Environmental Objectives in Power Production Unit Commitment and Dispatch

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This paper describes two approaches, referred to as Economic-Environmental Dispatch (EED) and Economic Environmental Unit Commitment (EEUC), that incorporate environmental externalities into electric utility operations decisionmaking. The main contribution is an analysis of how dispatch and unit commitment (UC) change as the total and relative weights assigned to environmental impacts vary. Traditional models of dispatch and UC are expanded beyond simply minimizing production cost, to consider emissions of air pollutants. The methodology uses powerful Lagrangian Relaxation dispatching and UC algorithms. As an example, the method is applied to a test system with multiple production units and one air pollutant. The test results indicate the effect of including environmental externalities in both UC and dispatch, rather than solely in dispatch. We believe the proposed EED and EEUC approaches are appropriate methods for solving the problem of internalizing the environmental impacts of electricity production. Thus, this methodology provides more accurate inputs to resource acquisition and/or DSM evaluation analysis than simple adders that do not account for operational effects, and enables comparison of dispatchable DSM with alternative dispatchable resources.

Background

Increasing concern has recently been given to environmental externalities because, it is claimed, electricity generation imposes environmental costs on society that are not reflected in the direct prices paid for electricity (Eto, J. and Helcke G. 1990). Electricity production from fossil fuel burning imposes burdens on the environment through emissions to air of SO_2, NO_x, CO_2, and particulates, through water pollution, and through land use effects, waste storage problems, etc. To the extent that these environmental burdens impose costs that are not directly paid for by the utility and, ultimately, its customers, externalities exist. Relative to a perfect market solution, therefore, the utility will overuse the unpaid for environmental resources in production, and the total consumption of electricity will be higher.

Fossil fired power plants pollute the air during normal power plant operation, and also, as addressed explicitly in this paper, during start-up, ramping and shut-down. Energy planners and regulators have begun to recognize such environmental externalities in resource planning, usually through adding environmental cost estimates when making *future* resource decisions. This approach tends to favor lower polluting new resource options (Ottinger, R.L., et.al. 1990, Koomey, J. 1990). However, an economically efficient way of treating environmental burdens on society should consider the overall cost-effective way of satisfying electricity demand; that is, the utility should choose the least-cost combination of operating decisions as well as resource addition decisions and retirement. In this paper, we incorporate environmental objectives into operational decisions, specifically, into short-term unit-commitment and dispatching. Production cost estimates derived in this way would provide more accurate inputs to resource acquisition and/or DSM evaluation analysis than simple adders that do not account for operational effects.

Several analysts have studied methods for incorporating environmental costs into power production (Busch, J.F. and F.L. Krause 1992, Bernow, S. and B. Biewald 1991 and Gent, M.R. and John Wm. Lamont 1971). Much of this work is based on monetary valuation of environmental impacts from electricity generation, using a method for monetization, such as damage cost or abatement cost. The electricity production cost modeling is usually performed by a load duration curve approach, which is appropriate for long term planning, but which respects few operating constraints. Then, dispatch is performed based on the sum of fuel cost, variable O&M, and environmental cost. Initially, we briefly address two specific issues related to such an approach: (1) how to establish representative estimates of environmental costs, and (2) how environmental objectives will influence the start/stop sequence of generators.

Monetizing Environmental Damage

A comprehensive analysis of external environmental costs of electricity must, in principle, treat every stage in the energy chain, from exploration to end-use, making such an analysis complex. The analysis should include estimates of insults, pathways, and stresses leading to environmental costs (Holdren, J. 1981). Insults are humankind's physical and chemical intrusions into the natural world, e.g., the use of land and water, or the emission of NO_x, SO_2 or CO_2. Pathways are those mechanisms by which insults are converted to stresses. Stresses, defined as physical changes in ambient conditions, such as temperature, humidity, pollutant concentrations, etc., then lead to an environmental cost estimate for electricity production.

Determining the monetary value of an environmental insult to use in a *damage cost* approach is a troublesome problem. Firstly, transport calculations and dose response relationships may be highly uncertain. And secondly, even if these difficult technical issues have been resolved, the tough philosophical question of valuing the consequences remains. Monetization includes valuing human morbidity and mortality, visibility, historic monuments, wildlife and ecosystem depletion, etc. The alternative approach proposes using the cost of controlling the respective pollutant or its *abatement cost* as an estimate of the environmental damage. (A discussion of the use of control costs is given in Chernick P. & E. Caverhill 1990).

The method described in this paper avoids the *a priori* discussion of how to appropriately value environmental impacts that is necessary in an adder approach. Rather, the impacts from implementing environmental objectives in power production UC and dispatch are explored by varying the external environmental cost of power plant emissions from zero to infinite. This communicates the range of choices and trade-offs between environmental objectives and direct cost, and allows the policymaker to subsequently analyze the effects of implementing a range of environmental cost estimates (from zero to infinite). Thus, the level of environmental cost is not explicitly needed by the policymaker or the utility planner.

Effect of Environmental Externalities on Start/Stop Decisions

The second issue to be addressed explicitly in this paper is the impact of recognizing environmental externalities on the *start/stop sequence* of generators. Finding an optimal start/stop sequence for generators is the core of the UC problem. Power production from fossil fuels emits gases and particulates to air during normal operation. However, during start-up and up-ramping, and part-load operation, emission rates deviate considerably from the levels of steady-state full operation. Therefore, commitment of units will depend both on how emissions are included in the UC criterion function and on how emissions during start-up depart from average emission rates. During recent years, extensive and productive research has focused on different methods for solving the standard UC-problem; however, little known work has been done on incorporating environmental effects into this problem. Similarly, many studies of environmental dispatch have not explicitly addressed the start/stop issue.

Outline

This paper presents a revised UC procedure, extending the traditional UC problem formulation by calculating the air pollution emissions from electricity production of fossil fuel power plants and explicitly incorporating them into the objective function. We refer to this formulation as *Economic-Environmental Unit-Commitment* (EEUC). The paper establishes an extended formulation of the power production UC and dispatch task as a multiobjective problem of simultaneously minimizing production cost and emissions of multiple pollutants. We comment on how to represent the technical, economic, and environmental behavior of the electricity production system, such as cost and emission during operation, start-up, shut-down, etc. Finally, we describe a solution approach to the stated problem, implement the solution approach into a computer model, and illustrate the use of this approach through a test system.

Problem Formulation

Consider the utility power planning problem as containing the following steps: (1) load forecasting (incorporating the effects of non-dispatchable DSM); (2) estimating available resources (taking account of hydro scheduling, fuel limits, nuclear refueling, random generator outages, etc.); (3) unit commitment (deciding when to start and stop resources, including dispatchable DSM, in anticipation of load); (4) dispatch (the process of up and down ramping units to meet load in real time); (5) expansion planning (deciding when to add new capacity and retire old).

A consistent treatment of environmental effects in the utility power planning problem should incorporate environmental objectives into all steps, (1)-(5). This delivers the true least-cost solution. As mentioned above, prior work on bringing environmental externalities into utility planning has focused on steps (4) and (5). In the following analysis, only steps (3) and (4) are addressed. Two versions of the same problem are studied. In the first, environmental objectives are incorporated into step

(4) only (EED); and, in the second, with environmental objectives recognized in both steps (3) and (4) (EUC). The differences between results in these two cases will demonstrate the potential improvement in modeling accuracy that can be derived by extending the internalization process back one more step.

Economic-Environmental Dispatch (EED)

The conventional approach to simulation of economic dispatch of an electric power production system, that is, step (4) of Problem Formulation, is based upon the incremental direct variable cost of the generating units. That is, the incremental fuel cost and the incremental portion of operation and maintenance costs are determined for each generating unit at every time period, usually an hour, and the units are then dispatched to serve customer loads in order of increasing incremental cost. The units with low direct incremental costs will thereby be utilized at higher capacity factors than will units with higher direct incremental costs.

If dispatching practices incorporate environmental goals, incremental environmental costs will be added to the sum of incremental costs resulting in changes in the dispatch order. Therefore, with an environmental dispatch approach, the amounts of pollution from the generating units are factored into the dispatch protocols, and, depending on how emissions are valued relative to direct operating cost, the dispatch of the power production system changes. Under traditional practice, dispatch is strictly on a minimum cost basis. Externalities do not affect the dispatch and emissions do only to the extent that they affect direct costs. In the alternative extreme, a least emissions dispatch would attempt to minimize the amount of system emission with no regard to direct operating costs. Any sensible solution, from a policy point of view, will lie between these extremes.

We formulate the *Economic-Environmental Dispatch (EED)* problem as follows:

$$Min! \ \{C_{tot}, E_{j\,tot}, j=1,2,\ldots,J\}$$

subject to feasibility constraints for every time period (hour). The constraints in the EED formulation include meeting customer loads, unit minimum and maximum loadings, reliability targets, etc. C_{tot} is direct operation cost, and $E_{j,tot}$ is emission of pollutant j, $j=1,2,\ldots,J$. Observe that $E_{j,tot}$ in the EED formulation includes emissions during normal operation of the system only. A detailed formulation of EED is given in Appendix 1.

Economic-Environmental Unit Commitment (EEUC)

Extending the EED problem to include UC, that is, step (3) as well as step (4), above, results in a problem considerably complicated by the presence of a limited unit loading range, start/stop decisions of generating units, ramp rate limits, and erratic fuel use and emissions behavior during non-steady state operation. These effects are addressed explicitly in this section. The unit-commitment (UC) task is usually formulated to determine which generating units should be committed for operation so that customer demand for electricity may be met as economically as possible, without violation of operating constraints. The UC task is part of the more general task of scheduling generating units over short time periods, ranging from 24 to 168 hours, to meet a projected time-varying electricity demand. The problem, as an optimization task, is complicated by the presence of time-dependent start-up costs, unit ramping limits, and minimum up and down times. Note also that the UC task is a single objective problem in that the only objective explicitly included in the criterion function is to minimize total generation costs. Throughout the last decade, many authors have contributed to this topic, and different methods and approaches have been used for solving the UC task (van den Bosch, P.P.J., G. Hondered 1985, Ružic, R. and N. Rajacovic 1991 and Zhuang, Fulin and F.D. Galiana 1987). The *Economic-Environmental Unit Commitment (EEUC)* approach expands on this work by incorporating environmental objectives into the UC problem formulation.

The criterion function in the EEUC formulation is principally identical to the one indicated in the EED-formulation above, however with major differences in how operating cost and emissions are calculated, and in the feasibility constraints. Total operating cost (C_{tot}) in the EEUC formulation represents the sum of generation, start-up, and shut-down costs. Total emission to air of pollutant j ($E_{j,tot}$) is given by the sum of emissions from generation, start-up, and shut-down of individual units. The criterion function is minimized for all time periods subject to the EEUC feasibility constraints: meeting time variable electricity demand, reliability targets, minimum and maximum generation limits, minimum down-time, minimum up-time, etc. A detailed mathematical formulation of the EEUC problem is given in Appendix 2.

Solution Method

One fundamental complication introduced into the EED and the EEUC formulation is that operating cost and each environmental impact (emissions to air) are heterogenous and non-commensurable. That is, they cannot be measured in a common unit. In addition, the objectives of minimizing operating cost and emissions are often in conflict with each other in the sense that lowest emission operation often gives highest cost and *vice versa*.

The Efficient Set

Our approach seeks to generate *the efficient set* of commitment schedules and dispatch plans. From this group of plans a best compromise operation plan should be selected by policymakers, who establish societal preferences and value trade-offs between direct costs and emissions. A reasonable procedure for finding the efficient set of operation plans in the short run is the weighting method (Cohon, J.L. 1978), which converts the multiobjective criterion function into a weighting problem. In the present case, where the objectives in the EED and the EEUC formulations are to minimize operating cost, C_{tot} and emission, $E_{j,tot}$, of pollutant j, $j=1,2,\ldots,J$, the *weighting problem* is

$$Min\ F = w_1 C_{tot} + \sum_{j=1}^{J} w_{j+1} E_{j,tot} \qquad (1)$$

with the weights w_1, w_{j+1}, $j=1,2,\ldots J$ summing to 1. Given a set of weights w_1, w_{j+1}, $j=1,2,\ldots J$, F is a single objective criterion function which is minimized subject to feasibility constraints. While this process is unwieldy for multiple pollutants, it correctly reflects the complexity of the planners problem. Additional complexity could be incorporated through an "i" subscript on the weights, if the externalities attached to emission of a unit of the same pollutant varies across sources. For longer term analysis, the weights could also change to reflect expected changing externalities. It should be emphasized that the weights used in the weighting problem are not value judgments of the relative importance of objectives. There is no inherent significance attached to them, and manipulating the weights yields the efficient set of alternative operation plans. However, we may obtain a monetary interpretation of the weights (e.g., in $ per kg emission) through manipulating (1).

$$Min\ F' = C_{tot} + \sum_{j=1}^{J} \frac{w_{j+1}}{w_1} E_{j,tot} \qquad (2)$$

The criterion functions F and F' clearly give identical solutions. The term w_{j+1}/w_1 may be interpreted as *the value assigned to pollutant j relative to money*. Thus, the ratio w_{j+1}/w_1 can be interpreted as the $/kg external cost assigned to pollutant j.

A two dimensional efficient frontier may be obtained by varying the environmental "cost" from zero ($w_1=1$) to infinite environmental "cost" ($w_1=0$), while holding the relative w_{j+1} constant (that is,

$$w_{j+\alpha_1}/w_{j+\alpha_2} = constant, \quad \alpha_1, \alpha_2 \ integers \le J).$$

These extremes represent conventional economic UC/dispatch ($w_{j+1}/w_1=0$ $/kg environmental cost) and least emissions UC/dispatch ($w_{j+1}/w_1=$"infinite" $/kg environmental cost) respectively. A hypothetical efficient frontier between emission to air and operating cost (direct cost) is illustrated in Figure 1. The formulation in (2) allows for a direct monetary interpretation of every point on the resulting efficient frontier.

The solution method is principally identical for the EED and the EEUC problem formulations, in terms of using the weighting method. However, the criterion functions and feasibility constraints to be solved are significantly different, as mentioned in the above problem formulations and formally stated in Appendices 1 and 2. Note that the solution is an optimum operation schedule over a period of probably a week or so. Longer term planning involves repeated applications of the same analysis. If externalities changed over time, the chosen path into the future could involve choosing solutions from subsequent weeks that were derived with different sets of weights. That is, the long run solution may be represented by a sequence of efficient sets.

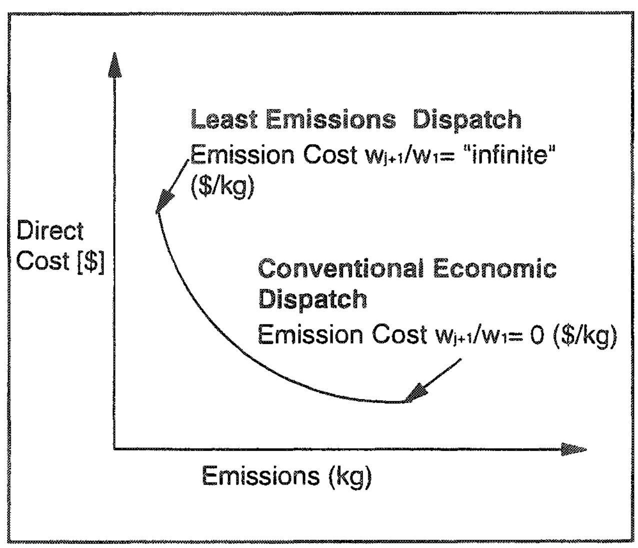

Figure 1. Economic-Environmental Dispatch (EED) or Economic-Environmental Unit Commitment (EEUC). Hypothetical illustration of the efficient frontier between direct costs and emission(s) to air.

Lagrangian Relaxation

The EED and the EEUC approaches are implemented in a computer model using a powerful Lagrangian Relaxation (LR) algorithm and dynamic programming. (Further details on the LR algorithm used to solve the EED and EEUC problems may be found in Gjengedal, T., Johansen, S. and O. Hansen 1992).

A Lagrangian Relaxation approach is particularly powerful because it provides a solution technique to a problem that has interdependencies across time periods, which simpler UC and dispatch simulation methods do not handle well. In addition to making the treatment of operational constraints more accurate, this advantage permits inclusion of time varying externalities into the analysis. While most emissions have a constant externality, some do vary over time. The obvious example of a time-varying case is the urban air quality, or smog, problem. In fact, in other ongoing work, we are extending the model in this direction to facilitate a study of the San Francisco Bay Area. In this case, a time varying dispatch penalty is imposed directly on polluting generation to simulate the effect of a localized smog precursor tax. In the Bay Area, photochemical smog is formed only under certain rare weather conditions, so the environmental cost of smog precursor emissions is high only while these conditions exist, while costs usually are small or zero.

Test Results

The above presented framework is general in that many environmental effects could be included. However, some, such as land use changes, are not easily quantified in the same manner as air or water emissions and the existence of externalities is not so clear-cut. At the moment, therefore, we are applying it only to air pollution issues.

To illustrate the EED and the EEUC approaches, they are applied to a test system. For illustration purposes, this sample analysis is limited to include minimization of operation cost and emissions of NO_x, i.e., $J=1$ pollutant. This gives a two-objective decision problem, which can be illustrated in a two-dimensional plane. In this test case, the weighting problem is as follows (with $J=1$ in eq. (2)):

$$Min\ F' = C_{tot} + \frac{w_2}{w_1}E_{1,tot} \qquad (3)$$

(3) is repeatedly solved, incrementally increasing the environmental "cost" w_2/w_1 [$/kg] from zero ($w_1=1$, $w_2=0$) to infinite ($w_1 \approx 0$, $w_2 \approx 1$), subject to feasibility constraints as indicated in the EED and EEUC problem formulations. The calculation process is repeated until no significant change in UC/dispatch is observed from increment to increment. This represents least-emissions UC/dispatch.

The above formulation shows a possible reduction of the dimensionality problem by fixing the relative importance of pollutants, e.g., NO_x is 100 times as important as SO_2. A convenient 2-dimensional efficient frontier between direct operation cost and total weighted emissions results. And, the example below includes one pollutant ($J=1$). However, our problem formulation allows for implementing multiple pollutants (J). A two-pollutant version of eq. (3) would be of the following form

$$Min\ F' = C_{tot} + \frac{w_2}{w_1}E_{1,tot} + \frac{w_3}{w_1}E_{2,tot} \qquad (4)$$

The terms w_2/w_1 and w_3/w_1 represent the $/kg environmental cost attached to each of the two pollutants, $E_{1,tot}$ and $E_{2,tot}$, respectively. The above formulation in eq. (4) results in a 3-dimensional frontier. Each solution of (4) represents an operation plan which is sited on this surface. However, as the number of pollutants included in the problem formulation increases, the dimensionality of the problem increases. A J pollutant case would result in a $J+1$ dimensional solution set, which is not easily displayed in a 2-dimensional frontier. As dimensionality increases, therefore, the value of this approach is reduced from a policymaking point of view.

We apply the solution method to an electric power production system consisting of 4 generators, with a total capacity of 1930 MW. The test system, given in Table 1, satisfies a time-varying load, D_t, $t=1,2,\ldots,48$, given in Figure 2. Spinning reserve requirement, R_t, $t=1,2,\ldots,T$, is 15% of the demand D_t. We neglect unit-ramping limits as well as fuel-use constraints in the test example, although the algorithm is capable of handling them. If boilers in the simulation have dual fuel capability, then high relative weights on emissions will tend to automatically encourage use of the cleaner fuel, even if it is more expensive than the alternative.

An extract of test results is given in Figures 3 and 4. Figure 3 shows dispatch and commitment profile for each unit in the test system for the conventional economic UC/dispatch case (environmental cost $w_2/w_1=0$ [$/kg]). Observe that the polluting unit 1 (coal) contributes significantly to serve customer load, since no weight is given to NO_x-emission in this case ($w_2=0$). Figure 4 shows the equivalent schedule in the least emission case

Table 1. Test System for the EED and EEUC Solution Approch(es)

		Coal	Gas 1	Gas 2	Oil
Cap.(MW)	P_{min}	125.0	150.0	50.0	125.0
Cap.(MW)	P_{max}	500.0	600.0	330.0	500.0
Generation	k_0	340.248	1787.70	523.68	504.35
cost	k_1	14.9588	17.9571	20.1443	33.8265
coeffs. ($)	k_2	9.1E-5	4.18E-3	3.39E-4	2.65E-3
Start-up	c_0	12500	12000	7500	12000
cost ($)	c_1	6250	6000	7500	6000
Stop cost ($)	$C_{d,i}$	12500	12000	7500	12000
Gen.	β_0	84.3431	93.1616	1.37681	18.8373
emission	β_1	3.7081	0.93579	0.05296	1.2634
coeff. (kg)	β_2	2.25E-5	2.18E-4	8.9E-6	9.88E-5
Start-up	E_0	6195.2	1243.2	38.85	892.8
emission. (kg)	E_1	3097.6	621.6	38.85	446.4
Min.down	$T^{min}_{d,i}$	12	6	1	6
Min. up	$T^{min}_{up,i}$	12	6	2	8
Cold start	$T_{cold,i}$	12	6	1	6

(environmental cost w_2/w_1=infinite [$/kg]). Observe that the polluting unit 1 (coal) now contributes significantly less. The customer load is satisfied by committing and dispatching less polluting units for operation.

Comparing EED and EEUC

Figure 5 shows the efficient frontiers between operating cost and emission, both in the EED and in the EEUC case. The dispatch and commitment profile for each unit in Figure 3 corresponds to the far right point on the efficient frontier curve(s), and Figure 4 corresponds to the far left point on the EEUC curve in Figure 5. In Figure 5, 5 points of emission cost (w_2/w_1) were used to develop the two efficient frontiers: these points are w_2/w_1=0$/kg ($w_1$=1.0), w_2/w_1=0.33$/kg (w_1=0.25), w_2/w_1=1$/kg ($w_1$=0.5), w_2/w_1=3$/kg (w_1=0.75), $w_2/w_1=\infty$ $/kg ($w_1$=0).

Figure 5 represents an interesting comparison between the following two cases, (1) using environmental objectives only when dispatching the power production system, that is, EED, and (2) implementing environmental objectives into both the unit commitment of the system and the dispatch, that is, EEUC. Intuitively, (2) provides greater flexibility for selecting operation strategies for reducing NO_x emissions from a power production system.

The results in Figure 5 indicate a significant NO_x-reduction potential from the test system. EED has a maximum reduction potential of 38% for NO_x, and the

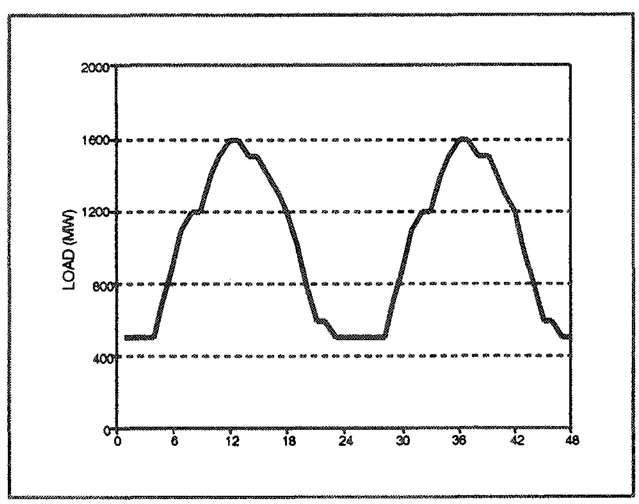

Figure 2. Load Profile for Test System

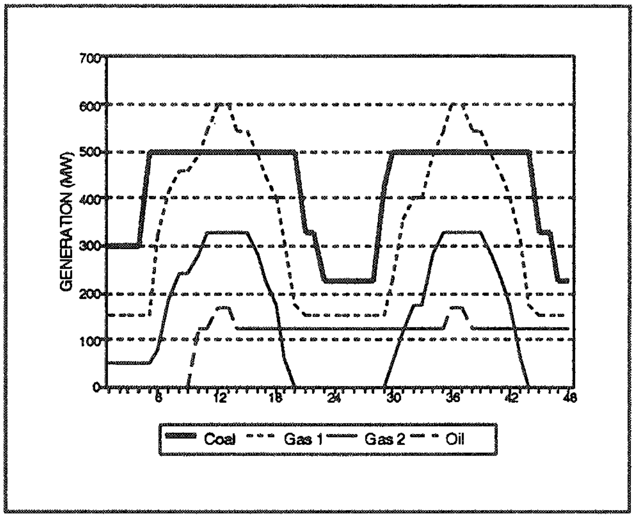

Figure 3. Conventional Economic Generation Schedule for the Test System, that is, Zero Environmental Cost w_2/w_1 [\$/kg NO_x] in eq. (3)

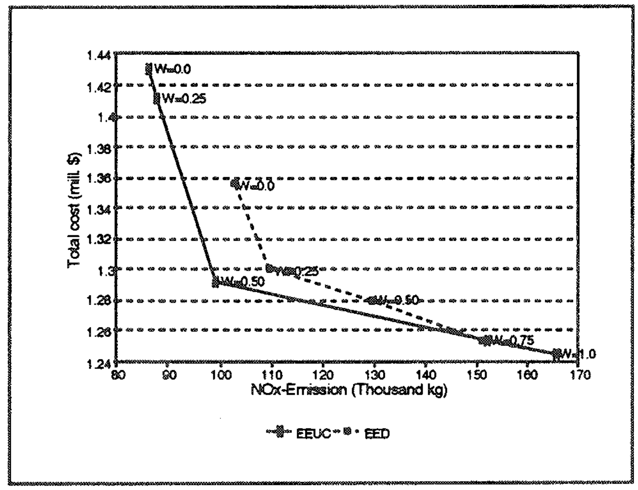

Figure 5. Efficient Frontier Between Operating Cost and Emissions for the Test System (i.e., environmental "cost" w_2/w_1 [\$/kg NO_x] Varies Incrementally from Zero to Infinite in eq. (3))

EEUC case has a potential of 48%. These NO_x-emission reductions are achieved at significant increases in operations costs of 8.8% in the EED case and 14.8% in the EEUC case. The higher cost increase in the EEUC case is due to the greater flexibility in operation strategies for reducing NO_x-emissions, allowing for higher NO_x-reduction. However, the last kgs of NO_x are removed at a very high cost.

In general, EEUC achieves a specific emission reduction at a lower corresponding cost than EED does, because EEUC better simulates actual potential for and cost of emission reductions, thereby facilitating better planning. However, for small emission reductions, EED may appear equally or only marginally less cost-effective, as indicated by Figure 5. In other words, ignoring environmental costs to start-up and shut-down of generators does not lead to significant errors when emission costs (\$/kg) are small.

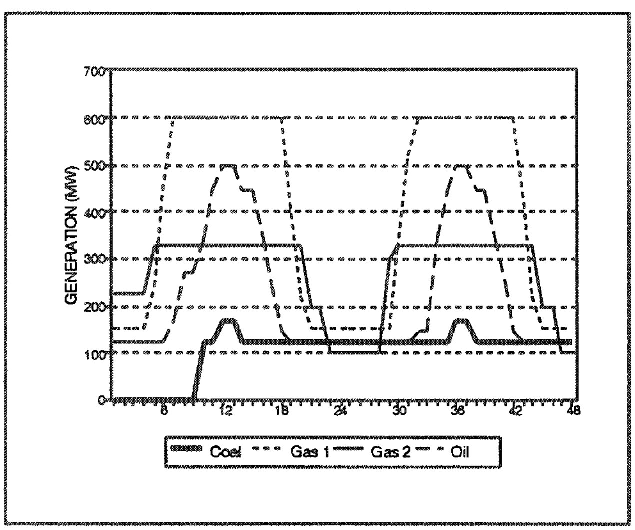

Figure 4. Least Emission Generation Schedule for the Test System, that is, Infinite Environmental Cost w_2/w_1 [\$/kg NO_x] in eq. (3)

In Figure 5, the two efficient curves are kinked. This kink appears at different weightings, at $w_2/w_1=3\$/kg$ ($w_1=0.25$) in the EED case and at $w_2/w_1=1\$/kg$ ($w_1=0.5$) in the EEUC case. This type of inflection point could be a likely place to set policies. If, or where, this kink will occur is system dependent. The EED- and the EEUC-formulations are principally different optimization problems; thus, in general, an inflection point may occur at different points in each solution. Dispatch/commitment may be significantly different for the same system. Most likely, pronounced inflection points like the ones in Figure 5 would not occur in large utility systems with numerous generators of various cost/emission characteristics.

Conclusions

The described approaches, economic-environmental dispatch (EED) and economic-environmental unit commitment (EEUC), represent ways of implementing environmental objectives into dispatch and unit commitment of electric power production systems. EED and EEUC are consistently defined and formulated, and solutions are illustrated using the weighting method. A monetary modification of the weighting method provides an explicit link to environmental cost studies, using \$/kg estimates of the emission weights. As expected, the test results indicate the EEUC approach as being more accurate, and having a larger emission-reduction potential than EED alone. The difference in direct operating cost between the two cases is small for low (\$/kg) values of emission cost, and rises as the external cost is increased. This intuitively correct result merely says the higher the perceived cost of pollution, the more there is to gain by doing a better job at cleaning up.

We consider the proposed EED and EEUC approaches to be an appropriate contribution to solving the problem of how to include environmental impacts from electricity production in operating and planning decisionmaking. This methodology can provide more accurate inputs to resource acquisitions and/or DSM evaluation analysis, and will provide a useful tool for evaluating variable externalities.

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Appendix 1: Problem Formulation of Economic-Environmental Dispatch (EED)

P_{it} = Power output from generator i, in time interval t (MW).
C_{it} = Operating costs for generator i, in time interval t ($).
E_{jit} = Emission, kg's emitted of pollutant j at generator i during normal operation in time interval t.
D_t = Power demand in time interval t (MW).
$P_{i,max}$ = Maximum capacity of generator i (MW)
$P_{i,min}$ = Minimum capacity of generator i (MW)
N = Number of generators in the system, i= 1,2,...,N
T = Number of time intervals (weeks), t=1,2,...,T
J = Number of pollutants, j=1,...,J
$E_{j,tot}$ = Total emission of pollutant j during normal operation
$\alpha_1\alpha_2$ = Integer constants

Ignoring power transmission losses, the problem is that of finding the variables P_{it} that minimizes total emission and total cost; hence, the following multiple criterion problem formulation:

$$Min! \ \{ \ C_{tot} \ , \ E_{j,tot} \ for \ j \ = \ 1,\ldots,J \ \} \tag{5}$$

Which is equivalent to:

$$Min! \ \{ \ \sum_t \sum_i C_{it} \ , \ \sum_t \sum_i E_{jit} \ for \ j=1,\ldots,J \ \} \tag{6}$$

Subject to the operating constraints:

$$P_{i,\min} \leq P_{it} \leq P_{i,\max} \quad for \ all \ i \wedge t \tag{7}$$

and the demand constraints:

$$\sum_{i=1}^{N} P_{it} = D_t \quad for \ all \ t=1,\ldots,T \tag{8}$$

Using a polynomial approximation of the heat rate curve, we obtain the following cost function C_{it} and emission curve E_{jit} during normal operation:

$$C_{it} = k_{0i}+k_{1i}P_{it}+k_{2i}P_{it}^2 \tag{9}$$

$$E_{jit}=\beta_{0ji}+\beta_{1ji}P_{it}+\beta_{2ji}P_{it}^2 \tag{10}$$

Where k_{0i}, k_{1i} and k_{2i} are polynomial heat-rate coefficients for generator i. And where β_{0ji}, β_{1ji}, β_{2ji} are polynomial emission coefficients for pollutant j from generator i. Please note that our formulation permits any emission curve to be implemented into the formulation. Here, we present a 2nd order polynomial approximation which may result from fitting a curve to emission measurements. In principle, real-life emissions during start-up may show significant excursions from any fitted curve, e.g., such as (9).

Appendix 2: Problem Formulation of Economic-Environmental Unit Commitment (EEUC)

n = Number of generation units in the system, i=1,2,....,n
T = Number of time intervals (hours), t= 1,2,...,T
$T^t_{d,i}$ = Down time, unit i [h]
$T_{cold,i}$ = Cold-start time, unit i [h]
$T^{min}_{up,i}$ = Minimum up time, unit i [h]
$T^{min}_{d,i}$ = Minimum down time, unit i [h]
D_t = Power demand in time interval t [MW]
J = Number of pollutants, j=1,2,....J
C_{tot} = Total system operating cost [$].
C_{it} = Operation cost of generator i, in time interval t. [$]
$C_{up,i}$ = Start-up cost, unit i [$], $C_{up,i}$ is a function of $T_{down,i}$
$C_{d,i}$ = Stop cost, unit i [$]
P_{it} = Generation at unit no. i, in time interval t [MW]
$P_{i,max}$ = Maximum capacity of generator i [MW]
$P_{i,min}$ = Minimum capacity of generator i [MW]
E_{jit} = Emission of pollutant j from generator i, in time interval t [kg]
$E_{j,tot}$ = Total emission of pollutant j from electric power production system [kg]

$E_{up,ji}$ = Emission of pollutant j during start-up of unit i [kg]
$E_{d,ji}$ = Emission of pollutant j during shut-down of unit i [kg]
R_t = Spinning reserve requirement in time interval t [MW]
$r_{i,max}$ = Maximum ramping-rate, unit i, in one time interval [MW]
X_{it} = Integer decision variable unit i, in time interval t, ($X_{it}=1$ if unit i is scheduled for operation in period t, $X_{it}=0$ if unit i is not scheduled for operation in period t)

Criterion function:

$$Min!\ [C_{tot},\ E_{j,tot} \quad for\ j=1,2,..J] \tag{11}$$

Total operation cost:

$$C_{tot}=\sum_{i=1}^{n}\sum_{t=1}^{T}[\ C_{it}+C_{up,i}+C_{d,i}\ ] \tag{12}$$

Direct cost during normal operation:

$$C_{it}=k_{0i}+k_{1i}P_{it}+k_{2i}P_{it}^2 \tag{13}$$

Where k_{0i}, k_{1i} and k_{2i} are polynomial operation cost coefficients for generating unit i.

The start-up cost, $C_{up,i}$, for unit i depends on how long the unit has been not operative. Our approach permits representation of any start-up cost function. A piece-wise linear approximation is implemented in this formulation

$$C_{up,i}=c_{0,i}+c_{1,i}T^t_{down,i} \quad for\ 0\leq T^t_{down,i}\leq T_{cold,i} \tag{14}$$

$$C_{up,i}=c_{0,i}+c_{1,i}T_{cold,i} \quad for\ T^t_{down,i}\geq T_{cold,i} \tag{15}$$

Where c_{0i} and c_{1i} are linear approximation start-cost coefficients for unit i. We represent the stop cost by an appropriate constant cost $C_{d,i}$, for unit i.

Total emissions of pollutant j to air:

$$E_{j,tot}=\sum_{i=1}^{n}\sum_{t=1}^{T}[\ E_{jit}+E_{up,ji}+E_{d,ji}\ ] \tag{16}$$

Emission to air during normal operation :

$$E_{jit}=\beta_{0ji}+\beta_{1ji}P_{it}+\beta_{2ji}P_{it}^2 \tag{17}$$

Where β_{0ji}, β_{1ji}, β_{2ji}, are polynomial emission coefficients for pollutant j from generator i.

We assume the start-up emission to be a function of unit down time, $T_{down,i}$, $i=1,2,\ldots,n$. We apply a linear approximation to emissions during start-up, $E_{up,i}$.

$$E_{up,ji}=E_{0,ji}+E_{1,ji}T_{down,i} \quad for\ 0\leq T_{down,i}\leq T_{cold,i} \tag{18}$$

$$E_{up,ji}=E_{0,ji}+E_{1,ji}T_{cold,i} \quad for\ T_{down,i}\geq T_{cold,i} \tag{19}$$

Where $E_{0,ji}$ and $E_{1,ji}$ are linear approximation start-up coefficients for pollutant j from unit i.

Emission of pollutant j during shut-down of unit i is represented by a constant $E_{d,ji}$, In principle any other representation may be included, e.g., $E_{d,ji}$ may be a function of P_{it}, $i=1,2,\ldots,n$, $t=1,2,\ldots,T$

Electricity demand (including network losses):

$$\sum_{i=1}^{n}P_{it}=D_t \quad for\ t=1,2,\ldots,T \tag{20}$$

Reliability (spinning reserve requirement):

$$\sum_{i=1}^{n}r_{it}\geq R_t \quad for\ t=1,2,\ldots,T \tag{21}$$

$$r_{it}\ =\ Min\ [r_{i,\max},(P_{i,\max}-P_{it})] \quad for\ all\ i\ \wedge\ t$$

Local constraints for each generating unit

- minimum and maximum generation limits

$$X_{it}P_{i,\min}\ \leq\ P_{it}\ \leq\ X_{it}P_{i,\max} \quad for\ all\ i\ \wedge\ t \tag{22}$$

- dynamic equation of down time, $T^t_{d,i}$, for unit i

$$T^{t+1}_{d,i}=(T^t_{d,i})(1-X^t_i) \quad for\ t=0,1,\ldots,T-1\ \wedge\ i=1,2,\ldots,n$$

- minimum down-time, $T^{min}{}_{d,i}$, for unit i

$$(X_i^{t+1} - X_i^t)(T_{d,i}^t - T_{d,i}^{min}) \geq 0 \quad for\ t=0,1,\ldots,T-1$$

$$\wedge\ i=1,2,\ldots,n$$

- minimum up-time, $T^{min}{}_{up,i}$, for unit i

$$(X_i^{t+1} - X_i^t)\left(\sum_{j=t+1-T_{up,i}^{min}}^{t} X_i^j - T_{up,i}^{min}\right) \geq 0 \quad for\ t=0,1,\ldots,T-1$$

$$\wedge\ i=1,2,\ldots,n$$