser, R. O'Connell, T. Hern, and B. Miller. Power system modeling of 20% wind-generated electricity by 2030. NREL IEEE PES 2008.

Relevance: NREL's study estimates what the United States generation portfolio would be composed of if 20% of the nation's power in 2030 came from wind. Hand et al. find that wind could provide 20% of the United States' electricity supply and would primarily avoid electricity from combined-cycle natural gas turbines and new coal plants which is contrary to the findings of Feeley, et al.

Abstract: "The Wind Energy Deployment System model was used to estimate the costs and benefits associated with producing 20% of the nation's electricity from wind technology by 2030. This generation capacity expansion model selects from electricity generation technologies that include pulverized coal plants, combined cycle natural gas plants, combustion turbine natural gas plants, nuclear plants, and wind technology to meet projected demand in future years. Technology cost and performance projections, as well as transmission operation and expansion costs, are assumed. This study demonstrates that producing 20% of the nation's projected electricity demand in 2030 from wind technology is technically feasible, not cost-prohibitive, and provides benefits in the forms of carbon emission reductions, natural gas price reductions, and water savings."

4.4   *Integration Studies*

The following are studies investigating significant penetrations of wind energy either for the United States or a given electricity market. EnerNex's Minnesota integration study, GE's ERCOT analysis, and CAISO's integration report are regarded as setting the industry standard for integration studies.

Citations

United States: U.S. DOE. 20% wind energy by 2030. Energy Efficiency and Renewable Energy. May 2008.

Texas: GE. "ERCOT Wind Impact Integration Analysis." February 27, 2008.

Bonneville Power Administration: Hirst, Eric. Integrating wind energy with the BPA power system: preliminary study." BPA, September 2002.

California: California ISO. "Draft: integration of renewable resources report." Renewables workgroup, September 2007.

Minnesota: EnerNex Corporation. "2006 Minnesota wind integration study." Volume 1.

4.5   *Variability Impact on Fossil Generators*

Renewable energy emissions studies have not accounted for the change in emissions from power sources that must be paired with variable renewable generators such as wind and solar. In most locations, natural gas turbines will be used to compensate for variable renewables. When turbines are quickly ramped up and down, their fuel use (and thus emissions of CO_2) may be larger than when they are operated at a steady power level. Systems that mitigate other emissions such as NOx may not operate optimally when the turbines' power level is rapidly changed.

4.5.1   Dry Low NOx combustion systems for GE heavy-duty gas turbines

Citation: Davis, L.B., and S.H. Black. "Dry Low NOx combustion systems for GE heavy-duty gas turbines." General Electric Power Systems. Document number GER-3568G. Retrieved from GE Power's technical library database. Available: http://www.gepower.com/prod_serv/products/tech_docs/en/downloads/ger3568g.pdf

Relevance: Davis and Black describe in detail NOx formation in GE's heavy-duty gas turbines and how NOx emissions are significantly reduced by their Dry Low NOx technology. Understanding the transient emission dynamics of thermal power plants is important before they are used to counter wind or solar power variability. Davis and Black provide system operators a

glimpse of the transient emission behavior of GE's implementation of using a lean burn to mitigate NOx emissions. Figure 26 shows the NOx and CO performance of GE's DLN system over power range of a gas turbine. What is neglected and could be of significance is the nature of NOx and CO emissions for varying ramp rates of the gas turbine.
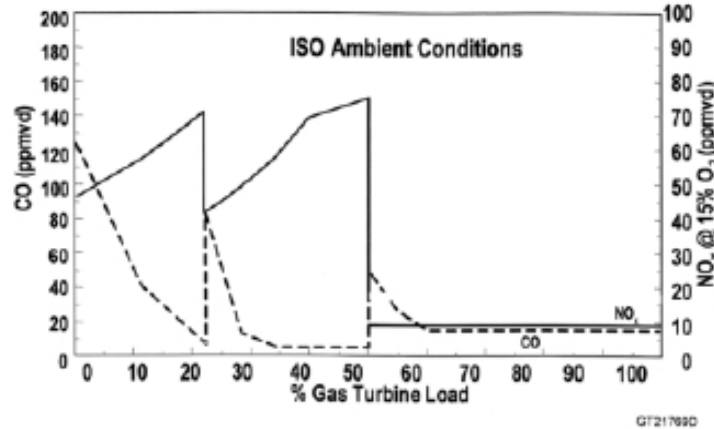

Figure 26 - Transient NOx and CO emission performance of GE's Dry Low NOx combustion systems [Davis and Black].

4.5.2 Evaluation of nitrogen oxide emissions during startup of simple cycle combustion turbines

Citation: Mulkey, Cynthia E. "Evaluation of nitrogen oxide emissions during startup of simple cycle combustion turbines." M.S. thesis, Florida State University, 2003. Available: http://etd.lib.fsu.edu/theses/available/etd-10302003-163346/unrestricted/Thesisfinal.pdf

Relevance: Mulkey, for her master's thesis, analyzed the startup emissions of several heavy-duty GE 7FA gas turbines installed with GE's DLN combustion system. While she concentrated on if startup emissions should be regulated by the EPA, her work has important insights into the effects variable power could have on the emissions of thermal power plants. As more wind is incorporated into a system, thermal power plants will be forced to deviate away from full-power steady-state conditions to operate over a wider power range. Mulkey's thesis published gas turbine NOx emission rates for their entire power range and her data indicate gas turbines will emit significantly more NOx if they are used to counter wind power variability.

Abstract: "Since the implementation of the Clean Air Act of 1970, regulations have been put into place to greatly reduce air pollution in this country. There has been much recent interest in startup emissions from combustion turbines largely because of the vast number of such turbines coming on line and the current push by the United Sates Environmental Protection Agency to set emission limits on these turbines during startup. The EPA recommends that state agencies establish Best Available Control Technology to limit carbon monoxide and nitrogen oxides during the startup and shutdown of these turbines. It is suspected that emissions during startup and shutdown periods can be a significant fraction of a combustion turbine's annual emissions,

particularly for simple cycle peaking units. Nitrogen oxides emissions during startup; (which requires the turbine to cycle from no load through to its normal operating rate); are higher than during operation at rated generating capacity, and are not well controlled because of the transient nature of the startup process. The same is true for the shutdown period (that requires cycling from capacity to no load). To be responsive to recommendations for emissions during startup and shutdown periods, the Florida Department of Environmental Protection has attempted to quantify and control these "excess" emissions in the past by limiting the duration of these periods. Because of continuing concerns, future determinations for new combustion turbines may include concentration or mass emission limits for nitrogen oxides, and perhaps carbon monoxide during startup and shutdown. Limiting the duration of the startup periods, presumably keeps emissions during such times within reason. However, startup emissions may be significant enough to require more elaborate limits. Startup data from several General Electric PG 7241FA (7FA) simple cycle gas turbines are reviewed and analyzed. Maximum nitrogen oxides concentrations and mass emissions during startup are examined and compared as well as the durations of the startup events. Recommendations for reasonable limits during startup are explored including a limit of total pounds of NOx emitted during startup, mass emission rates during the startup period, and mass emission rates during the first hour of operation. The overall significance of startup emissions from these units when compared to total annual emissions of the same units, and emissions of other higher polluting units is also considered."

4.6 *Environmental Impact*

Wind power's primary environmental benefit is a reduction in emissions for the electricity sector by avoided generation from fossil fuel generators, referred to as emissions displacement. Each MWh of wind energy can forgo a MWh of fossil fuel energy but complexities arise in determining what type of generation is displaced. Additionally, variability can adversely alter the emission rates of generators. Efforts to limit wind's variability through the use of storage have been explored.

4.6.1 **Environmental impacts of wind-energy projects**

Citation: National Research Council of the National Academies. Environmental impacts of wind-energy projects. Washington, D.C.: The National Academies Press, 2007.

Relevance: The NRC has put together a comprehensive review of wind power's environmental impacts including the effect on bats, ecology, and emissions. They provide the best review of the current methods to estimate how much emissions are displaced by wind power. First, the generators whose emissions were displaced need to be identified. Two methods used to identify the displaced generators are economic dispatch analysis and generation portfolio analysis. Economic dispatch analysis assumes the displaced generators are those with the highest marginal costs of operation (transmission constraints are considered in some studies). In portfolio analysis the emissions displaced are calculated through the differences in a system's generation portfolio before and after a variable renewable power plant is added. This approach assumes a renewable

plant displaces generation equally from all assets, not solely from the generators operating on the margin. Second, emission factors are used to estimate how much emissions will be displaced by wind power. Emission factors are obtained from measuring emissions of power plants operating at full-power steady-state conditions and do not reflect ancillary emissions generated from thermal power plants compensating for wind's variability.

Important citations contained within:
Keith, G.; Biewald, B.; Sommer, A.; Henn, P.; Breceda, M. Estimating the Emission Reduction Benefits of Renewable Electricity and Energy Efficiency in North America: Experience and Methods. Synapse Energy Economics: Cambridge, MA, 2003. http://www.synapse-energy.com/Downloads/SynapseReport.2003-350 09.CEC.Emission-Reduction-Benefits-Renewables-and-EE-Estimates.03-18.pdf.
Consolidated Baseline Methodology for Grid-Connected Electricity Generation from Renewable Sources; ACM0002 / Version 7; United Nations Framework Convention on Climate Change: Nusa Dua, Bali, 2007. Visit http://cdm.unfccc.int/index.html.

4.6.2 Wind generation, power system operation, and emissions reduction

Paper repeated due to relevance.

Citation: Denny, Eleanor and Mark O'Malley. "Wind generation, power system operation, and emissions reduction." IEEE Transactions on Power Systems. Vol. 21, issue 1. February 2006: 341-347.

4.6.3 Emissions and energy efficiency assessment of baseload wind energy systems

Citation: Denholm, P.; Kulcinski, G. L.; Holloway, T. "Emissions and energy efficiency assessment of baseload wind energy systems." *Environ. Sci. Technol.*; 2005; 39(6); 1903-1911.

Relevance: Using storage is another viable means to reduce wind's variability. CAES (compressed air energy storage) is a large scale storage solution under development in the United States. A baseload power plant can be constructed by coupling a CAES system with a wind plant. Denholm et al. model a wind + CAES system and estimate the efficiency and emissions of the model system. While they found a significant increase in efficiency and significant decreases in emissions, their approach to estimating emissions relied upon the traditional methods of emission factors that Denny and O'Malley have indicated are inadequate.

Abstract: "The combination of wind energy generation and energy storage can produce a source of electricity that is functionally equivalent to a baseload coal or nuclear power plant. A model was developed to assess the technical and environmental performance of baseload wind energy systems using compressed air energy storage. The analysis examined several systems that could be operated in the midwestern United States under a variety of operating conditions. The systems can produce substantially more energy than is required from fossil or other primary

sources to construct and operate them. By operation at a capacity factor of 80%, each evaluated system achieves an effective primary energy efficiency of at least five times greater than the most efficient fossil combustion technology, with greenhouse gas emission rates less than 20% of the least emitting fossil technology currently available. Lifecycle emission rates of NOX and SO_2 are also significantly lower than fossil-based systems."

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6. APPENDIX A

Background Information on NO_x Modeling Methods

Due to the non-linear dynamics of NO_x formation as well as the multitude of mitigation options, a variety of techniques have been developed to model the emission rate of a natural-gas turbine. The EPA maintains a database of emission factors, reported typically in pounds per MMBtu, which the EPA created to aid in the development of regional and national emissions inventories [16]. This has limited applicability to the model required here because the emission factors were calculated from turbines operating at or near their nameplate capacity and because the gas turbine in the model was expected to experience significant cycling through its load range, the use of emission factors would be insufficient. Company-published performance data is typically acquired in laboratory settings under steady-state conditions and is primarily for the description of NO_x mitigation technologies only and not the combination of NO_x mitigation technologies with specific turbines. Additionally, the company-published performance data does not capture the transient conditions of natural-gas turbine emissions required for an accurate model. As a result, this method would be insufficient to use in the model. Advanced methods involve modeling the thermodynamics of the combustion chambers and are typically done to understand the formation of NO_x within the combustion chamber. Such approaches require verifying the results with experimental data and are time intensive to develop. As a result, this study deviates from past techniques by modeling emission rates based on a generator's power level and ramp rate.

7. APPENDIX B

LM6000 Constraint Curves Sensitivity Analysis

A sensitivity analysis on the constraint curves imposed on the LM6000 was conducted to see how much the results of the model are dependent on the positioning of the constraint curves. There are seven separate constraint curves as seen in Figure 27. To test the sensitivity of the results to their positioning, each curve was offset by +2 MW/min and -2 MW/min and then the relative percent change of the result was calculated by subtracting the original result from the new result and then dividing by the original result.
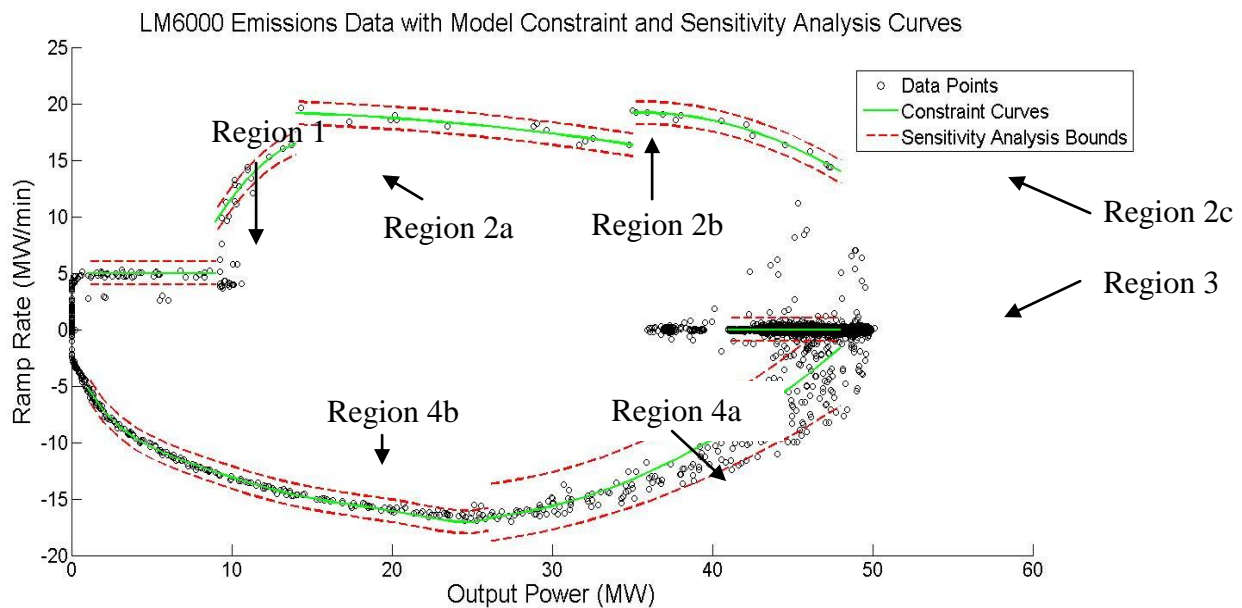

Figure 27 - Scatter plot of LM6000 emissions data with the constraint curves superimposed. Additionally, the sensitivity analysis bounds are plotted. The sensitivity bounds are the constraint curves shifted by +2/-2 MW/min.

The results for the CO_2 expected emissions reduction are shown in Figure 28. The CO_2 results are not sensitive to changes in the constraint curves with the results changing by a maximum of only 0.6% when +2 MW/min is added to the region 3 curve. The results for the NO_x expected emissions reduction are graphed in Figure 29. The NO_x results are sensitive to shifts in the constraint curves with a maximum relative change of 26% when +2 MW/min is added to the region 2b curve. The results are also sensitive to the placement of the region 4b constraint curve with relative changes of 15% in each direction.
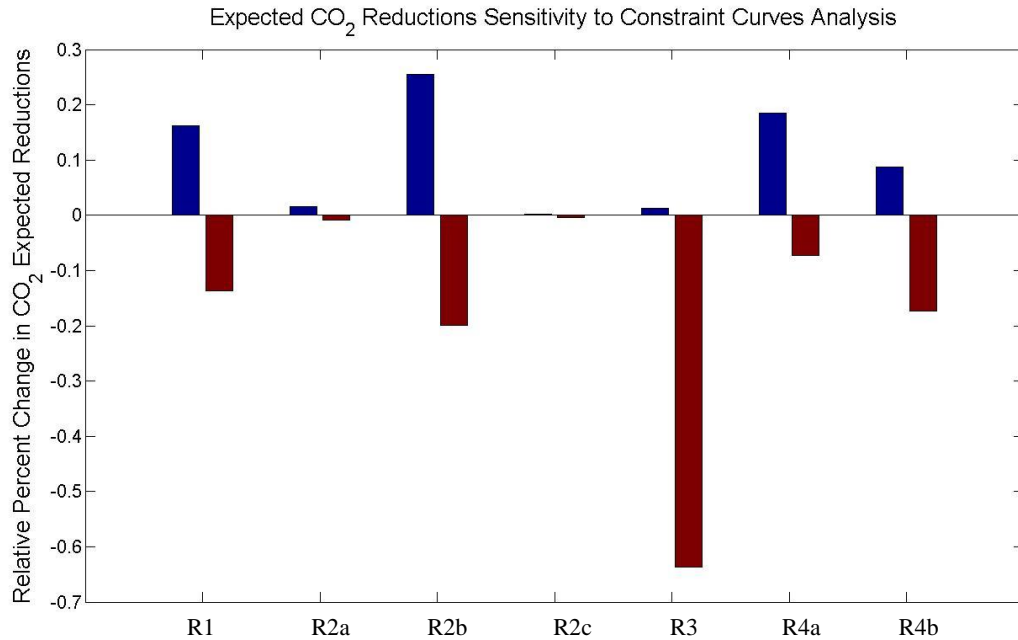
Figure 28 - CO₂ sensitivity results to shifting the constraint curves by +2/-2 MW/min. The CO₂ results are not sensitive to changes in the constraint curves with a maximum relative percent change of 0.6%.
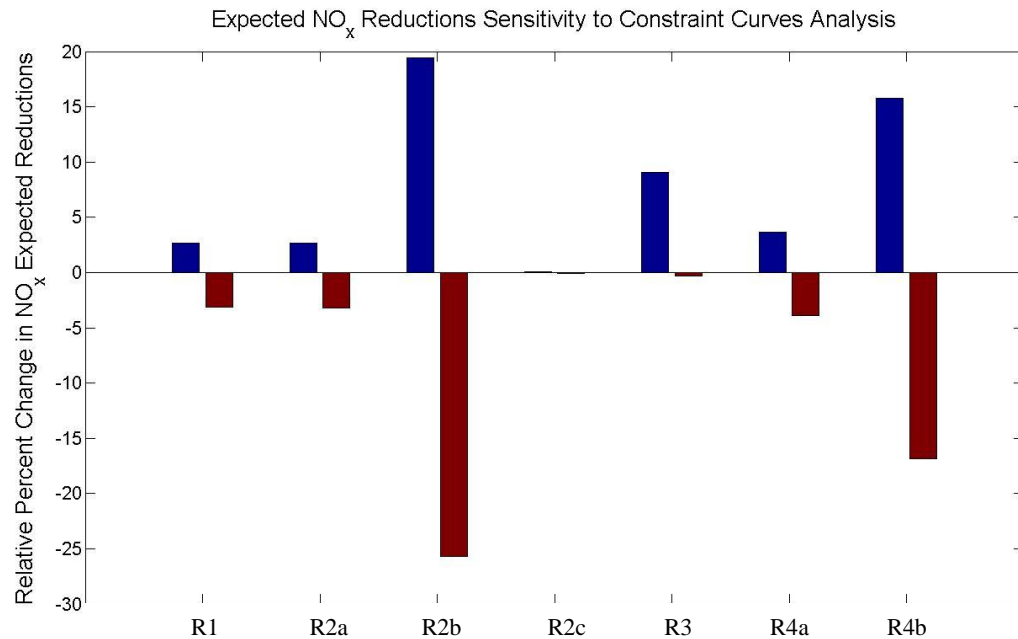

Figure 29 - NOₓ sensitivity results to shifting the constraint curves by +2/-2 MW/min. The NOₓ results are most sensitive to changes in the Region 2b and Region 4b constraint curves with a maximum relative percent change of 25% occurring for a -2MW/min shift of Region 2a's constraint curve.