Paper 212, IT P401

On-Line Emission Monitoring for Power Generation Modeling

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Abstract

The most important legislation affecting the electric power sector is the two-phase requirement of the U.S. Clean Air Act Amendments (CAAA) that mandates limits on the emission of pollutants. The overall goal of the CAAA under Title IV is to reduce SO_2 and NO_X emissions by 10 and 2 million tons per year respectively. NO_X requirements will force electric utilities to install low-NO_X burning technology to limit NO_X emission to less than .45 lb/MMBtu. SO_2 emission from all generating units in the United State is capped at 8.9 million tons per year. CAAA makes provision for electric utilities to buy and sell emission allowances. Title I of the Act mandates a cap for the amount of allowances the EPA can issue per year. Furthermore, by year 2010, only 8.95 million allowances are to be distributed for all utilities in the nation; as a result, the management and planning methods of operation of the industry will have to be modified to meet these emission constraints. This paper explore the use of public-domain information such as the one offered by the Environmental Protection Agency (EPA) to monitor emissions from power plants. The emission data is to develop a set of operation characteristics in terms of power generation, fuel consumption, and the amount of pollution released. The objective is to minimize environmental pollution caused by fossil-fuel power plants. Finally, test results are provided to illustrate the proposed solution method to the environmentally constrained power generation problem.

Introduction

There is a substantial volume of literature discussing various emission compliance strategies in view of the CAAA. These strategies include boiler modifications, construction of cleaner new power plants, coal cleaning, and the installation of electrostatic precipitators and stack gas scrubbers. Implementing these cleaning measures require considerable lead time, initial capital investment, retrofit, pipelining, operating and maintenance costs. As a result, many coal-burning power plants across the nation are still operating with insufficient pollution controls. Therefore, the combustion cleaning technologies available today must be complemented by other effective planning techniques to further reduce environmental pollution.

Developing real-time models to accurately predict the amount of pollution released from fossil fuel is important for effective planning. This entails the development of a database of information of existing electric power plants. To date no such comprehensive data exists. Current studies [1-9] investigate the power generation problem under different operation conditions including environmental constraints. However, the proposed problem formulation

ISBN 978-1-60643-379-9

is based on the unit input-to-output generation techniques. That is, the output power as a function of the fuel intake of the system. Similarly, modeling the relation between the amounts of pollution released and the power output of the generating unit has extensively been reported in the literature [10-13]. Although various plant models are discussed, they are generic in nature and more accurate modeling is need. Therefore, one of the goal of this study is to develop a set of operation characteristics in terms of fuel consumption, power generation, and the amount of emission released. The aim is to derive physically meaningful emission functions for every fuel type and pollutant under different cleaning technology schemes. Once mathematically defined, it will become possible to derive a set of accurate machine models that can be used for improved plant operation. In a typical utility for instance, there are hundreds of generating units to be considered. At any given time, plant operators and engineers will be able to use these models to evaluate the environmental impact of each machine before being committed to any operation schedule

Emission Data Base

For every power generating company in the United States, the Emission and Generation Resource Integrated Database (E-GRID) reports information on:

- Emission in tons or pounds for four major pollutants including NOX and SO2.
- Pollution emission rates in lbs. Per million Btu and lbs. per megawatt-hour.
- Generation resources mix in megawatt-hour and percent.
- Identification, ownership, corporate affiliation, and location information.
- Separate data files at the boiler and generator level.

E-GRID includes 18 integrated data files that can be accessed in spreadsheet forms at the agency Web site http://www.epa.gov/airmarkets/egrid. E- GRID has many academic uses and is often cited in relevant research and analysis papers prepared by various consulting groups and universities. Information pertaining to a 4- unit power plant identified as “Windsor” is presented here for demonstration purposes. The facility name and unit identification numbers are listed in Table 1. The boiler and fuel types of each unit are specified along with the corresponding emission cleaning technologies used.

Table 1. Unit Characteristics for Power Plant “Windsor”

Facility	Facility ID (ORISPL)	Unit ID	Unit Type(s)	Fuel Type(s) (Primary)	NO_x Control(s)	PM Controls(s)
Windsor	504	1	Dry bottom wall-fired boiler	Coal	Low NOx Burner Technology	Electrostatic Precipitator
Windsor	504	2	Dry bottom wall-fired boiler	Coal	Low NOx Burner Technology	Electrostatic Precipitator
Windsor	504	3	Dry bottom wall-fired boiler	Coal	Low NOx Burner Technology	Electrostatic Precipitator
Windsor	504	4	Dry bottom wall-fired boiler	Coal	Low NOx Burner Technology	Electrostatic Precipitator

Additional information pertaining to the unit generation capacities, fuel types, and annual net generation of the plant "Windsor" are provided in Table 2.

Table 2. Unit Types and Generation Capacities

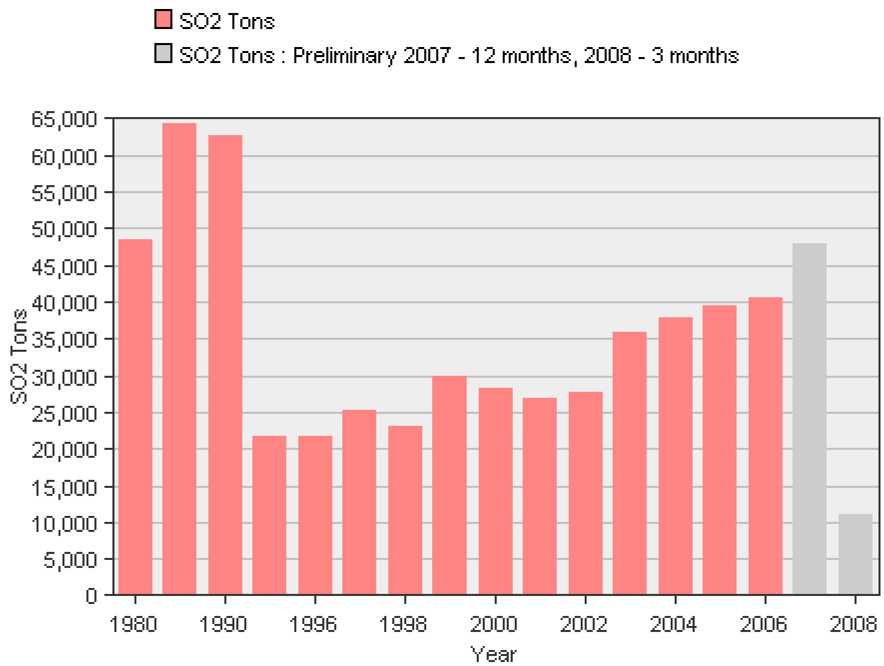
Generator ID	Number of associated boilers	Prime mover type	Primary generator fuel	Generator nameplate capacity (MW)	Generator capacity factor	Annual net generation (MWh)	Ozone season net generation (MWh)
1	1	ST	BIT	125.00	0.4203	460241.0	205322.0
2	1	ST	BIT	125.00	0.4673	511651.0	226397.0
3	1	ST	BIT	125.00	0.4303	471228.0	205520.0
4	1	ST	BIT	578.00	0.4762	2411284.0	1158621.0

Total emissions of SO_2, CO_2 and NO_X for six consecutive years are depicted in Table 3.

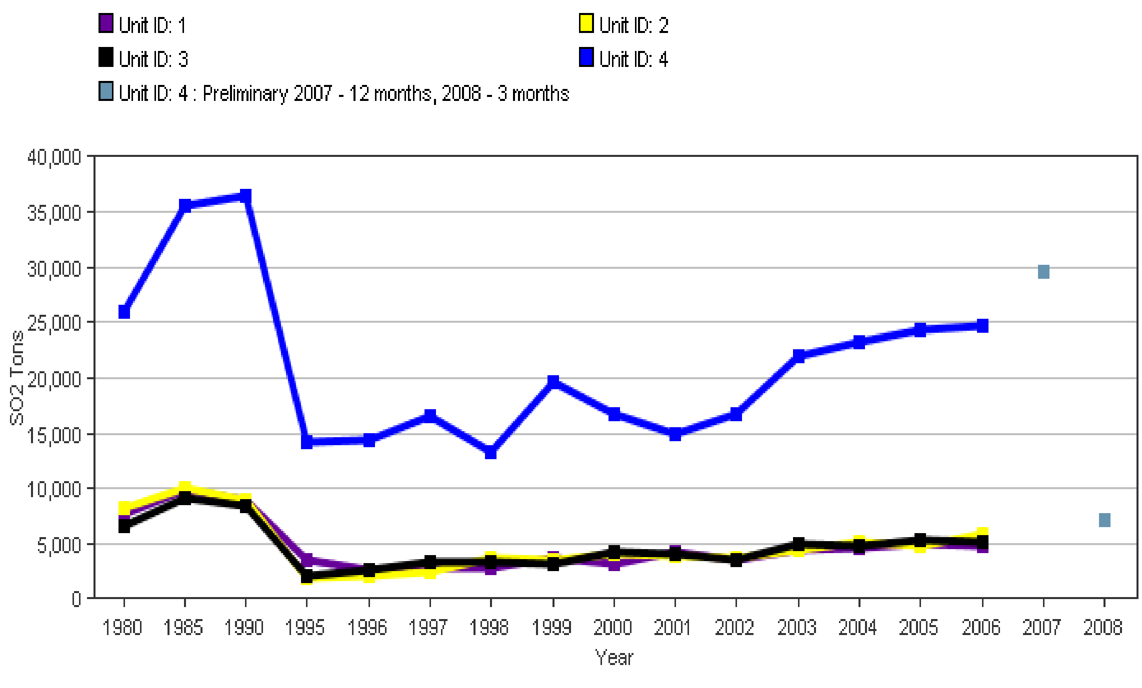
Table 3. Facility Total Emission Summary

Facility Name	Operating Year	# of Months Reported	SO_2 Tons	CO_2 Tons	NO_x Tons	Ozone Season NO_x Tons	Heat Input (mmBtu)	Ozone Season Heat Input (mmBtu)
Windsor	2007	12	47,808.7	5,188,147.0	7,781.9	1,949.9	50,566,735	22,397,763
Windsor	2006	12	40,578.6	4,509,401.4	5,782.8	1,931.7	43,951,326	23,913,760
Windsor	2005	12	39,548.3	4,728,708.4	6,749.7	2,002.2	46,088,834	23,426,667
Windsor	2004	12	37,696.3	4,181,281.6	6,182.8	1,705.3	40,753,260	19,169,162
Windsor	2003	12	35,922.6	4,981,806.1	7,436.7	1,877.7	48,555,660	20,810,510
Windsor	2002	12	27,593.6	4,272,063.9	8,409.7	3,389.9	41,638,096	21,584,468

The emissions summaries for two of the above mentioned pollutants are plotted below in Graph1 through Graph 4 to help visualize the emission impact of the plant under consideration.

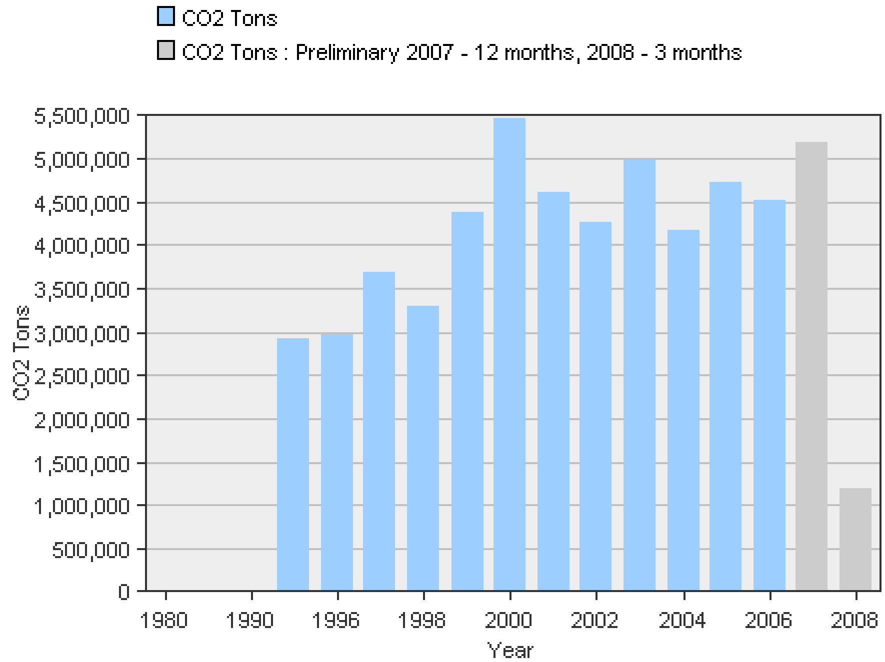


Graph 1. Facility SO_2 Emission Summary

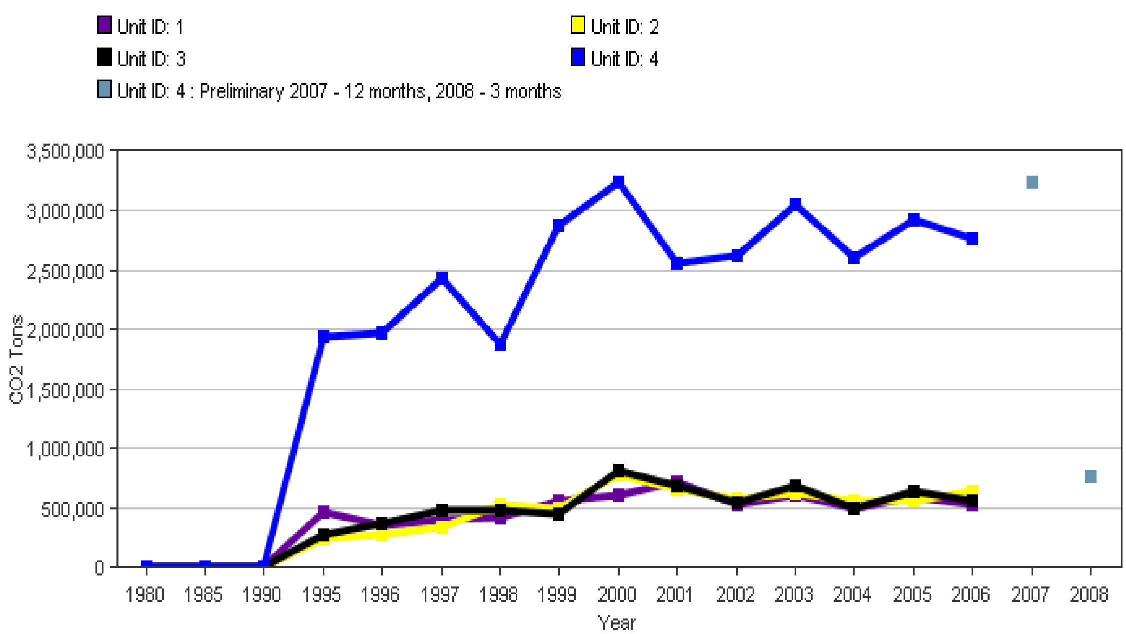


Graph 2. SO_2 Emission Summary for Each Unit

ISBN 978-1-60643-379-9



Graph 3. Facility CO_2 Emission Summary



Graph 4. CO_2 Emission Summary for Each Unit

ISBN 978-1-60643-379-9

Furthermore, hourly emissions can be obtained for any unit operating in the United States. Using system identification techniques, a set of unit quadratic functions can be obtained for each fuel and pollutant type under consideration. As shown in Table 4, fifteen hours of NO_X and SO_2 emission data for the Windsor power plant are available for such system identification. More information pertaining to hourly power generation and unit capacity limits can also be obtained from the on-line Emission and Generation Resource Integrated Database.

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Table 4. Hourly Emission for Windsor Unit 2

UNIT	DATE	HR	GLOAD	SO2_MASS	SO2_RATE	NOX_RATE	NOX_MASS	HEAT_INPUT
2	1/1/2007	0	51	1091.196	2.137	0.405	206.78	510.568
2	1/1/2007	1	52	1124.865	2.136	0.409	215.366	526.568
2	1/1/2007	2	51	1123.261	2.15	0.405	211.613	522.5
2	1/1/2007	3	51	1118.001	2.132	0.399	209.276	524.5
2	1/1/2007	4	51	1104.7	2.151	0.408	209.536	513.568
2	1/1/2007	5	51	1077.163	2.149	0.416	208.541	501.3
2	1/1/2007	6	52	1125.456	2.134	0.407	214.665	527.432
2	1/1/2007	7	55	1203.643	2.147	0.435	243.818	560.5
2	1/1/2007	8	56	1224.254	2.174	0.453	255.13	563.2
2	1/1/2007	9	58	1251.495	2.164	0.453	261.97	578.3
2	1/1/2007	10	56	1219.093	2.159	0.453	255.733	564.532
2	1/1/2007	11	56	1208.599	2.167	0.457	254.915	557.8
2	1/1/2007	12	56	1148.216	2.155	0.455	242.469	532.9
2	1/1/2007	13	56	1145.559	2.145	0.44	234.96	534
2	1/1/2007	14	56	1147.963	2.139	0.452	242.543	536.6
2	1/1/2007	15	56	1148.838	2.141	0.433	232.391	536.7

Problem Formulation

The power generation under environmental constraints can be formulated as an optimization problem whose solution determines the set of on-line units that must be committed to a generation schedule. In general, three types of emission constraints for each pollutant can be defined. These include the two-phase requirements of the CAAA and any additional local requirements:

1. Unit Maximum Hourly Emission *(UME_{ij})*:

$$E_{ij}(P_{ij}) \le UME_{ij} \quad (kg/h),\ \forall\, j,\ \forall\, i \qquad (1)$$

where i and j are the unit number and pollutant type respectively.

2. Unit quadratic hourly emission function :

$$E_{ij}(P_{ij}) = e_{2ij} P_{ij}^{2} + e_{1ij} P_{ij} + e_{0ij} \qquad (2)$$

Where P_{ij} *(MW)* is the unit output power.

3. System Maximum Hourly Emission *(SME_j):*

$$\sum_{i=1}^{N} E_{ij}\ (P_{ij}) \leq SME_j\ \ (kg/h),\ \forall\ j \tag{3}$$

Where N is the number of generating units.

4. System Maximum Daily Emission $(SMDE_j)$:

$$\sum_{k=1}^{M} \sum_{i=1}^{N} E_{ij}\ (P_{ij})\, d_{ik} \leq SMDE_j\ \ kg),\ \forall\ j \tag{4}$$

Where M is the number of stages usually in hours.

If P_i (MW) is the power allocated to a given unit , then the hourly fuel consumption (MBtu /h) or production cost (\$/h), is

$$C_i(\ P_i\ ) = c_{2i}\ P_i^2 + c_{1i}\ P_i + c_{0i}\ \ (\$/h) \tag{5}$$

The total hourly production cost is determined by

$$PCOST\ \ (k) = \sum_{i=1}^{N} C_i(\ P_i\ )\ \ \ (\$/h) \tag{6}$$

In addition, All generating units must satisfy the following conditions:

- Power Balance Constraint:

$$PD_k = \sum_{i=1}^{N} P_i\ \ \ (\ MW\ ),\ \forall\ k \tag{7}$$

where PD_k is the system hourly demand at stage k.

- Unit Capacity Constraints:

$$P_{i,\min} \leq P_i \leq P_{i,\max}\ \ (MW),\ \forall\ k \tag{8}$$

- System Spinning Reserve Constraint:

$$SSR\,(k) \geq MSSR\ \ \ (\ MW\ ),\ \forall\ k \tag{9}$$

where

$$SSR\,(k) = \sum_{i=1}^{N} \min(\ MSR_i\ , P_{i,\max}\ \text{-}\ P_i\ ) \tag{10}$$

MSR_i is unit maximum spinning reserve and $MSSR$ is the minimum system spinning reserve.

Emission Capacity Units

Using the emission function determined above, the unit maximum emission could be converted into a new bound on the unit upper capacity limit so that constraint (1) is never violated. This can efficiently be accomplished as follows:

1) Set $E_{i\,j}\,(P_{i\,j})$ **=** $UMHE_{i\,j}$ in (2) and solve for $P_{i\,j}$, then:
   If $P_{i,\min} \leq\ \ P_i\ \leq P_{i,\max}$, unit i can always meet emission constraint (1).
   If $P_i\ < P_{i,\,min}$ **,** unit i can never meet (1) and therefore must be taken off-line.
   If $P_i\ > P_{i,\,max}$, the power capacity of unit i must permanently be reduced to $P_{i\,j} = P_{i,\,max}$.

2) Repeat step 1) for all emission types. Unit capacity constraint (8) is then set to

$$P_{i,\min} \le Pi \le P'i,\max \tag{11}$$

where

$$P'i,\max = \min\{P_{i1},...P_{ij},...,P_{iJ}\} \tag{12}$$

Once the above procedure is performed on all units as described, unit maximum emission limits will not be checked again for compliance since any set of units, subject to (11), can be dispatched with emission constraint (1) automatically met.

Emission Dispatch Strategies

The economic dispatch problem is to determine the power generation for each unit such that the production cost (5) is minimized, subject to constraints (7) and (11). The power balance equality constraint (7) is included in the cost function via LaGrange multiplier λ^c to form the augmented objective function[26]

$$F^C = \sum_{i=1}^{N} C_i\ (P_i) + \lambda^C (PD_k - \sum_{i=1}^{N} P_i\ ) \tag{13}$$

for which the Kuhn-Tucker optimality conditions are

$$\lambda^C = \frac{dC_i\ (P_i)}{dP_i}\ \ (\$/MWh) \tag{14}$$

Thus knowledge of λ^C uniquely specifies the generation level of each unit. That is

$$P_i = \frac{\lambda^C - c_{1i}}{2c_{2i}}\quad (MW) \tag{15}$$

Another emission dispatch is formalized with the objective to maximize the total generation while meeting system hourly emission constraint exactly. Since (3) is now an equality constraint, it is included via LaGrange multiplier λ_j^D to form the augmented objective function

$$F_j^D = \sum_{i=1}^{N} P_{ij} + \frac{1}{\lambda_j^D}(SME_j - \sum_{i=1}^{N} E_{ij}(P_{ij})) \tag{16}$$

Subject only to constraint (11).

The Kuhn-Tucker optimality conditions are

$$\lambda_j^D = \frac{dE_{ij}\ (P_{ij})}{dP_{ij}}(kg/MWh) \tag{17}$$

and the generation level of each unit is

$$P_{ij} = \frac{\lambda_j^D - e_{1ij}}{2e_{2ij}} \quad (MW) \tag{18}$$

System Data and Results

Our system consists of 4 thermal units and two pollutants to consider. The unit characteristics and cost parameters are given in Table 5. Data regarding unit emission parameters and hourly maximum emissions are given in Tables 6 and 7 respectively. The system hourly and daily maximum emissions are set to SME_1 = 450 (*kg/h*)) for pollutant type 1 and SME_2 = 52.20 (*kg/h*) for pollutant type 2. Finally, the system spinning reserve *MSSR* is set equal to 300 (*MW*).

Table 5. Unit Characteristics

N_O	P_{MAX}	P_{MIN}	*MSR*	c_2	c_1	c_0
1	600	300	200	.00120	1.000	50
2	550	200	200	.00130	1.090	52
3	520	220	150	.00140	1.150	90
4	500	200	150	.00150	1.180	94

Table 6. Emissions data for pollutant type 1

No	e_{21}	E_{11}	E_{01}	$UMHEi_1$
1	.0009	.0037	9	250
2	.0008	.0037	8	200
3	.0007	.0038	7	150
4	.0006	.0020	6	120

Table 7. Emissions data for pollutant type 2

No	e_{21}	E_{11}	E_{01}	$UMHEi_1$
1	.000129	.0037	.9	30
2	.00013	.0037	.8	25
3	.00012	.0038	.7	20
4	.00002	.0020	.6	15

Due to space limitation only the emissions of units scheduled at a given stage are shown in Tables 8. Comparing these values with the unit emission limits as given in Tables 6 and 7, it is evident that hourly maximum emission constraint (1) is met by every generating unit. As shown, the total emission for type 2 is exactly equal to SME_2 (52.2 (*kg/h*) as set by the proposed emission dispatch strategy.

Table 8. Emissions for each unit at stage k

Unit	Type 1 (kg/h)	Type 2 (kg/h)
2	152.43	22.61
3	128.79	20.00
4	93.30	9.59
Total	374.52	52.2

Note: Unit 1 is not scheduled by the optimization algorithm to operate at that stage

Conclusion

This paper described research effort aimed at minimizing environmental pollution caused by fossil-fuel power plants using unit scheduling techniques. Efficient operation methods were developed to work in conjunction with existing cleaning technologies methods to provide utilities with a powerful tool to further reduce pollution beyond conventional means. The operation characteristics of electric machines were investigated in terms of power generation, fuel consumption, and the amount of pollution released using on-line emission data from existing power plants. Employing system identification techniques, a set of machine models were developed and used to measure emission levels. Test results are provided to illustrate the merits of the proposed dispatching method. Another potential application for this study is to involve students in collecting emission data as part of renewable energy supported curriculum. EPA emission data can provide a significant source of instructional technologies via computer simulations and the Internet that students can access and analyze as a component of existing curriculum requirements.

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Biography

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