CMU - FUTURE ENERGY SYSTEMS: EFFICIENCY, SECURITY, CONTROL

Incorporating Wind into a Natural-gas Turbine Baseload Power System Increases NO_x and CO_2 Emissions from the Gas Turbines

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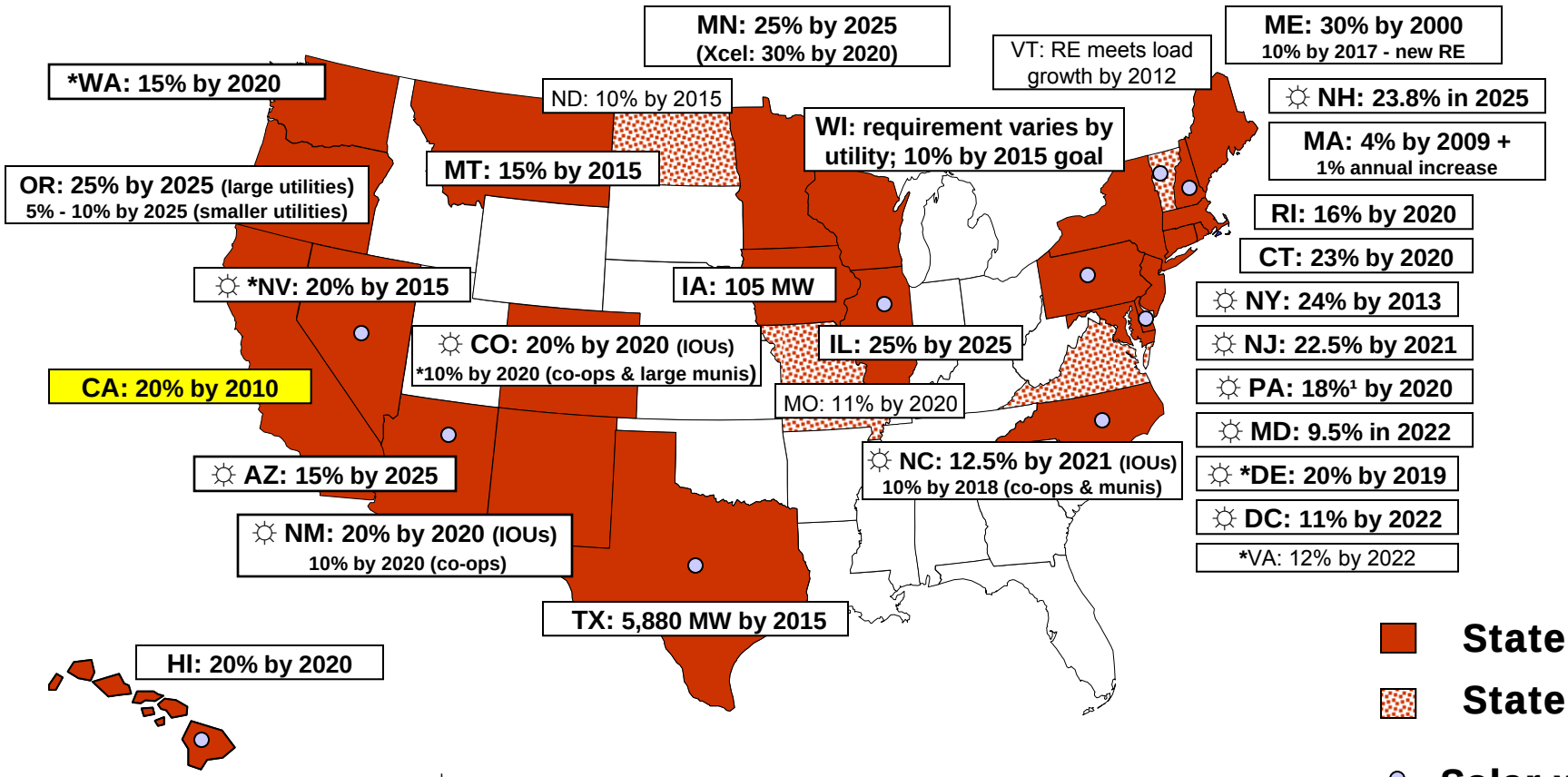
Today I will discuss

- Background and Motivation
- Research Question
- Approach
  - Actual wind data
  - Actual emissions data from two types of natural-gas turbines
- Model Construction
  - General Electric LM6000 turbine
  - Siemens-Westinghouse 501FD turbine
- Results
- Implications

Renewables Portfolio Standards

DSIRE: www.dsireusa.org

September 2007

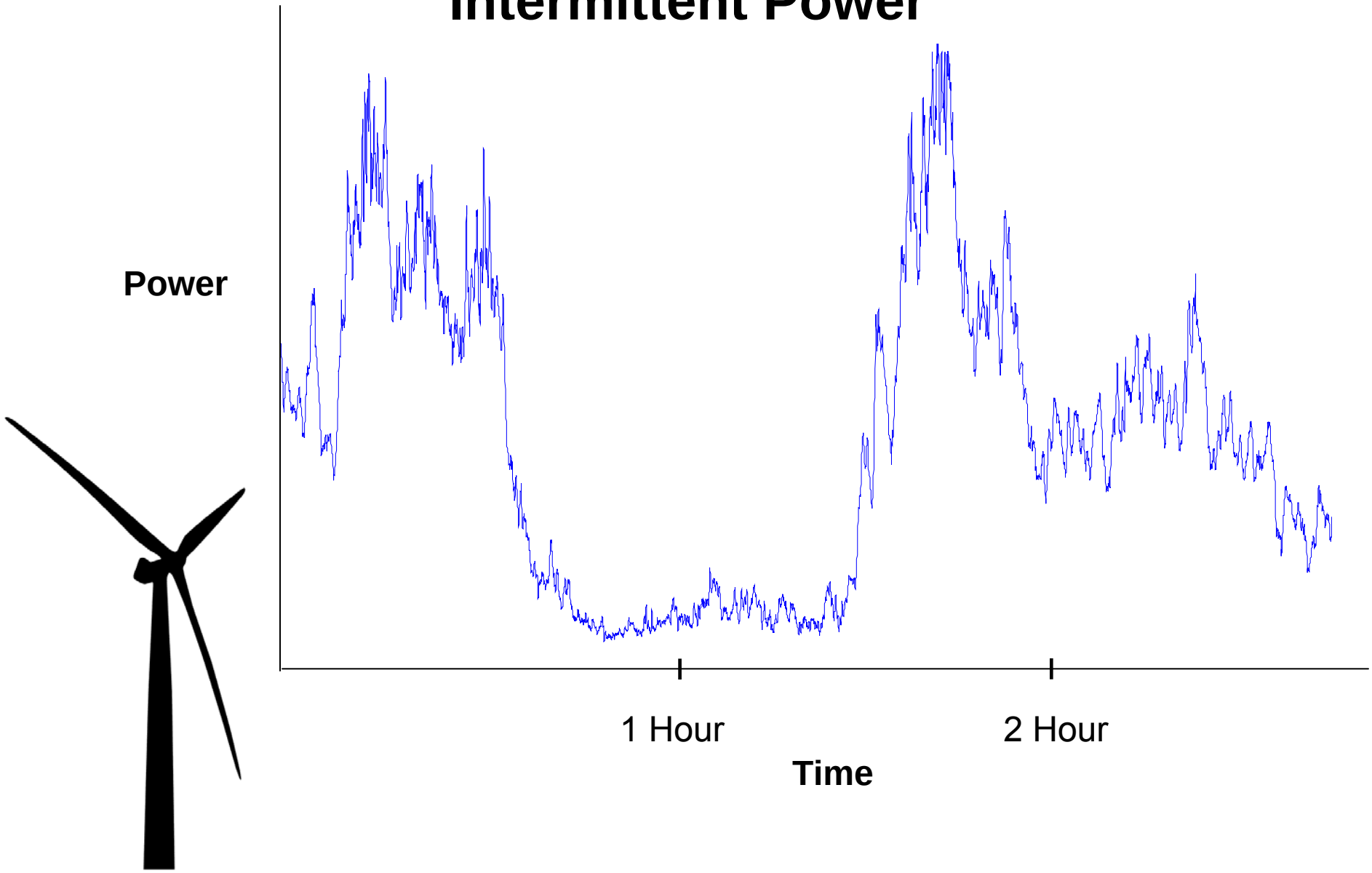


☼ Minimum solar or customer-sited RE requirement

* Increased credit for solar or customer-sited RE

[1]PA: 8% Tier I / 10% Tier II (includes non-renewables)

Intermittent Power



Research Question

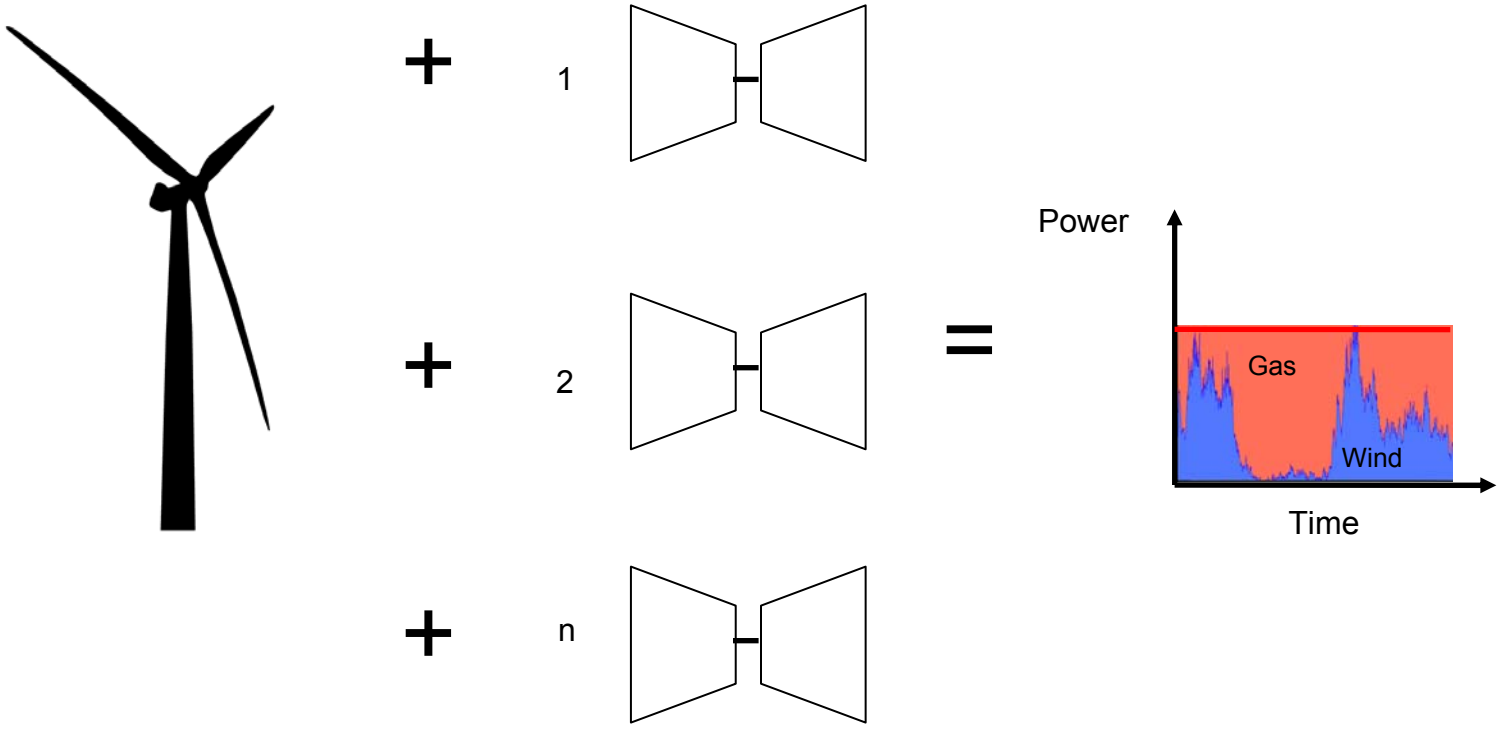
Does operating one or more gas turbines to fill in intermittent wind power result in increased NO_x and CO_2 emissions compared to full-power steady-state operation of natural-gas turbines?

Approach

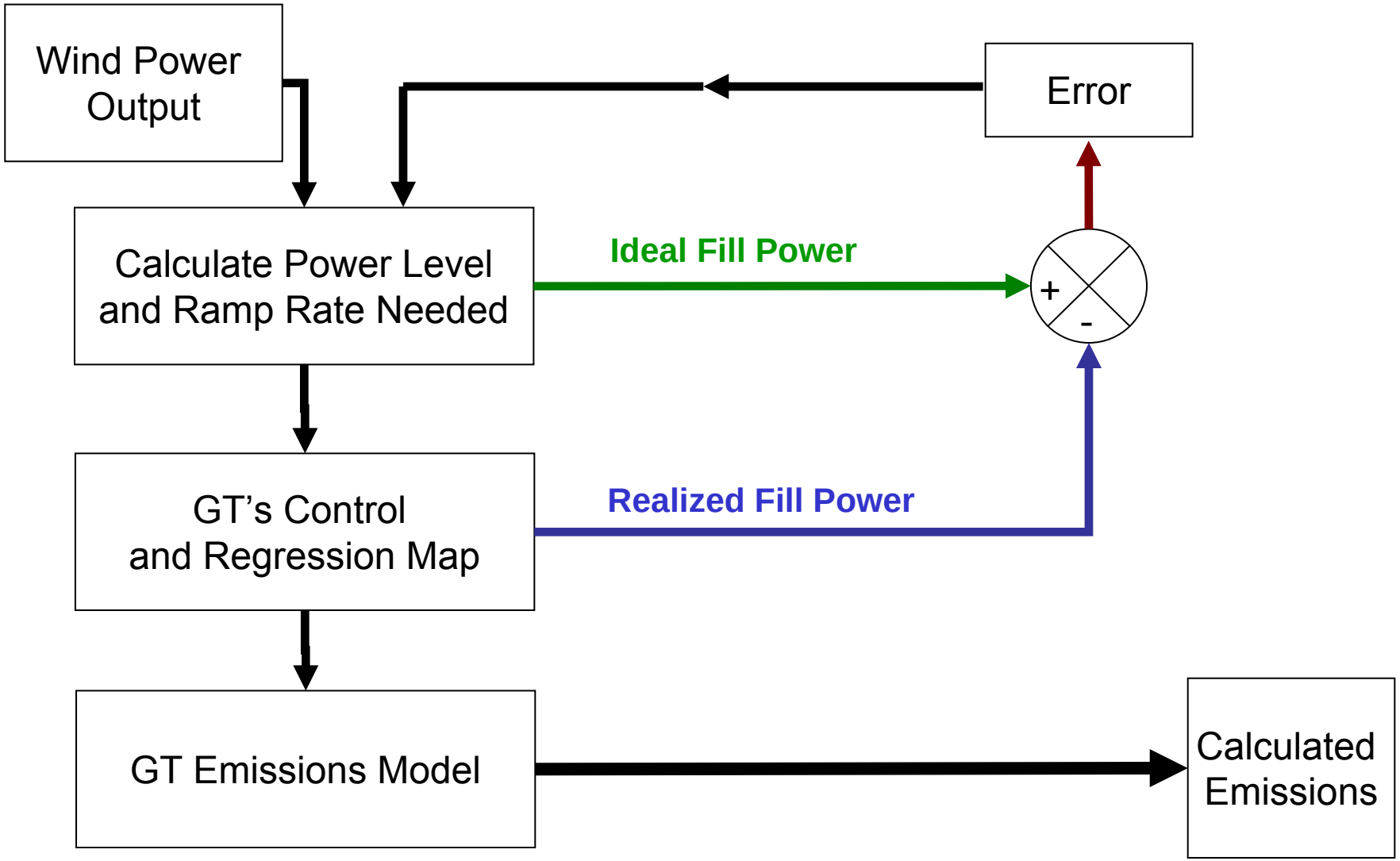
Variable Power

Compensating Power

Firm Power



Approach


Wind Power Output
Error
Calculate Power Level and Ramp Rate Needed
Ideal Fill Power
+
-
GT's Control and Regression Map
Realized Fill Power
GT Emissions Model
Calculated Emissions

Objective Function for Baseload Plant

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

where:

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

$$P_{\text{Target},i} \equiv Expected\ Power\ Plant\ Output \quad (2)$$

$$P_{Total,i} \equiv P_{Wind,i} + n \cdot P_{GasTurbine,i} \equiv Total\ Power\ Generated \quad (3)$$

$$i \equiv time\ index \quad (4)$$

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

$$\dot{P}_{GasTurbine} \equiv \frac{dP_{GasTurbine}}{dt} \equiv Ramp\ rate \quad (5)$$

subject to:

$$P_{Total} = \text{Constant} \quad (6)$$

$$P_{Wind\ Max} = n \cdot P_{GasTurbine\ Max} \quad (7)$$

$$0 < P_{GasTurbine} \leq P_{Max} \quad (8)$$

$$\dot{P}_{Min} \leq \dot{P}_{GasTurbine} \leq \dot{P}_{Max} \quad (9)$$

Calculating Pollutant Mass Emissions of Baseload Plant

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

where:

M_{Total} = Total Mass of Pollutant Emitted (11)

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

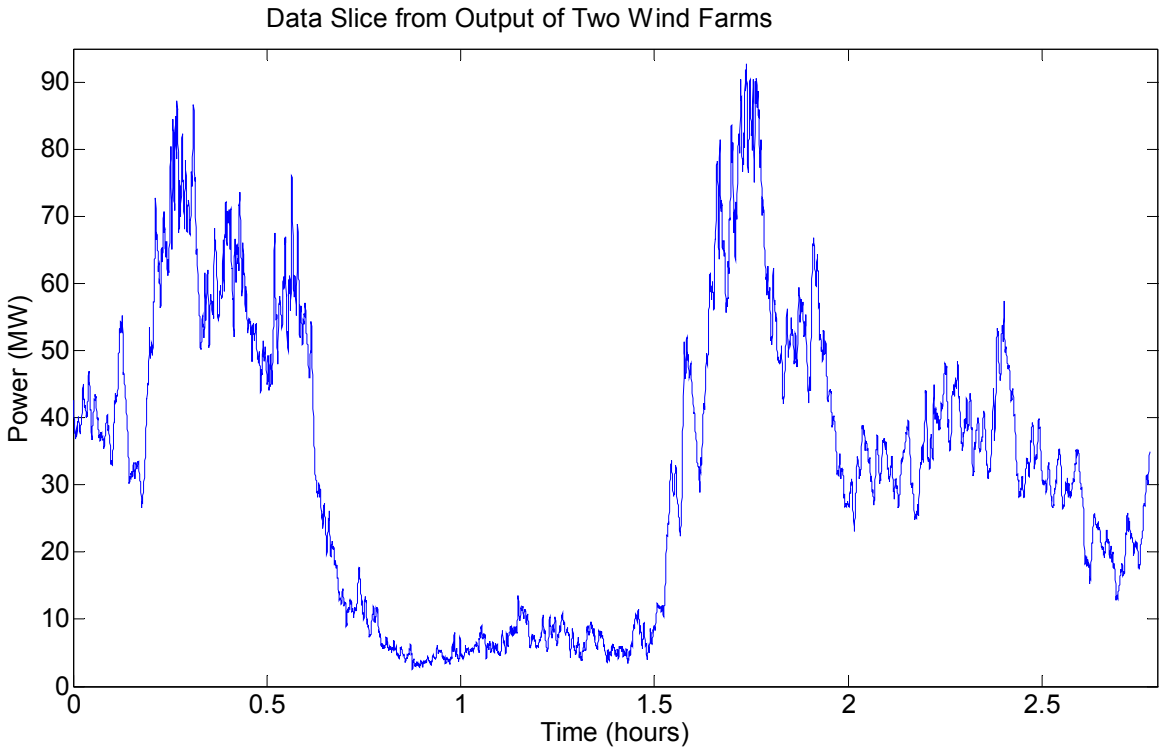
= Mass Emission Rate of Gas Turbine for Time Period i

Δt = Time Interval of Data Set (13)

k = Time Length of Data Set (14)

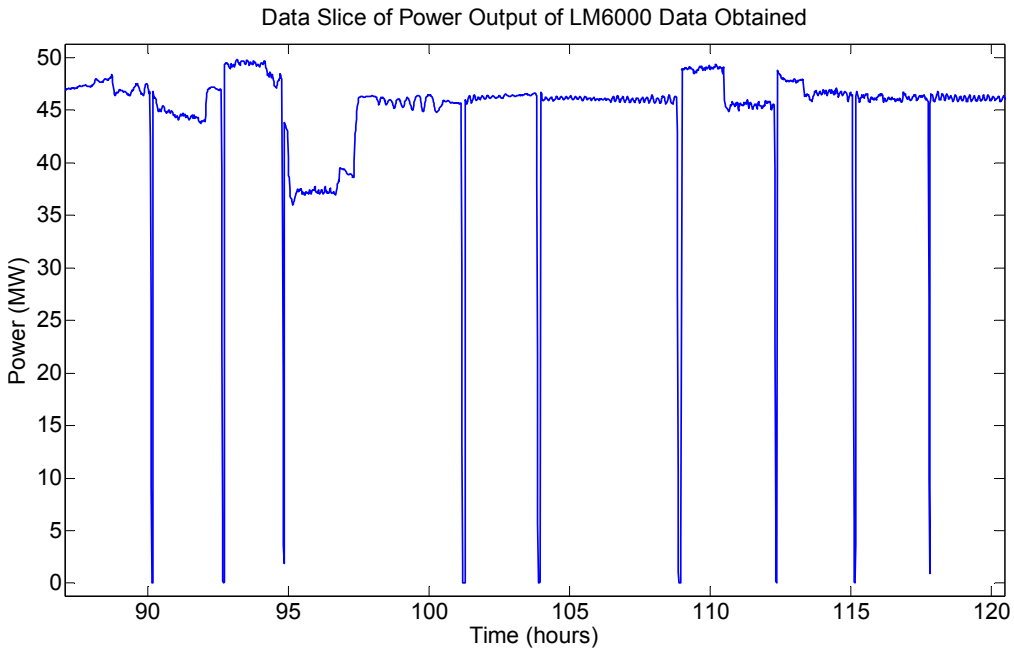
Wind Data Obtained

- Wind Data
  - Output of 3 existing wind farms
    - *Eastern*
    - *Southern Great Plains*
    - *Central Great Plains*
  - 1 to 10 seconds resolution
  - 32 total days of data
  - From anonymous source

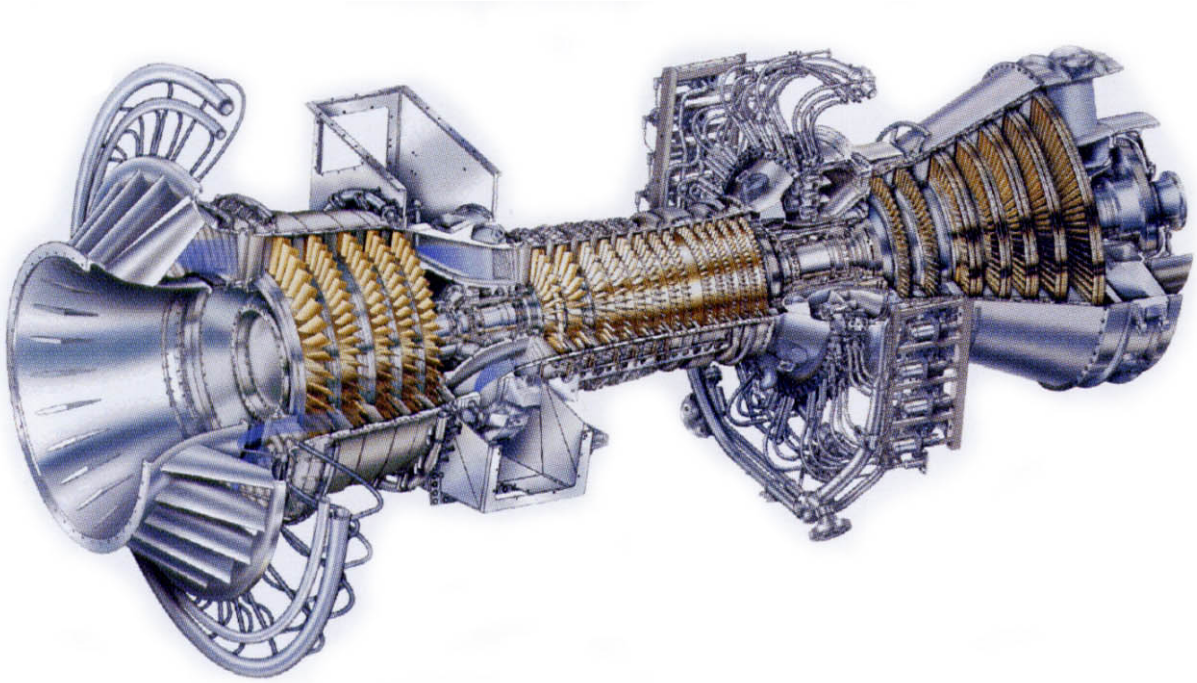


Gas Turbine Data Obtained

- NO_x emissions & heat rate for 7 CTs & 1 NGCC
  - 1 minute resolution
  - Ranges from 38 days of data to 135 days of data
  - CTs are LM6000s
  - Have
    - Gas flow (HSCFH)
    - Load (MW)
    - NO_x ppm and lbs
    - NO_x ppm corrected to 15% O_2
    - O_2 %
    - Heat rate (mBtu/hr)
  - From anonymous source

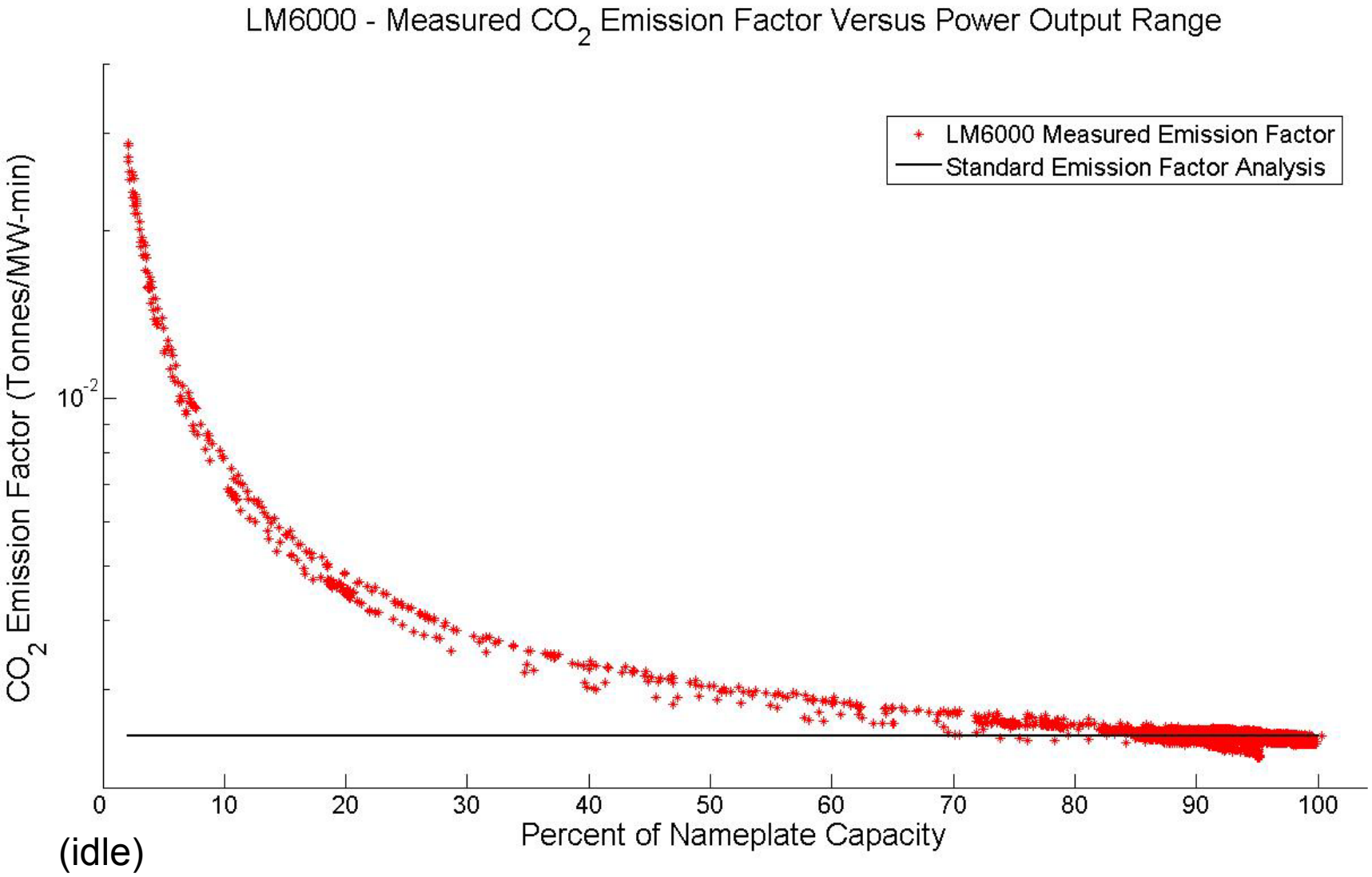


GE LM6000 – Rated 40-45MW

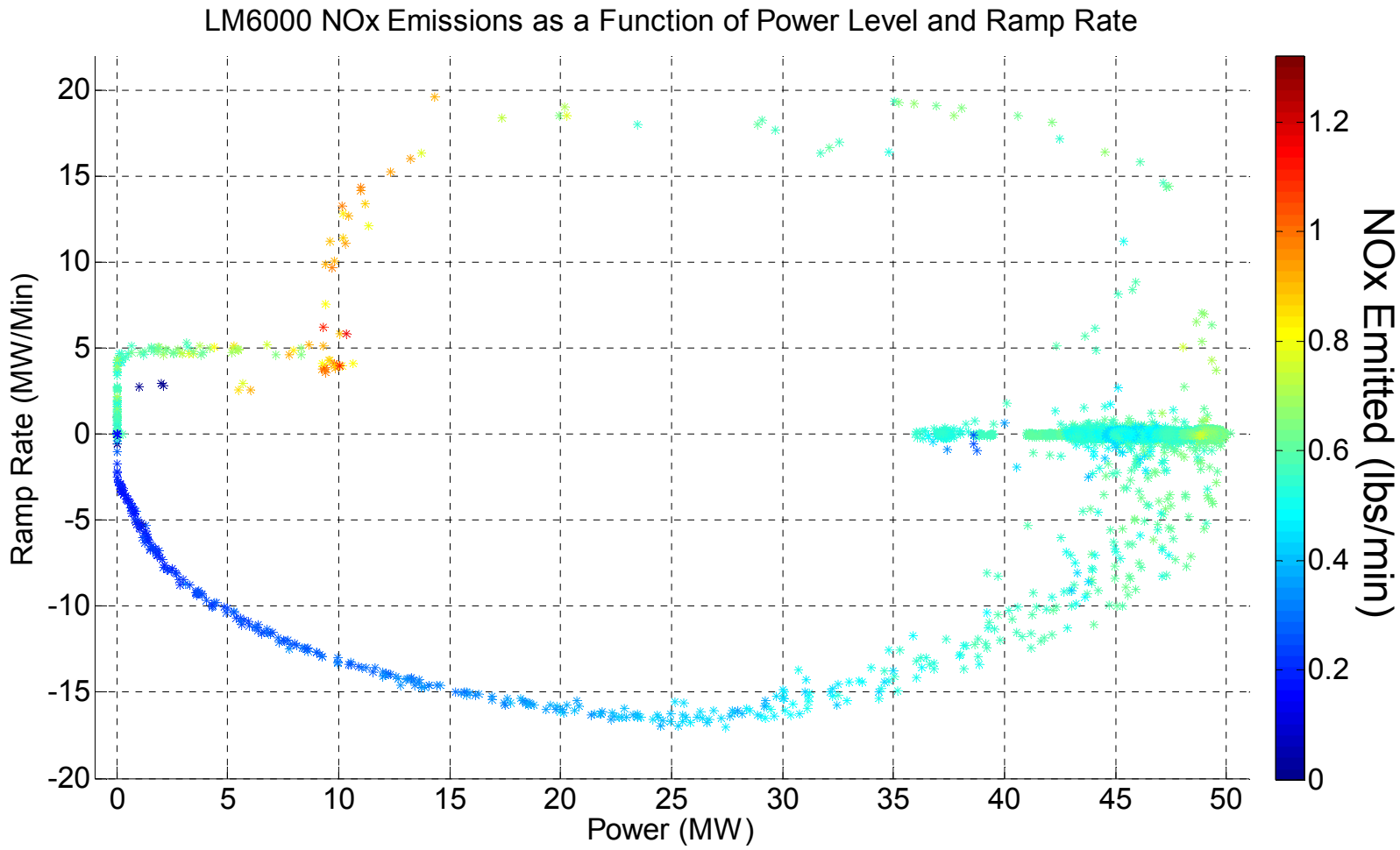


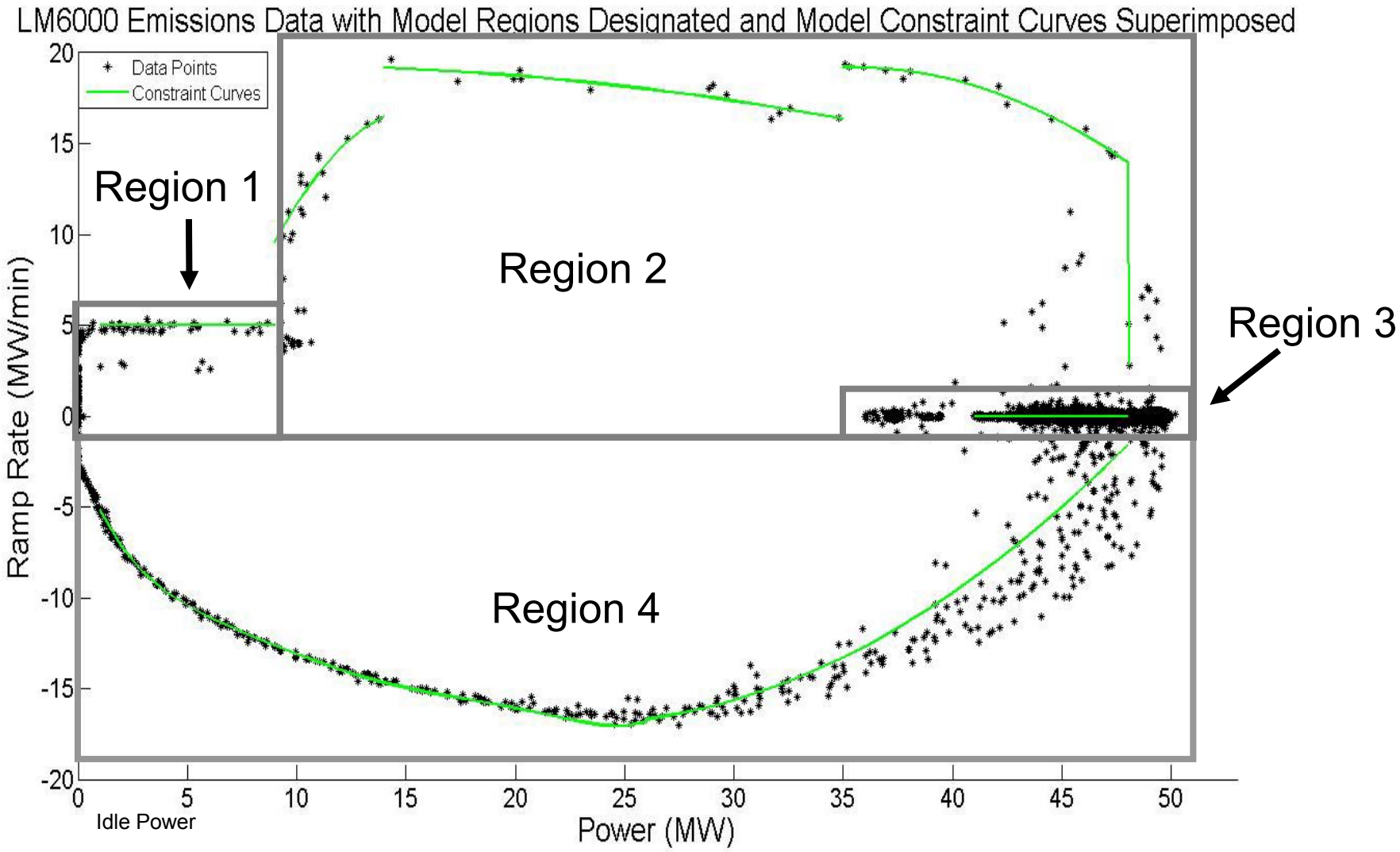
Source: www.sealegacy.com Oct. 4th, 2007

CO_2 Emissions vs Power for LM6000

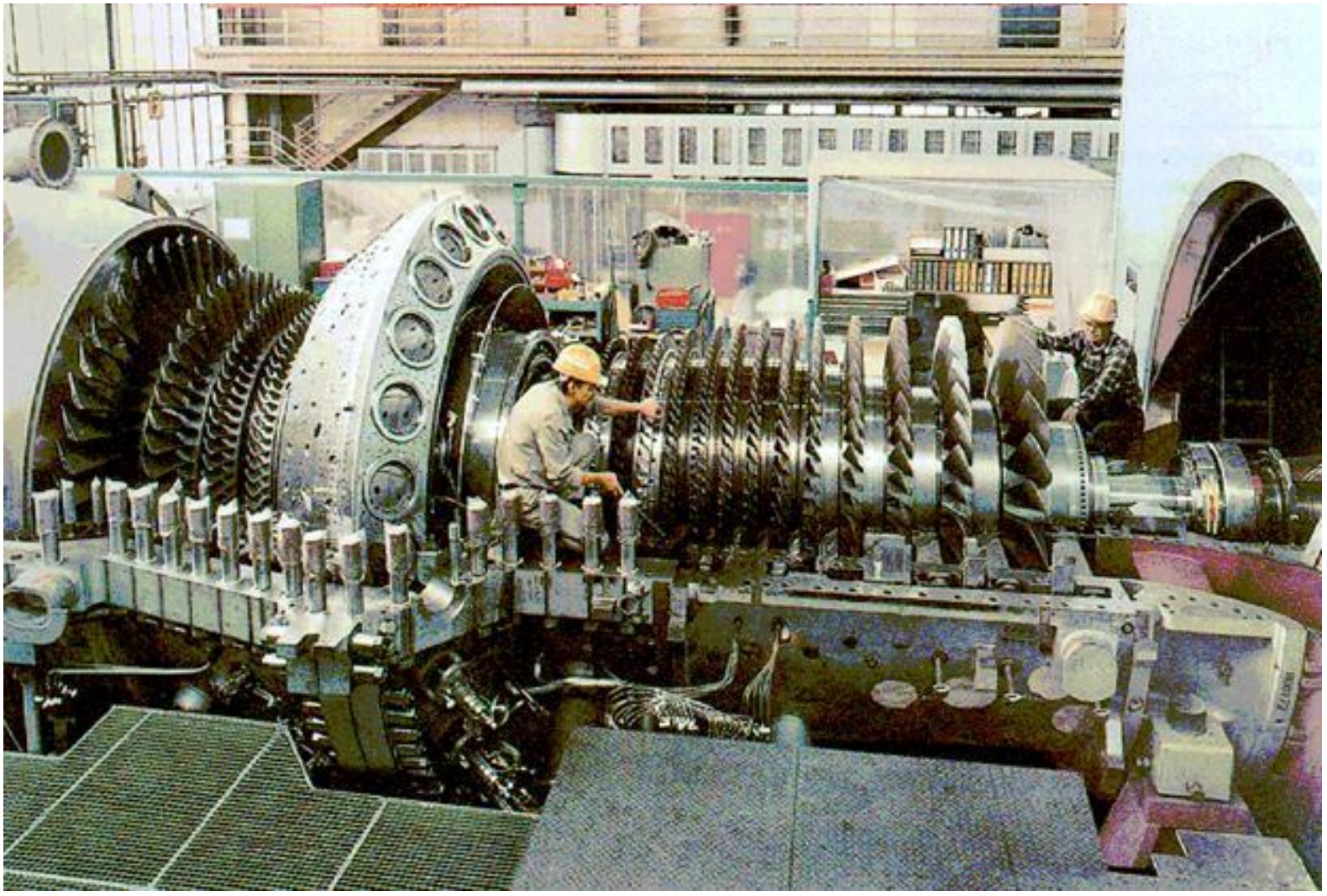


Model Construction - Regression Analysis

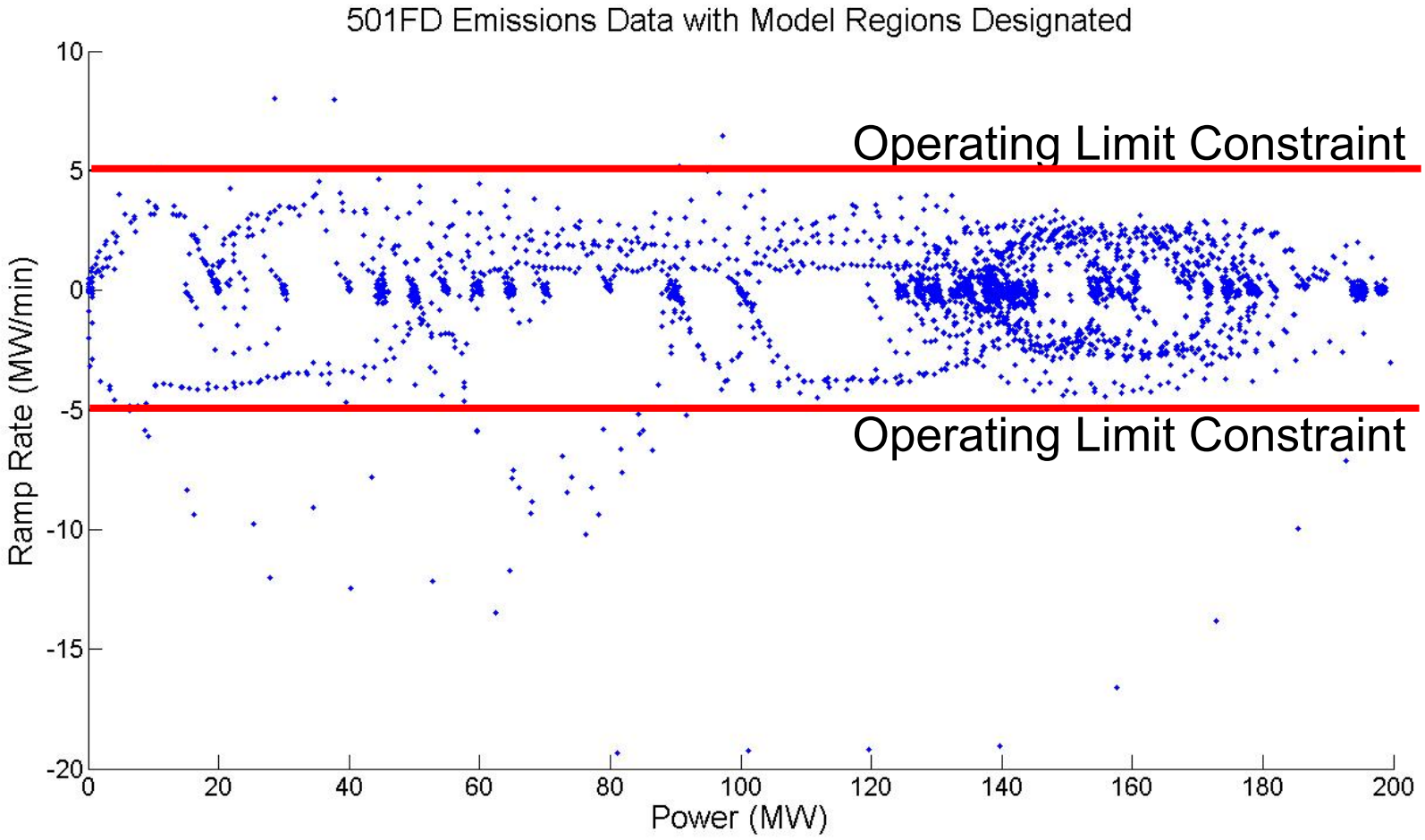



LM6000 Emissions Data with Model Regions Designated and Model Constraint Curves Superimposed
Data Points
Constraint Curves
Region 1
Region 2
Region 3
Region 4
Ramp Rate (MW/min)
Power (MW)
Idle Power
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
20
25
30
35
40
45
50

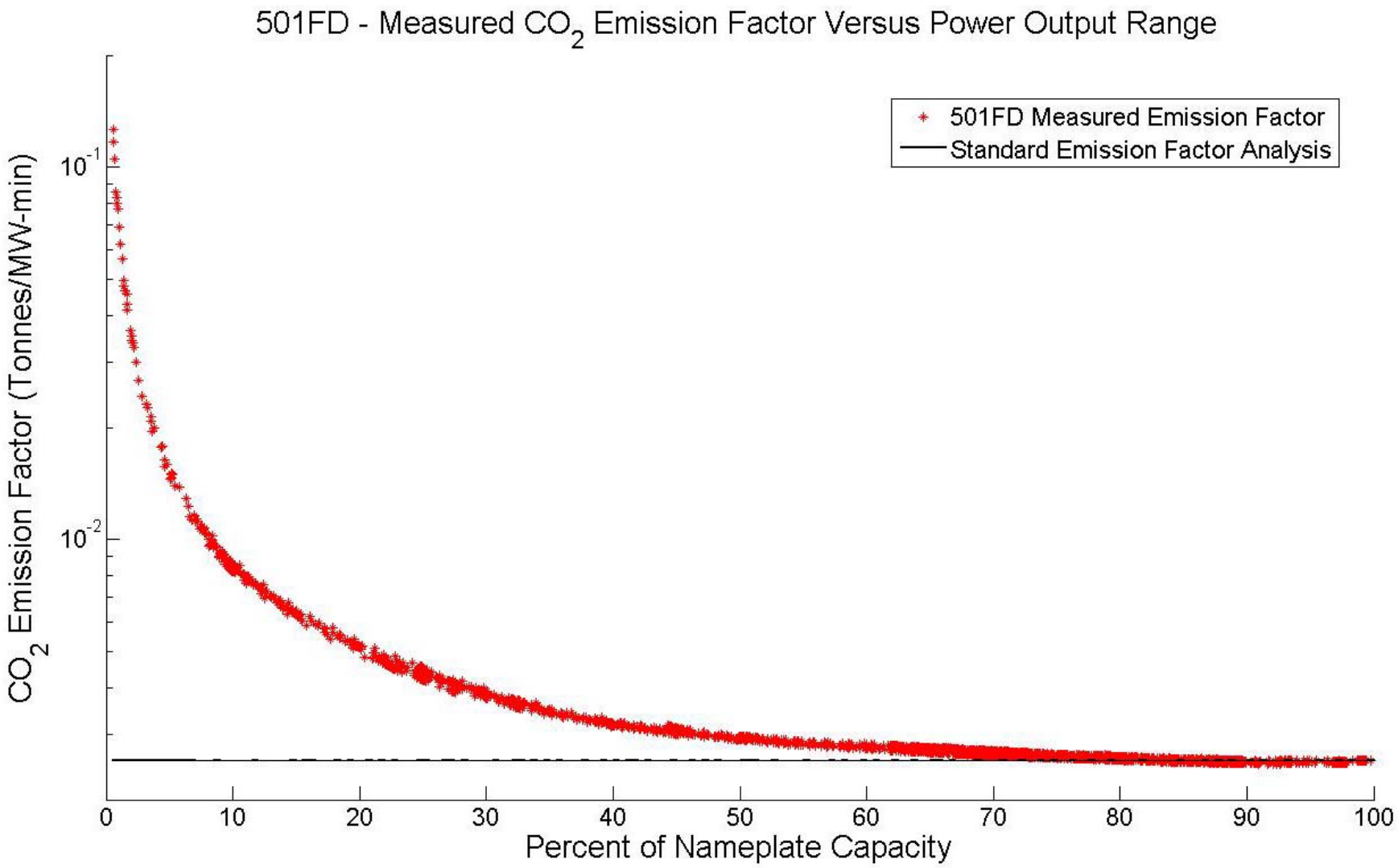
Siemens-Westinghouse Combined-Cycle Turbine – Rated 200 MW



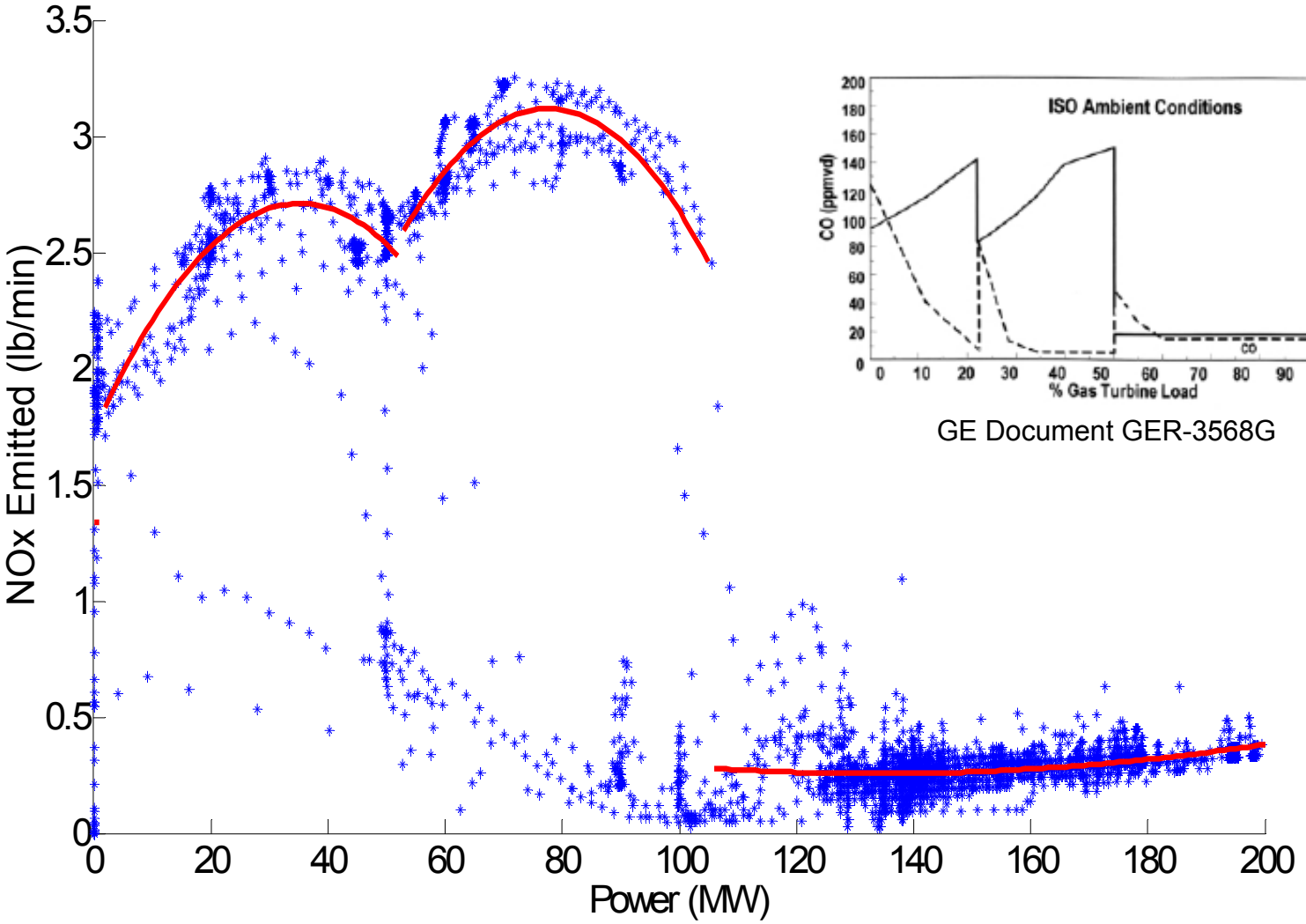
www.summitvineyardllc.com


501FD Emissions Data with Model Regions Designated
Operating Limit Constraint
Operating Limit Constraint
Ramp Rate (MW/min)
Power (MW)
10
5
0
-5
-10
-15
-20
0
20
40
60
80
100
120
140
160
180
200

CO_2 Emissions vs Power for SW 501FD



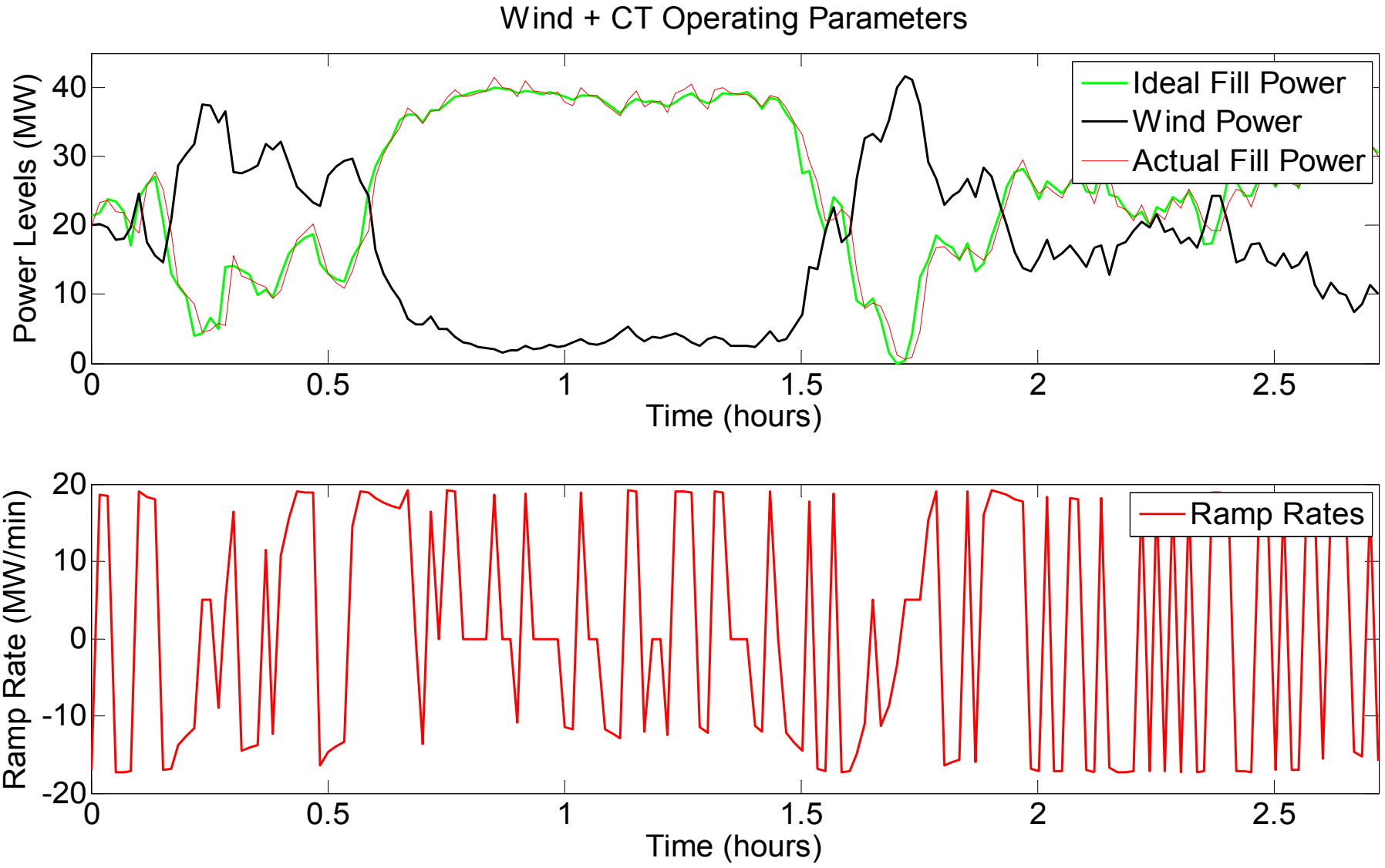
Siemens-Westinghouse - Regression Analysis



GE Document GER-3568G

Results

Results (1) – LM6000



Expected Emission Reductions Calculation

$$\text{Expected Emission Reduction} = 100 * \left[\frac{M_{Total,Natural\ Gas} - M_{Total,Wind+NatuarlGas}}{M_{Total,NaturalGas} * Wind\ \ Penetration} \right]$$

Example Calculations

If *Wind Penetration* is 0.5, then expect $M_{Total,\ Wind\ +\ NaturalGas} = 0.5 \cdot M_{Total,NaturalGas}$

$$\text{Expected Emission Reduction} = 100 * \left[\frac{M_{Total,Natural\ Gas}(1-0.5)}{M_{Total,NaturalGas} * 0.5} \right] = 100\%$$

If *Wind Penetration* is 0.3, then expect $M_{Total,\ Wind\ +\ NaturalGas} = 0.7 \cdot M_{Total,NaturalGas}$

$$\text{Expected Emission Reduction} = 100 * \left[\frac{M_{Total,Natural\ Gas}(1-0.7)}{M_{Total,NaturalGas} * 0.3} \right] = 100\%$$

Expected Emissions Reduction

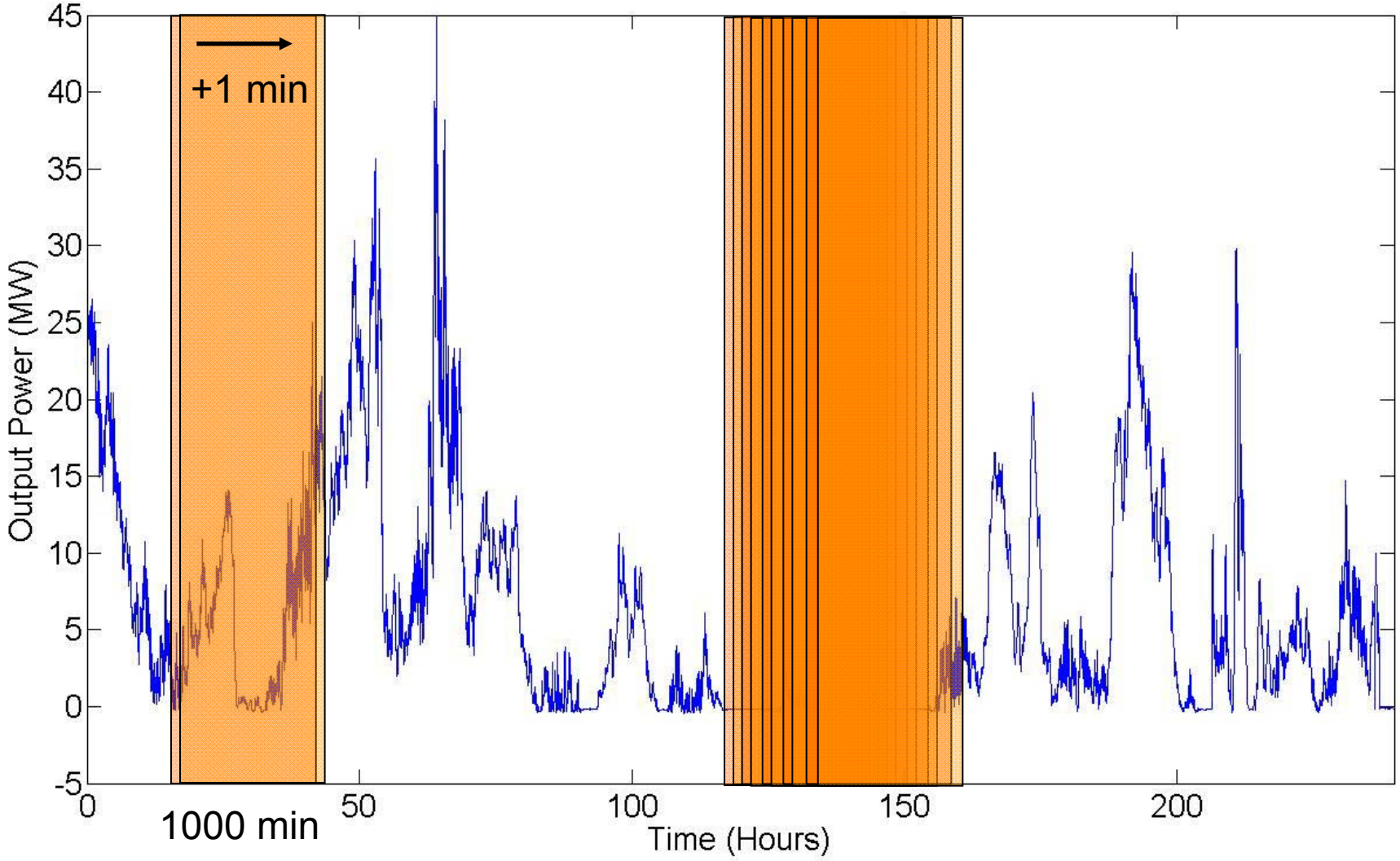
Eastern Wind Farm

Turbine	*Expected Emissions Reduction*	*Emissions Reduced*	*Mass Emitted by Wind + NG*
LM6000 (CT)			
NOx	**29%** ± *4%*	**290 lbs**	**8,300 lbs**
CO2	**80%** ± *1%*	**176 tons**	**1,595 tons**
501FD (NGCC, DLN)			
NOx	**-240%** ± *250%*	**1,500 lbs**	**6,400 lbs**
CO2	**76%** ± *1%*	**732 tons**	**6,968 tons**

Expected Emissions Reduction

Wind Farm	Eastern	Southern Great Plains	Central Great Plains
LM6000 (CT)			
NOx	**29%**	**21%**	**31%**
	± 4%	*± 3%*	*± 4%*
CO2	**80%**	**77%**	**77%**
	± 1%	*± 1%*	*± 1%*
501FD (NGCC, DLN)			
NOx	**-240%**	**-600%**	**-530%**
	± 250%	*+ 100% -75%*	*+ 150% - 5%*
CO2	**76%**	**76.8%**	**78.9%**
	± 1%	*± .2%*	*± 0.1%*

Generating Smaller Wind Data Sets



1000 min

(16.6 hrs)

Implications

- 1 MWh of wind energy **does not** eliminate 1 MWh of emissions
- Impacts
  - Clean Air Interstate Rule (CAIR)
    - Significant penetration of wind power will make it harder for CAIR to achieve emission reduction goals
  - Emission displacement studies
    - Overestimating the amount emissions are displaced by wind
  - Life Cycle Analyses
    - Don’t account for wind’s effect of decreasing emission efficiencies of conventional generators
  - Technology
    - Not all gas turbines are equally suitable for pairing with wind
    - R&D program to improve emissions of heavily cycled gas turbines

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Anonymous resource for power plant emissions data,

Anonymous resource for wind data

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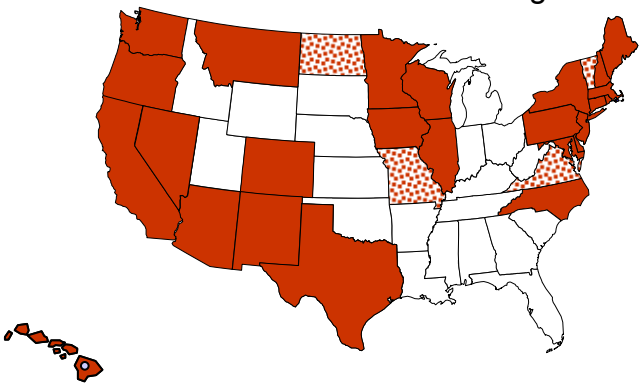
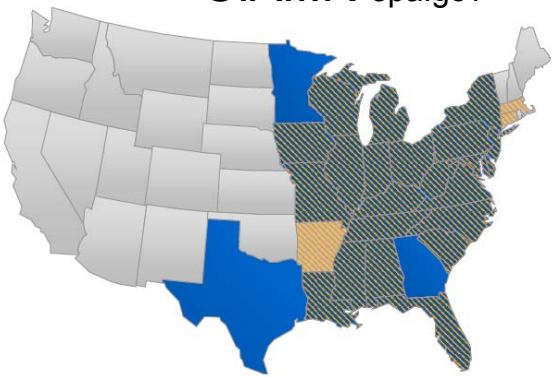
RPS dsireusa.org



C.A.I.R epa.gov



Questions?

LA Smog Apt

Renewable Portfolio Standard which would require electric utilities to obtain 15 percent of their electricity from wind, solar, or biomass energy by 2020

– NYTimes June 15th, 2007