29
5-9-77
25 CIP

Department of Energy

Regional Studies Program

MASTER

A Linear Programming Model for County-
Level Electric Facility Siting

June 1977

Brookhaven National Laboratory

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

THE BROOKHAVEN NATIONAL LABORATORY REGIONAL ENERGY STUDIES PROGRAM

BNL 23388

INFORMAL REPORT

A Linear Programming Model for
County-Level Electric Facility Siting

by

Peter M. Meier

June 1977

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Policy Analysis Division
National Center for Analysis of Energy Systems
Brookhaven National Laboratory
Upton, New York 11973

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

The Department of Energy (DOE) is the successor to the Energy Research and Development Administration (ERDA) and all references to ERDA herein shall be deemed to refer to DOE.

PREFACE

This report is one of a continuing series of policy analysis and model development studies in the area of energy facility siting prepared by the Brookhaven National Laboratory Regional Energy Studies Program, sponsored by the Division of Technology Overview, U.S. Energy Research and Development Administration. The intent of the research component addressed to siting model development is to prepare assessment tools appropriate to the regional scale of energy policy analysis. This contribution documents a siting methodology developed specifically to bridge the gap between regional energy system scenarios and environmental transport models.

Other reports in this series on energy facility siting include:

P. Meier, "Energy Facility Location: A Regional Viewpoint", BNL-20435, May 1975.

Energy Policy Analysis Group, et al., "A Preliminary Assessment of a Hypothetical Nuclear Energy Center in New Jersey", BNL-50465, Nov. 1975.

T. Backstrom and M. Baram, "Artificial Islands for Clustersiting of Offshore Energy Facilities: An Assessment of the Legal and Regulatory Framework", BNL-50566.

P. Meier and D. Morell, "Issues in Clustered Nuclear Siting: A Comparison of a Hypothetical Nuclear Energy Center in New Jersey with Dispersed Nuclear Siting", BNL-50561.

R.L. Church and J.L. Cohon "Multiobjective Location Analysis of Regional Energy Facility Siting Problems" BNL 50567.

ABSTRACT

A mathematical programming approach to the disaggregation of regional electric sector energy scenarios is developed, with particular emphasis on integration with the Brookhaven Regional Energy System Optimization model that defines the regional generation mix, and the Brookhaven atmospheric transport models that allow computation of air quality given emissions at the county level. The model sites generation and transmission facilities by county, in such a way as to satisfy exogenously specified generation constraints at the power pool level. Land use, water resources and air pollution constraints, as well as cost penalties for various cooling and air pollution control modes, are included. The objective function can be specified either in terms of costs, or in terms of minimizing emissions subject to fiscal constraints. The model is particularly suited to the evaluation of siting strategy trade-offs, and as a component of integrated environmental-economic analysis of energy planning options.

ACKNOWLEDGEMENTS

I am indebted to Jared Cohon, of the Johns Hopkins University, and Richard Church, of the University of Tennessee, for their contributions to the development of this model, both by virtue of their earlier work for the Brookhaven National Laboratory Regional Studies Program in the siting model development area as well as for their helpful comments on an early version of this paper. Much of the not inconsiderable burden of data assembly and computer programming fell on Martha McCoy and Robert Stern, without whose invaluable assistance the model would still be in the realm of theory rather than available for policy analysis. Finally I am indebted to Adele Hough, who bore the tedium of typing many versions of this equation ridden paper with humor and competence.

The responsibility for the accuracy and opinions expressed in this paper, however, rests exclusively with the writer, and do not necessarily represent the views of either the U.S. Energy Research and Development Administration, or the Brookhaven National Laboratory.

TABLE OF CONTENTS

	<u>Page</u>
1. Introduction	1
2. Notation	5
3. Model Formulation	7
4. Siting Constraints	17
5. The Transmission System	36
6. Sample Results	42
7. Notes	45

1. INTRODUCTION

The use of mathematical models in energy system planning has become almost commonplace in the past few years, and both optimization and simulation analyses of global,¹ national² and regional³ energy-economic systems have found widespread application in policy studies. Although such energy system models undoubtedly afford valuable insights to improved public policy making, especially where linked with Input-Output and/or econometric models of the economy,⁴ the difficulty of integration of environmental impact considerations appears to be a major shortcoming of current modelling approaches.⁵

Thus far the typical approach is one based on a computation of aggregate residuals; models are used to determine the optimal technology mix; emission coefficients are applied to each system component for pollutants of interest (SO_2 , particulates, etc.); and the environmental impact expressed as total emissions.⁶ Yet it seems clear that such numbers are of questionable value for environmental policy analysis, let alone for any credible examination of environmental-energy-economic trade-offs. Attempts to refine such computations by replacing the usual objective function specification of cost minimization by minimization of emissions (weighted, say, according to health impact and constrained by some investment limit) must also be regarded as somewhat dubious surrogates for proper environmental analysis.⁷

If one examines health impacts as a more specific example, the difficulty is readily seen to lie in the fact that health impacts are largely determined by the exposure of populations to ambient levels of pollutant concentration, not to aggregated emission levels: and ambient atmospheric (or water) concentrations can be determined only by application of appropriate environmental transport models to specific point source emission data. The essential feature of such models, of course, is their locational specificity: a computation of atmospheric sulfate levels, for example, requires knowledge of stack locations to a considerably more exact level than the level of disaggregation of currently available energy system-economic models. Thus the prediction that so many Gw of coal fired electric generation capacity with a given emission control technology will be located in, say, a particular

Census⁸ or Reliability Council Region⁹ (typical outputs of multi-regional energy system models) still yields relatively little of policy relevant value. To be sure, the regional scale imparts more information than a national level aggregation, but one is still some way from the desirable scale.

The importance of moving beyond mere analyses of residuals is perhaps nowhere as striking as with the key coal related health impact issues of sulfates and ozone. Both pollutants are known to be of significant health impact, and known to be correlated with the presence of coal combustion, yet neither substance occurs in significant amounts as a stack emission. Rather, local ambient levels are determined by complex atmospheric conversion processes that can be captured only by the application of regional scale meteorological models. Thus, sulfur dioxide (SO_2) and nitrogen oxide (NO_x) stack emissions are not amenable to simple linear transformation to sulfate (SO_4) and ozone concentrations, which in turn underscores the very limited value of SO_2 and NO_x residuals as measures of environmental damage.

It is clear, then, that there is a need for bridging the gap between energy system scenarios on the one hand, and environmental transport models on the other; and this bridge, obviously, is a siting of pollution emitting facilities to a level of geographic detail consonant with the spatial resolution of environmental models. It appears, moreover, that the level of spatial resolution that best represents the compromise between the ability to disaggregate a regional scenario on the one hand, and the necessity for locational specificity of environmental models on the other, is the county. Thus the objective of this report is to develop a model that achieves this link; in our case the specific design criteria are the ability to interface with the Brookhaven integrated multi-regional energy and interindustry model¹⁰ which determines the regional configuration of the electric sector, and the Brookhaven Diffusion-Trajectory Model for study of regional air quality and health impact issues.¹¹

It should be stressed that the requirements for a siting analysis addressing the rather distant time horizon of 2000 and beyond, the typical

planning horizon of scenario analyses, are clearly different to the requirements for a siting analysis within the normal planning horizon of electric utilities whose objective is to actually identify specific sites. In our case, the rationale for siting facilities has little to do with assisting utilities identify future sites;¹² rather, it is dictated by the requirement that for meaningful environmental analysis of regional scale problems to be conducted, facilities must be located in space at about the county level of detail. The overriding objective is to demonstrate the relationship of siting policy to environmental impact, and, as such, a siting exercise of the type implied here will always involve at least two siting scenarios. Interest is thus focussed not on whether, say, mine-mouth siting is "better" or "worse" than load center siting of coal electric plants, (a question that would require a multi-objective analysis on a case by case basis, clearly beyond the logistic capabilities most types of assessment exercise), but to illustrate what typical siting patterns would be if one were to follow either a mine-mouth or a load center strategy, and what regional scale impacts would follow.

A further factor that makes difficult a utility-oriented approach is the importance of "judgement" in actual utility siting decisions. Given the fragmentation in the electric utility sector, a systematic view of what constitutes "judgement" would obviously be very difficult; and even more so in an attempt to predict what the judgemental factors might be in 1990, at which time siting decisions for the year 2000 would be imminent. Thus, rather than attempting application of computationally and conceptually complex multi-objective goal programming models or the complex systems that would formalize the participation of utilities in the assessment process,¹³ a more tractable analytical course seemed to be one that rested upon using unambiguously defined objective functions (minimizing cost, minimizing emissions subject to capital or cost constraints, etc), and then to present interested parties with the scenario results in an attempt to identify the constraints that would arise if public policy did follow certain paths. Thus we extend the "what if" type of assumption used in the definition of the technology scenarios to the siting area; and in both cases the objective is to identify environmental ramifications and constraints to postulated assumptions.

Finally, this type of approach also permits consistency between energy-economic modelling systems and siting, by allowing the same type of objective function to be used in both cases.

To address these rather difficult demands, we develop in this report a linear programming siting model that translates the electric sector generation mix specified by a regional energy system scenario to the facilities required at the county level. In its basic form, the model can be characterized as a multi-commodity transshipment problem, encompassing fuel mining and transportation costs (for each of the many types of coal, each of differing heat value and sulfur content), electric transmission and cost penalties for various environmental control technologies. Because the generation mix is fixed for any given run by the scenario model output, the integer variables associated with the usual generation mix optimization questions are not required, and a linear programming formulation appears quite adequate.¹⁴

2. NOTATION

General Rules of Notation

1. Capacity Variables are denoted by Upper Case
2. Energy Variables are denoted by Lower Case
3. The Asterisk Superscript denotes a variable or constant specified by the regional Reference Energy System Scenario
4. The subscript i indicates the County; there are assumed to be n counties in the region
5. The subscript k indicates the type of generation facility, by fuel

$k = 1$ or C Coal
 $= 2$ O Oil
 $= 3$ N Nuclear (LWR)
 $= 4$ T Combustion Turbine
 $= 5$ H Hydro-Electric
 $= 6$ P Pumped Hydro electric

A dimensional equation is written underneath each new equation, with the dimensions of each variable indicated in square brackets. A set of empty square brackets denotes a dimensionless parameter or variable.

Parameters

γ_{Ei} Extraction cost for coal in region i , in \$/ton
 β_i Heat content of coal in region i , in tons/ 10^{15} Btu
 γ_T Transportation cost of coal, in \$/ton/mile
 δ_{ij} Distance from county i to county j , in miles
 τ_c Capital cost of transmission, in \$/GW/mile
CRF Capital recovery factor, in year⁻¹
 δ_k Capacity factor for generation facilities of Type k
 ρ_k Heat rate for generation facilities of Type k , in Btu/Kwh

π	Capacity factor for transmission lines
Ω	Transmission loss factor, miles ⁻¹
τ_E	Cost per Kwh (lost in transmission)
g_k^*	Fraction of total regional resource use in the k-th fuel/generation type category.
R^*	Total Resource Use as specified by Scenario, 10^{15} Btu/yr
R'	Total Resource Use as computed by model, 10^{15} Btu/yr

Capacity and Demand Variables

Y_{ij}	Transmission line capacity between county i and county j, in Gw
X_i^k	Generation capacity of type k in county i, Gw
D_i	Peak electricity demand in county i, Gw

Energy Variables

y_{ij}	electric energy transmission from county i to county j, in Gwh/yr
d_T^*	total regional electric energy demand, in Gwh/year
r_k^*	annual fuel use for type k, in 10^{15} Btu/yr

Resource Variables

C_i	coal mined in county i, in 10^{15} Btu per year
C_{ij}	coal shipments from county i to county j, in 10^{15} Btu/year
r_{ki}	fuel use of type k in county i, in 10^{15} Btu/year

3. MODEL FORMULATION

3.1 Introduction

Given a particular specification of the generation mix, the siting problem can be reduced to the determination of that set of facility locations that minimizes the sum of coal extraction, coal transportation, and electric transmission costs, subject to meeting certain energy and resource mass balance conditions. Since the generation mix for any particular run is given as part of the scenario, the baseline costs of the generating facilities themselves do not enter into the computation, and only those that are location specific are considered (e.g. due to cooling, or air quality constraints).

The basic formulation is developed in this section, and in Section 4 we shall add a series of further constraints to include air quality, water use, and other siting considerations. In structure the LP is partly a transportation model (with the possibility of coal shipments from each producing county to each consuming county), part transshipment model (with shipments of electricity only between adjacent counties). Although the transshipment formulation for coal considerably enlarges the size of the problem, it is necessary to account for individual county-to-county shipments because coal from different counties may have different heat, sulfur and ash content (whereas in electric transmission no such distinction need be made).

3.2 Model Description

The objective function may be stated as

$$\text{Min } Z = \sum_{i=1}^n C_i \beta_i \gamma_{Ei} + \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n C_{ij} \delta_{ij} \gamma_T$$

Coal Extraction Cost

Coal Transportation Cost

$$+ \text{CRF} \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} \delta_{ij} \tau_c + \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n y_{ij} \delta_{ij} \tau_E 10^6 \Omega$$

$$\left[\frac{\$}{\text{yr}} \right] \left[\text{Gw} \right] \left[\text{Mi} \right] \left[\frac{\$}{\text{Gw-Mi}} \right] \left[\frac{\text{Gwh}}{\text{yr}} \right] \left[\text{Mi} \right] \left[\frac{\$}{\text{Kwh}} \right] \left[\frac{\text{Kwh}}{\text{Gwh}} \right] \left[\frac{1}{\text{Mi}} \right] \quad (1)$$

Capital Cost of Transmission

Energy Cost of Transmission Losses

The last two terms may be combined, however. If π is the assumed load factor for transmission lines, then

$$Y_{ij} 8760 \pi = y_{ij} \quad (2)$$

$$\left[\text{Gw} \right] \left[\frac{\text{hrs}}{\text{yr}} \right] = \left[\frac{\text{Gwh}}{\text{yr}} \right]$$

Hence

$$\sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n y_{ij} \delta_{ij} \tau_E 10^6 \Omega = \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} 8760 \pi \delta_{ij} \tau_E 10^6 \Omega \quad (3)$$

and thus the last two terms of the objective function may be written as

$$\sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} \delta_{ij} \left\{ \tau_c \text{CRF} + 8760 \pi \tau_E 10^6 \Omega \right\} = \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} \delta_{ij} k_2 \quad (4)$$

The assumption of a load factor constant for all transmission lines is, of course, somewhat unrealistic. A more rigorous treatment of transmission is deferred to Section 5, however, in view of the substantial problems that arise, especially the almost threefold increase in problem size.

This minimization is subject to the following constraints:

a. Mass Balance for Coal

If c_i is the quads of coal mined in county i

c_{ij} is the quads of coal exported from county i to county j

r_{ci} is the quads of coal burned at electric generating facilities in county i

then the mass balance for coal can be written

$$c_i + \sum_{\substack{j=1 \\ j \neq i}}^n c_{ji} - \sum_{\substack{j=1 \\ j \neq i}}^n c_{ij} - r_{ci} = 0 \quad i=1, \dots, n \quad (5)$$

Coal Mined
in Region i

Coal
Imports

Coal
Exports

Coal burned
in County i

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right]$$

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right]$$

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right]$$

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right]$$

b. Mass Balance for Electric Energy

If y_{ij} represents the quantity of electric energy shipped from county i to county j

Ω represents the transmission losses, in Gwh of loss per Gwh entering the transmission line per mile of line.

δ_{ij} is the length of the transmission line between county i and county j.

ρ_k is the heat rate of coal generating plants in Btu per Kwh

then the mass balance condition for electric energy can be written

$$\sum_{k=1}^K r_{ki} 10^{15} \frac{1}{\rho_k} \frac{1}{10^6} - \sum y_{ij} + \sum y_{ji} \left(1 - \Omega_{ji}\right) = d_T^* f_i \quad (6)$$

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right] \left[\frac{\text{Btu}}{\text{Btu}^{15}} \right] \left[\frac{\text{Kwh}}{\text{Btu}} \right] \left[\frac{\text{Gw}}{\text{Kw}} \right] \quad \left[\frac{\text{Gwh}}{\text{yr}} \right] \quad \left[\frac{\text{Gwh}}{\text{yr}} \right] \left[\frac{1}{\text{mi}} \right] \left[\text{mi} \right] \quad \left[\frac{\text{Gwh}}{\text{yr}} \right]$$

Electricity Generated Exports Imports Demand
in county i

The Right Hand Side (RHS) of this equation represents the demand for energy in county i: it is given by the total regional electric demand d_T^* , specified by the regional scenario, and the fraction of that total regional demand assigned to county i, f_i . The determination of the f_i is discussed elsewhere.¹⁵

c. Fuel Mix Constraints

For each fuel type, the reference energy system scenario specifies some level of annual fuel use r_k^* , in 10^{15} Btu/yr. If r_{ik} is the fuel use of type k in county i, we have k constraints of the type:

$$\sum_{i=1}^n r_{ik} = r_k^* \quad k=1, \dots, k \quad (7)$$

d. Relationship between Capacity and Generation

If the heat rate of the k-th generation type is ρ_k , and the annual plant capacity factor is δ_k , then

$$r_{ki} = x_i^k \delta_k 8760 \rho_k 10^6 \frac{1}{10^{15}} \quad (8)$$

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right] \left[\text{Gw} \right] \left[\frac{\text{hrs}}{\text{year}} \right] \left[\frac{\text{Btu}}{\text{Kwh}} \right] \left[\frac{\text{Kw}}{\text{Gw}} \right] \left[\frac{\text{Btu}^{15}}{\text{Btu}} \right]$$

$$r_{ik} = x_i^k h_k \quad (9)$$

$$\text{where } h_k = \delta_k 8760 \rho_k 10^6 \frac{1}{10^{15}} \quad (10)$$

Thus one may rewrite constraint (6) as

$$\sum_{k=1}^K x_i^k 8760 \delta_k - \sum y_{ij} + \sum y_{ji} (1 - \Omega \delta_{ij}) = d_T^* f_i \quad (11)$$

and constraint (9) as

$$\sum_{i=1}^n x_i^k = r_k^* / h_k \quad (12)$$

thereby eliminating the use of the r_{ki} variables¹⁶

Notice that in (12), we have moved the h_k into the right hand side of the constraint. This is because post-optimality analysis of the LP solution for variations in the RHS coefficients is considerably easier than for variations in the LHS of the constraints.

Finally, by use of Eq. (2), we can also eliminate the y_{ij} in (11); which, if (2) is substituted in (11), can be written in the form

$$\sum_{k=1}^K x_i^k 8760 \delta_k - \sum_{\substack{j=1 \\ j \neq i}}^n y_{ij} 8760 \pi + \sum_{\substack{j=1 \\ j \neq i}}^n y_{ji} 8760 \pi (1 - \Omega \delta_{ji}) = d_T^* f_i$$

or

$$\sum_{k=1}^K x_i^k \delta_k - \pi \sum_{\substack{j=1 \\ j \neq i}}^n y_{ij} + \pi \sum_{\substack{j=1 \\ j \neq i}}^n y_{ji} (1 - \Omega \delta_{ji}) = \frac{d_T^* f_i}{8760} \quad (13)$$

3.3 The Interface to the Reference Energy System

Even though the preceeding model formulation is based directly on Reference Energy System Information, the results generated by the model may not be consistent with the RES. There are a number of reasons for this, some of which are discussed in later sections of this report (especially Section 4.5). The most important discrepancy to be resolved at this point, however, concerns transmission losses. The RES assumes that the energy loss in transmission and distribution is 10%, and the RES mass balance of Btu's in the electric sector is defined on this basis. However, the transmission losses of our model compute to

$$\sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n y_{ij} (1 - \Omega \delta_{ij}) \quad (14)$$

or

$$\sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n 8760 \pi Y_{ij} (1 - \Omega \delta_{ij}) \quad (15)$$

a quantity that is unlikely to be exactly equal to $0.1 d_T^*$ as specified by the RES. Obviously, if one wishes to be assured of a feasible solution to the LP, one must choose between using d_T^* or the r_k^* as an input to the model, and let the other be computed according to transmission losses by the model. For reasons which will be apparent later, we shall elect to use d_T^* as the input, and have the model compute the resource use for each generation type, given the generation mix as specified by the RES.

In other words, we must replace (9) with

$$\sum_{i=1}^n r_{ki} - g_k^* R' = 0 ; \quad k=1, \dots, K \quad (16)$$

FIGURE 1: ELECTRIC SECTOR REPRESENTATION IN THE TYPICAL REFERENCE ENERGY SYSTEM

where R' denotes the total resource use as computed by the model. g_k^* is the fraction of total resource use in the k -th generation type, given by

$$g_k^* = \frac{r_k^*}{R^*} \quad (17)$$

where r_k^* and R^* are taken directly from the RES (See Figure 1). Making the now usual conversion to capacity variables, (16) can be written as

$$\sum_{i=1}^n x_i^k h_k - g_k^* R' = 0 ; \quad k=1, \dots, K \quad (18)$$

3.4 Reserve Margins

In addition to meeting energy mass balance for each county, the system as a whole must meet certain reliability criteria. In particular, reserve margin requirements must be met. The reserve margin μ is defined by

$$(1 + \mu) = \frac{\text{System Capacity}}{\text{Peak System Load}} \quad (19)$$

hence

$$(1 + \mu) \leq \frac{\sum_{k=1}^K \sum_{i=1}^n x_i^k}{\frac{d_T^*}{\text{SLF 8760}}} \quad (20)$$

or

$$\sum_{k=1}^K \sum_{i=1}^n x_i^k \geq (1 + \mu) \frac{d_T^*}{\text{SLF 8760}} \quad (21)$$

3.4 Summary of the Basic Model

A summary of the model as discussed thus far may be useful at this point:

$$\text{Minimize} \quad \sum C_i \beta_i \gamma_{Ei} + \sum \sum C_{ij} \delta_{ij} \gamma_T + \sum \sum Y_{ij} \delta_{ij} k_2$$

(Objective Function)

Subject to the Constraints:

$$C_i + \sum C_{ji} - \sum C_{ij} - X_i^k h_i = 0; i=1, \dots, n$$

(Coal Mass Balance)

$$\sum_{k=1}^K X_i^k \delta_k - \pi \sum Y_{ij} + \pi \sum Y_{ji} (1 - \Omega \delta_{ij}) = \frac{d_{Tf_i}^*}{8760}; i=1, \dots, n$$

(Energy Balance)

$$\sum_{k=1}^K \sum_{i=1}^n X_i^k \geq (1 + \mu) \frac{d_T^*}{8760 \text{ SLF}}$$

(Reserve Margin)

$$\sum X_i^k h_k - g_k^* R' = 0; k=1, \dots, K$$

(Fuel Mix-Capacity Constraints)

and the usual non-negativity conditions

(22)

$$X_i^k, Y_{ij}, C_{ij}, C_i \geq 0$$

Note that we have $2n+K+1$ constraints and $2n(n-1)+n+nk+1$ variables, which, for the PJM power pool that comprises about 100 counties, and with $K=5$, would result in 206 constraints and 20401 variables.

This number of variables is of course quite excessive, although the number of constraints is quite manageable, and well within the bounds of computation time and cost set as one of the model development criteria.

However, as we shall note in the following section, in the typical problem a large number of the variables would in fact be omitted. Also, the above assumes that there will be $n(n-1)$ terms in Y_{ij} ; however, because the transmission portion of the problem is treated as a transshipment problem, transmission interconnections are allowed only for adjacent counties, and thus the typical number of Y_{ij} variables would be on the order of $4n$ rather than n^2-n , resulting in the elimination of a further number of the possible variables. Finally, the above estimates assume that each county is a potential source of coal; in the Northeast, only the PJM Power Pool has any significant coal resources within its territory, and even here perhaps less than 50% of the total number of counties would in fact be entered as coal sources. Thus, taking into account these provisos, a more realistic estimate of the number of variables for the 100 county PJM problem is in the order of 2800, which is quite reasonable.

4. SITING CONSTRAINTS

4.1 Seismic Risk Constraints on Nuclear Capacity

Seismic Risk can be incorporated as an exclusionary constraint on nuclear capacity by deleting variables. If S is the set of counties barred to nuclear capacity, then we simply delete all

$$X_i^N \text{ for } i \in S \quad (23)$$

These variables are then not available for entry into the optimal solution.

The other alternative would be to add constraints of the form

$$X_i^N = 0 \text{ for } i \in S$$

but this procedure would needlessly expand the problem size.

4.2 Population Density Constraints on Nuclear Capacity

If Q is the set of counties barred to nuclear capacity on grounds of population density, we again delete all

$$X_i^N \text{ for } i \in Q \quad (24)$$

4.3 Consumptive Water Use Constraints

Consumptive water use constraints can be handled both on a county and a River Basin basis. Let S_ℓ be the set of counties in the ℓ -th river basin, and let U_N be the consumptive use per Gw of Nuclear Capacity, and U_F the consumptive use per Gw of fossil capacity. Then if the total maximum allowable consumptive use for power generation is U_ℓ^T , we have constraints of the form:

$$U_N \sum_{i \in S_\ell} X_i^N + U_F \sum_{i \in S_\ell} X_i^C + U_F \sum_{i \in S_\ell} X_i^O \leq U_\ell^T; \ell=1, \dots, L \quad (25)$$

At the county level, total consumptive use may also be constrained to a fraction f_w of the available low flow, h_i

$$U_N X_i^N + U_F X_i^C + U_F X_i^0 \leq f_w h_i; i=1, \dots, n \quad (26)$$

or, in the even that a river is the boundary between two or more counties, (which is often the case), say the counties S,

$$U_N \sum_{i \in S} X_i^N + U_F \sum_{i \in S} X_i^C + U_F \sum_{i \in S} X_i^0 \leq f_w h_i \quad (27)$$

The consumptive use constraints of the form (25)-(27) may, of course, be too restrictive, since two methods can be used to get around such limitations. The first is by low flow augmentation, which requires construction of a reservoir. The second is by the use of dry cooling (assuming, of course, that once-through cooling in inland & estuarine areas continues to be precluded).

Introducing the new variables

A_ℓ = Low flow augmentation reservoir capacity, in 1000 acre-ft, in the ℓ -th river basin.

$D_{\ell r}, D_{\ell f}$ = Gw of dry cooled nuclear & fossil, respectively, in the ℓ -th river basin

$\frac{1}{\theta_\ell}$ = 1000 Acre foot of storage required to develop an additional cfs of low flow, in the ℓ -th river basin (in the Delaware, for example, θ is about .420 1000AF/cfs).¹⁷

Then (25) may be rewritten as

$$U_N \sum_{i \in S_\ell} X_i^N + U_F \sum_{i \in S_\ell} X_i^C + U_F \sum_{i \in S_\ell} X_i^0 - \theta_\ell A_\ell - D_{\ell n} U_N - D_{\ell f} U_F \leq U_\ell^T \quad (28)$$

with the additional restrictions that

$$\sum_{i \in S_\ell} x_i^N - D_{\ell n} \geq 0 ; \ell=1, \dots, L \quad (29)$$

$$\sum_{i \in S_\ell} x_i^C + \sum_{i \in S_\ell} x_i^O - D_{\ell f} \geq 0 ; \ell=1, \dots, L \quad (30)$$

And the objective function requires the addition of two further terms, namely

$$CRF \sum_{\ell=1}^L A_\ell Z_{R\ell} + \sum_{\ell}^L (D_{\ell n} P_N + D_{\ell f} P_F) \quad (31)$$

Cost of Reservoir Capacity Penalty for Dry Cooling

where $Z_{R\ell}$ is the cost per unit of reservoir capacity, in \$/1000 AF (for which estimates are available, by river basin, from U.S. Corps of Engineers Studies).¹⁸

P_N is the cost of dry cooling at nuclear stations (see below, Section 4.5).

P_F is the cost of dry cooling at fossil stations (see below, Section 4.5).

Notice that this allows a fairly accurate simulation of reality. In the Delaware River Basin, for example, under current conditions and policy, there can be no consumptive withdrawals without offsetting storage, and thus we would simply set $u_\ell^T \equiv 0$. Also, if one wanted to examine the impact of not allowing low-flow augmentation reservoirs¹⁹ in a particular river basin (or basins), one would simply delete the appropriate A_ℓ variable(s). Alternatively, one can limit the amount of low-flow augmentation by addition of constraints of the form

$$A_\ell \leq A_\ell(\max) \quad (32)$$

4.4 Consumptive Use in Estuaries

Special conditions may apply to thermal plants in estuaries in respect to consumptive water use. In particular, as the location of a plant moves further toward the ocean, the amount of low flow augmentation to be

provided upstream becomes less. For example, the Hope Creek nuclear plant, located in Salem County about midway between the start of the Delaware estuary (at Trenton) and the Ocean, has been required by the Delaware River Basin Commission to provide low flow augmentation in the amount of 18% of what it would have had to provide if it had been located further upstream near Trenton.²⁰

Eq. (28) can readily be modified to account for this special condition. If we define the set of estuarine counties in the ℓ -th river basin as E_ℓ , then (28) can be reformulated as²¹

$$\begin{aligned} & U_N \sum_{i \in S_\ell - E_\ell} X_i^N + U_F \sum_{i \in S_\ell - E_\ell} X_i^C + U_F \sum_{i \in S_\ell - E_\ell} X_i^N - \theta_\ell A_\ell - D_{\ell n} U_N - D_{\ell f} U_F \\ & + U_N \sum_{i \in E_\ell} X_i^N t_i + U_F \sum_{i \in E_\ell} X_i^C t_i + U_F \sum_{i \in E_\ell} X_i^O t_i \leq u_\ell^T \end{aligned} \quad (33)$$

where t_i is the reduction in requisite flow augmentation applicable to the i -th county; hence the product $U_N \cdot t_i$ is the consumptive use of freshwater in county i . t_i for Salem county would thus be .18.

If we define $t_i = 1$ for all $i \in S_\ell - E_\ell$, then we may rewrite (33) as

$$\begin{aligned} & U_N \sum_{i \in S_\ell} t_i X_i^N + U_F \sum_{i \in S_\ell} t_i X_i^C + U_F \sum_{i \in S_\ell} X_i^O t_i - \theta_\ell A_\ell - D_{\ell n} U_N - D_{\ell p} U_F \\ & \leq u_\ell^T; \ell=1, \dots, L \end{aligned} \quad (34)$$

4.5 Penalties for Evaporative and Dry Cooling Systems

Both evaporatively cooled and dry-cooled thermal facilities impose significant additional costs to electric generation. To the extent that the model allows an examination of the trade-off between cooling mode and location, any cost penalty over once-through cooling should also be

captured in the objective function. Once-through cooling, although currently precluded in Inland waters, is an allowable option for off-shore and possibly even some coastal facilities.

Because consumptive use constraints are handled on a river basin basis, we shall introduce the following new variables

E_{ln} = Gw of Evaporatively cooled nuclear capacity in the l -th river basin

E_{lF} = Gw of Evaporatively cooled fossil capacity in the l -th river basin

D_{ln} = Gw of Dry cooled nuclear capacity in the l -th river basin

D_{lF} = Gw of Dry cooled fossil capacity in the l -th river basin

plus the penalty coefficients:

P_{en} = Penalty, in \$/yr/Gw of evaporative nuclear

P_{ef} = Penalty, in \$/yr/Gw of evaporative fossil

P_{dn} = Penalty, in \$/yr/Gw of dry nuclear

P_{df} = Penalty, in \$/yr/Gw of dry fossil

A number of factors must be considered in deriving the appropriate penalty costs.²² First, a plant of, say, 1200 Mw cooled by once-through would have lower design capacity if cooled by wet or dry towers, say $D_{o,k}$ for a plant of type k , cooled by towers of type o . But, further, the operation of the towers themselves requires diversion of some of that design capacity, say $P_{o,k}$. Thus the net plant send-out, available to meet the electric demands of consumers, is only $N_{o,k} = D_{o,k} - P_{o,k}$, as illustrated on Figure 2.

FIGURE 2: DEFINITION CF NET OUTPUT

If the Net Plant capability for a nominally sized 1200 Mw plant of type k, cooled by towers of type 0 is N_c , then for 1 Gw of net output the nominal plant size is

$$\frac{1200}{N_{o,k}}$$

Hence the capacity penalty in KW, is

$$\left(\frac{1200}{N_{o,k}} - 1 \right) 10^6$$

If the capital cost per KW of capacity of type k is $\bar{C}_k$, then the annual penalty cost is given by

$$\left(\frac{1200}{N_{o,k}} - 1 \right) 10^6 \cdot \bar{C}_k \cdot \text{CRF} \quad (35)$$

Also if the capital cost for cooling system construction of type 0 at a facility of type k is given by $\bar{C}_{o,k}$ \$/KW of design capacity then the cost per Gw of net output is

$$\bar{C}_{o,k} 10^6 \text{ CRF } \frac{1200}{D_{o,k}} \left[\frac{\$}{\text{Kw}} \right] \left[\frac{\text{Kw}}{\text{Gw}} \right] \left[\frac{\$}{\text{yr}} \right] \left[\frac{\text{Gw}}{\text{Gw}} \right] \quad (36)$$

Hence the total penalty cost is the summation of (35) and (36), namely,

$$P_{o,k} = \text{CRF } 10^6 \left\{ \frac{1200}{D_{o,k}} \bar{C}_{o,k} + \left(\frac{1200}{N_{o,k}} - 1 \right) \bar{C}_k \right\} \quad (37)$$

The necessary cost estimates to allow computation of (37) are available from a number of sources. Table 1 shows a compilation of values of $D_{o,k}$, $P_{o,k}$ and $N_{o,k}$ for a variety of cooling alternatives for a 1200 Mw nuclear plant, taken from a recent NRC study. Construction costs for nuclear and

TABLE 1: POWER PENALTY DUE TO COOLING SYSTEM^a

	Once-through	Evaporative			Dry Cooling	
		Mechanical draft	Natural draft	Pond	Mechanical draft	Natural draft
1. Plant capability, at design, Mw ($D_{0,N}$)	1200	1177	1170	1159	1022	1029
2. Pumping power requirement, Mw	4.8	9.5	10.2	6.5	5.1	5.5
3. Fan power requirement, Mw	0.0	5.0	-	-	21.6	-
4. Total power requirement, ($P_{0,N}$)	4.8	14.5	10.2	6.5	26.7	5.5
5. Net plant capability, Mw ($N_{0,N}$)	1195.2	1162.5	1159.8	1152.5	995.3	1023.5

^aBased on data in NRC NECSS, Pt. III, Table 3.4

TABLE 2:

INCREMENTAL CAPITAL COSTS OF CLOSED CYCLE COOLING SYSTEMS OVER
ONCE-THROUGH COST^a

<u>Cooling System Type</u>		$\bar{C}_{O,F}$ \$/Kw ^c <u>Fossil</u>	$\bar{C}_{O,N}$ \$/Kw ^c <u>Nuclear</u>
Once-through with offshore subaqueous discharge ^b		3.00	4.70
Evaporative	Mechanical Draft	4.35	6.50
	Natural Draft	7.25	11.60
	Cooling Pond	5.50	7.80
Dry	Mechanical Draft	28.90	45.10

^aSource: Booz, Allen and Hamilton "Decision Guidelines for Power Facility Siting in New England" Nov. 1975, p. 621.

^bi.e. with multi-port diffuser system on the ocean bed

^cKw of design capacity

coal capacity can be obtained from power pool planning reports, in absence of which a number of national average estimates can be used.²³ Table 2 shows the values of $\bar{C}_{O,k}$ used for the NEPOOL simulations.

Finally, we must modify constraints (29) and (30), since in fact the slack variables of those two inequalities equal the evaporative cooling variables E_{ln} , E_{lf} , and (29) and (30) should be written

$$\sum_{i \in S_l} x_i^n - D_{ln} - E_{ln} = 0 \quad (36)$$

$$\sum_{i \in S_l} x_i^c + \sum_{i \in S_l} x_i^o - D_{lf} - E_{lf} = 0 \quad (37)$$

4.6 Interbasin Water Transfers

Interbasin water transfers are readily incorporated into the model. Let $q_{i,j}$ be the quantity of water, in cfs, transferred from county i to county j , where i and j are assumed to be in different river basins. Since the objective of such a transfer in the problem context is the augmentation of low flow for consumptive cooling use, the possibility of an interbasin transfer can be included by a further addition to the constraint set (16), namely,

$$\begin{aligned}
 & U_N \sum_{i \in S} x_i^N + U_F \sum_{i \in S} x_i^C + U_F \sum_{i \in S} x_i^0 - \theta_{\ell} A_{\ell} - \sum_{\substack{i \in S \\ j \notin S}} q_{ji} \\
 & \quad \text{Consumptive use in the} \quad \quad \quad \text{Low Flow} \quad \quad \quad \text{cfs imported} \\
 & \quad \quad \quad \ell\text{-th river basin} \quad \quad \quad \text{augmentation in} \quad \quad \quad \text{from other} \\
 & \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{the } \ell\text{-th basin} \quad \quad \quad \text{basins} \\
 & + \sum_{\substack{i \in S \\ j \notin S}} q_{ij} - D_{\ell n} U_N - D_{\ell f} U_F \leq u_{\ell}^T \quad (40) \\
 & \quad \quad \quad \text{cfs exported} \quad \quad \quad \text{dry cooling} \\
 & \quad \quad \quad \text{to other basins}
 \end{aligned}$$

The objective function also needs to be extended to include a set of terms expressing the cost of inter basin transfer, namely

$$\sum_{i=1}^n \sum_{j=1}^n q_{ij} \delta_{ij} \lambda \quad (41)$$

where λ is the cost of transporting water, in \$/cfs/mi

Clearly, in any given run of the extended model, inter-basin transfers can be precluded by simply deleting all the $q_{i,j}$ variables, in the manner of treating seismic and population density exclusions (see Sections 4.1 and 4.2)

4.7 Off-Shore Siting

Offshore siting is readily incorporated into the model by defining a set of offshore "counties" such that there is one offshore county for each coastal onshore county, as indicated on Figure 3. If the set of such counties is denoted O , then runs of the extended siting model for which we do not wish to allow off-shore siting is attained by deletion of

$$x_i^N \text{ for all } i \in O \text{ and/or } x_i^C \text{ for all } i \in O \quad (42)$$

which once again would then not be available for entry into the solution basis.

4.8 Coal Imports

Thus far we have assumed that all coal used in a region is also mined in the same region, with no imports from other regions (as indicated by Eq. (5)). However, the RES (or RESOM) scenarios fully encompass inter-regional coal shipments, which can readily be included in the siting model. Let the quantity of coal shipped from Region ρ to the region of interest be C_{ρ}^* . Also, let the set of counties through which imported coal from the ρ -th import source would need to enter the region be denoted ε_{ρ} ; these are the counties on the border of the study region closest to their respective sources (or "Gateway Counties"). In effect, coal imported into one of the gateway counties is then available for transportation to all of the other counties in the region in the same way as coal mined in the gateway counties. However, since it is necessary to keep track of the quality and Btu content of each coal shipment, the distinction between coal mined, and coal imported in the gateway counties must be maintained (e.g. coal mined in a particular gateway county might be high-sulfur, but imports from the West entering into that same county for subsequent distribution in the region may be low-sulfur). A convenient way of maintaining this distinction is by the addition of "dummy" counties, one for each gateway county, which are available only as sources of coal, not as locations of facilities. Thus, for each set of gateway counties ε_{ρ} , one defines a set of dummy counties ε_{ρ}' , as illustrated on Figure 4. The total number of dummy counties is denoted e .

FIGURE 3: Offshore Counties

FIGURE 4: COAL IMPORTS

One then needs to add the further constraint set

$$\sum_{i \in I_p'} \sum_{j=1}^n C_{ij} = C_p^* ; \quad p=1, \dots, P$$

In addition, the index of summation for the coal import term of constraint (5) must be changed from n to $n+e$, hence

$$C_i + \sum_{\substack{j=1 \\ j \neq i}}^{n+e} C_{ji} - \sum_{\substack{j=1 \\ j \neq i}}^n C_{ij} - r_{Ci} = 0 ; \quad i=1, \dots, n$$

4.9 Emission Controls

If the sulfur in coal is assumed to be converted to SO_2 in stoichiometric proportions, namely

then 1.998 lbs of SO_2 will be formed per lb. of sulfur in the coal. Thus, if the sulfur content is σ , then the SO_2 production is 3996σ lb/ton. For a typically Northern Appalachian Bituminous coal of 27.22×10^6 Btu/ton,²⁴ SO_2 production would be 146.8σ lb/ 10^6 Btu. The new federal source performance standard for SO_2 emissions from new coal fired plants is 1.2 lb/ 10^6 Btu, from which we note that the maximum sulfur content that can be burned under the current standard (and under the above assumptions) without any control is $1.2/146.8 = 0.00817$, or 0.8% S by weight.

It follows that if the removal performance of the control technology applied is χ , then the SO_2 emitted is given by

$$1,998 \quad 2000 \quad \sigma \quad \beta \quad (1 - \chi) \quad \frac{1}{10^9} \leq \xi \quad (44)$$

$$\left[\frac{\text{lbSO}_2}{\text{lb S}} \right] \left[\frac{\text{lb}}{\text{ton}} \right] \left[\frac{\text{lbS}}{\text{lb}} \right] \left[\frac{\text{ton}}{10^{15} \text{Btu}} \right] \left[\right] \left[\frac{10^{15} \text{Btu}}{10^6 \text{Btu}} \right] \left[\frac{\text{lbSO}_2}{10^6 \text{Btu}} \right]$$

The new source performance standard, however, may vary from county to county, according to the particular requirements of State Implementation Plans;²⁵ moreover, since coal burned in any county may come from a variety of sources, one needs to apply (44) to a weighted average of coal burned in each county i , namely

$$\frac{\sum_{\substack{j=1 \\ j \neq i}}^{n+e} C_{ji} 3996 \beta_j \sigma_j (1-\chi_i) + (1-\chi_i) 3996 \beta_i \sigma_i \left\{ C_i - \sum_{j=1}^n C_{ij} \right\}}{10^9 \left\{ \sum_{\substack{j=1 \\ j \neq i}}^{n+e} C_{ji} + C_i - \sum_{j=1}^n C_{ij} \right\}} \leq \xi_i \quad (45)$$

which can be rewritten as

$$\begin{aligned} & 3996 (1-\chi_i) \sum_{j=1}^{n+e} C_{ji} \beta_j \sigma_j + 3996 (1-\chi_i) \beta_i \sigma_i C_i - 3996 (1-\chi_i) \beta_i \sigma_i \sum_{\substack{j=1 \\ j \neq i}}^n C_{ij} \\ & \leq \xi_i 10^9 \sum_{\substack{j=1 \\ j \neq i}}^{n+e} C_{ji} + \xi_i 10^9 C_i - \xi_i 10^9 \sum_{\substack{j=1 \\ j \neq i}}^n C_{ij} \end{aligned}$$

or

$$\begin{aligned} & \sum_{j=1}^{n+e} C_{ji} \left\{ 3996 (1-\chi_i) \beta_j \sigma_j - 10^9 \xi_i \right\} + C_i \left\{ 3996 (1-\chi_i) \beta_i \sigma_i - 10^9 \xi_i \right\} \\ & - \sum_{\substack{j=1 \\ j \neq i}}^n C_{ij} \left\{ 3996 (1-\chi_i) \beta_i \sigma_i - 10^9 \xi_i \right\} \leq 0 \quad (46) \end{aligned}$$

Defining $e_i = 3996 (1-\chi_i) \beta_i \sigma_i - 10^9 \xi_i$

$$e_{ij} = 3996 (1-\chi_i) \beta_j \sigma_j - 10^9 \xi_i$$

we obtain, finally, the constraint

$$\sum_{\substack{j=1 \\ j \neq i}}^{n+e} c_{ji} e_{ij} + c_i e_i - \sum_{\substack{j=1 \\ j \neq i}}^n c_{ij} e_i \leq 0 \quad (47)$$

4.10 Land Use Constraints

Counties may be ineligible for all categories of facilities on a number of grounds not already noted under 4.1 and 4.2. Such reasons may include

- State and Federal Lands
- Endangered Species
- Prohibitory Legislation

Such restrictions are again simply handled by deletion of all capacity variables for the set of such counties, say W: that is,

$$\text{delete all } X_i^k, k=1, \dots, K \text{ for } i \in W \quad (48)$$

4.11 Coal Reserves

If the coal reserves, in 10^6 tons, of county i are denoted by R_i , then if the planning horizon is M years, the annual rate of coal extraction in county i, C_i , is bounded by the equation

$$C_i \leq R_i \frac{1}{M} \frac{1}{\beta_i} 10^6$$

$$\left[\frac{\text{Btu}^{15}}{\text{yr}} \right] \left[10^6 \text{ tons} \right] \left[\frac{1}{\text{yrs}} \right] \left[\frac{\text{Btu}^{15}}{\text{tons}} \right] \left[\frac{\text{tons}}{10^6 \text{ tons}} \right] \quad (49)$$

We are currently formulating a more sophisticated treatment of extraction constraints resting on existing production rates, a parametric analysis of the ability to open new mines (and hence possible future maximum extraction rates), and the degree to which coal is preempted by metallurgical uses.

4.12 Existing Facilities

In applying the model to a real situation, cognizance must of course be paid to existing capacity. Thus, for example, in a model run for the year 2000, some part of the necessary capacity is already in place, or would be in place by, say, 1985. In effect, then, one must constrain some of the X_{ik} to at least their 1985 values (minus any planned or likely retirements between 1985 and 2000). This is accomplished by adding a series of constraints of the type

$$X_{ik} \geq \bar{X}_{ik} - R_{ik} \text{ for any } \bar{X}_{ik} > 0 \quad (50)$$

where $\bar{X}_{ik}$ is the installed capacity of type k in county i in the preceding scenario year

R_{ik} are the capacity retirements of type k in county i in the interval between the preceding scenario year and the year of the model run

Thus, for the 2000 model run, the $\bar{X}_{ik}$, R_{ik} refer to 1985 and the 1985-2000 interval, respectively; and for the 2020 model run, to 2000 and the interval 2000-2020.

Similarly, for existing transmission links, we add bounds of the form

$$Y_{ij} \geq \bar{Y}_{ij} \text{ for any } \bar{Y}_{ij} > 0 \quad (51)$$

But since capital costs of new transmission facilities are considered in the objective function (as opposed to generating costs), an adjustment must be made to the transmission cost term, and Eq. (4) must be replaced by

$$\begin{aligned} \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} \delta_{ij} 8760 \pi \tau_E 10^6 \Omega \\ + \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^n \left(Y_{ij} - \bar{Y}_{ij} \right) \tau_C \delta_{ij} \text{ CRF} \end{aligned} \quad (52)$$

Thus, in the event that $Y_{ij} = \bar{Y}_{ij}$ (an existing link being adequate in capacity), no capital costs are incurred, and only energy losses are included in the objective functions. And if $Y_{ij} > \bar{Y}_{ij}$, then Eq. (52) assures that only the incremental expansion costs are included in the optimization.

4.13 Coal Characteristics

Thus far we have assumed that the coal in each coal burning county is of uniform sulfur, ash and heat content. Clearly that may not always be true (in fact it is rarely the case). If the i -th county has ρ major coal types, then for each county for which $\rho > 1$, one can add $\rho - 1$ dummy counties, which serve only as coal sources. Thus the coal mass balance constraint set (5) must be rewritten

$$\sum_{k=1}^{\rho} C_{ik} + \sum_{\substack{j=1 \\ j \neq i}}^n \sum_{k=1}^{\rho} C_{jik} - \sum_{\substack{j=1 \\ j \neq i}}^n \sum_{k=1}^{\rho} C_{ijk} - r_{Ci} = 0 \quad (53)$$

Coal mined Coal imports Coal exports Coal Burned

where C_{ik} is the k -th type of coal mined in county i

C_{ijk} is the coal of type k transported from i to j

4.14 Pumped Storage

The addition of pumped storage as a generation type requires extension only to the electric energy constraint (Eq. 13), which requires the following redefinition

$$\sum_{\substack{k=1 \\ k \neq 6}}^K X_i^k \delta_K - \pi \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} + \pi \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ji} (1 - \Omega \delta_{ji})$$

non pumped Exports Imports
storage generation

$$- \frac{1}{E_p} X_i^6 \delta_6 + X_i^6 \delta_6 = \frac{d_T^* f_i}{8760} \quad (54)$$

pumping pumped demand
energy storage
generation

where ϵ_ρ is the overall efficiency of pumped storage.

Hence

$$\sum_{\substack{k=1 \\ k \neq 6}}^K x_i^k \delta_K - \pi \sum_{\substack{j=1 \\ j \neq i}}^n y_{ij} + \pi \sum_{\substack{j=1 \\ j \neq i}}^n y_{ji} \left(1 - \Omega \delta_{ji} \right) + \left(1 - \frac{1}{\epsilon_\rho} \right) x_i^6 \delta_6 = \frac{d_T^* f_i}{8760} \quad (55)$$

Unless otherwise noted, we shall use $\epsilon_\rho = 0.61$, consistent with Lee.²⁶

5. THE TRANSMISSION SYSTEM

5.1 Demand and Transmission Load Factor Constraints

In section 3.2 we made the rather sweeping assumption of a constant load factor for all transmission links, and were thus able to relate the y_{ij} to the Y_{ij} by a simple linear expression (Eq. 2), resulting in the elimination of the Y_{ij} variables. A more rigorous treatment of the relationship between y_{ij} and Y_{ij} would recognize that the load factor is not a constant, but will vary according to the particular circumstances. In fact, the relationship between the two variables should be stated as

$$y_{ij} \frac{1}{8760} \leq Y_{ij} \quad \text{for all adjacent } i,j \quad (56)$$

$$\left[\frac{\text{Gwh}}{\text{yr}} \right] \quad \left[\frac{\text{year}}{\text{hr}} \right] \quad \left[\text{Gw} \right]$$

or

$$\frac{y_{ij}}{8760} - Y_{ij} \leq 0 \quad \text{for all adjacent } i,j \quad (57)$$

From which it follows that the load factor for a transmission line is given by

$$\pi_{ij} = \frac{y_{ij}}{8760 Y_{ij}} \quad (58)$$

One should note that for a 100-county problem, we have added, typically, 400 Y_{ij} variables, and 400 additional constraints corresponding to Eq. (57). One should also recognize that the combination of energy losses and capital costs for transmission into a single objective function coefficient is no longer permissible (recall Eq. 2,3, and 4); and in fact one would revert to the original statement of objective function coefficients for the transmission terms as given in Eq.(1).

It should be obvious, however, that the distinction between y_{ij} and Y_{ij} , as captured in Eq.(56), makes sense only if explicit consideration is given to peak demands. More particularly, if there is no other constraint on the Y_{ij} , then one can be sure that Eq.(57) will be satisfied as an equality in all cases, as any excess capacity would imply a higher than necessary capital cost. Consequently, we must add the following peak demand constraint for each county:

$$\begin{array}{ccccccc}
 - \sum Y_{ij} & + & \sum Y_{ji} & + & \sum X_i^k \alpha^k & = & D_i \\
 \text{Power} & & \text{Power} & & \text{Installed} & & \text{Peak} \\
 \text{Exports} & & \text{Imports} & & \text{Capacity} & & \text{Demand}
 \end{array} \quad (59)$$

where D_i is the peak demand in county i , in Gw, and α_k is the assumed availability of the k -th generating type in the peak period. If the SLF denotes the system load factor, then the peak demand can be expressed in terms of the energy demand as

$$D_i = d_T^* \frac{1}{\text{SLF}} \frac{1}{8760} f_i \quad (60)$$

and thus Eq. (59) can be rewritten as

$$- \sum Y_{ij} + \sum Y_{ji} + \sum X_i^k \alpha^k = \frac{d_T^* f_i}{8760 \text{ SLF}} \quad (61)$$

This formulation, to be sure, assumes that there are no significant differences in demand shapes within the region, an assumption that does not appear too serious if the regions are no larger than power pools. We are currently working on an econometric analysis to make more rigorous estimates of peak demands at the county level, relating peak demands and power flows as yielded by A.C. Load flow analysis to estimates of population, industrial activity and socio-economic variables.

As of the time of writing, we have not fully explored the significance of these refinements, and thus a judgement as to whether the additional

computational effort is cost-effective is not yet possible. Moreover, it may well be that the additional refinement of a probabilistic statement of Eq.(61) will be necessary for a properly rigorous model of the electrical system performance, and work is currently underway to investigate the feasibility and necessity of reformulating the model in terms of the chance-constrained programming model of Charnes and Cooper.

5.2 Capacity determinations of Existing Lines

In section 4.12 we introduced bounds of the form

$$Y_{ij} \geq \bar{Y}_{ij} \text{ for any } \bar{Y}_{ij} > 0$$

where $\bar{Y}_{ij}$ is the existing capacity between i and j. If one examines the transmission grid map, however, there is no indication for a given link (i,j) as to whether power flows from i to j or j to i. Inspection of the load flow diagram would of course give an indication of the flow direction, but since the load flow analysis is available only for the existing year, imposition of additional transmission facilities (as calculated by the model for the scenario year) makes it quite likely that significant load flow changes will have occurred. Thus a flow from i to j in the existing year by no means assures a similar flow direction in the scenario year.

Fortunately, however, close inspection of the model formulation reveals a simple method for resolving this difficulty. In fact for a given node pair (i,j), only one of the two possible flow directions can be non-zero; thus if $Y_{ij} > 0$, $Y_{ji} = 0$; or if $Y_{ji} > 0$, $Y_{ij} = 0$. Non zero values of both Y_{ij} and Y_{ji} would imply a closed loop, which cannot occur. Thus in place of Eq. (51) we may write

$$Y_{ij} + Y_{ji} \geq \bar{Y}_{ij} \tag{62}$$

Since the slack in this equation is the incremental capacity required (in the event that $\bar{Y}_{ij}$ is inadequate), this can be written as

$$Y_{ij} + Y_{ji} - Y_{ij}^{(N)} = \bar{Y}_{ij} \quad (63)$$

where $Y_{ij}^{(N)}$ is the incremental transmission capacity to be constructed by the scenario year. The old objective function specification Eq. (52) must also be replaced by

$$\begin{aligned} & \sum_{i,j \notin E} \sum_{k \in E} Y_{ij} \delta_{ij} k_2 + \sum_{i,j \in E} Y_{ij} \delta_{ij} 8760 \pi \tau_E 10^6 \Omega \\ & + \sum_{i,j \in E} \sum_{k \in E} Y_{ij}^{(N)} \tau_c \delta_{ij} CRF \end{aligned}$$

where E is the set of (i,j) for which $\bar{Y}_{ij} > 0$.

It remains only to determine the numerical value of $\bar{Y}_{ij}$ from an inspection of the existing year transmission grid. Inspection readily yields the voltage and number of circuits crossing a county line. Then, armed with the standard surge impedance loading curve (see Figure 5), and the distance δ_{ij} between the two counties of interest, one can readily compute the total line loading between the two counties, yielding the requisite value of $\bar{Y}_{ij}$.

5.3 System Reserve

Addition of the demand constraints makes the old reserve margin constraint Eq. (21) redundant; recall that

$$\sum_i \sum_k X_i^k \geq (1 + \mu) \frac{d_T^*}{SLF \ 8760} \quad (21)$$

but the summation of the peak demand constraint set (61) yields

$$\sum_i \sum_k X_i^k \alpha^k = \frac{d_T^*}{SLF \ 8760}$$

Figure 5: Transmission Line Capability in Terms of Surge-Impedance Loading

hence from Eq. (19)

$$(\mu + 1) = \frac{\sum x^k}{\sum x^k \alpha^k}$$

from which it follows that μ is a direct function of the α_k chosen in Eq.(61).

Unless we have more specific information for a given power pool, we shall use the following values for α^k :³

k = 1	(coal)	$\alpha_k = .85$
k = 2	(oil)	= .85
k = 3	(Nuclear)	= .69
k = 4	(Gas Turbine)	= .80
k = 5	(Hydro)	= .96

Since the model will ensure that there is no serious imbalance between supply and demand (as currently exists, for example, in NEPOOL), computed reserve margins should lie in the 15 to 30 percent range if the above specifications are used. For example, using the 1974 generation mix for the New York Power Pool,⁵

x^1	=	3.26
x^2	=	12.57
x^3	=	1.95
x^4	=	3.63
x^5	=	5.03

μ computes to 17.5%, an eminently reasonable figure.

6. SAMPLE OUTPUT

To illustrate the application of the model to integrated assessment studies, we include here some siting scenarios excerpted from the siting analysis conducted for the National Coal Utilization Assessment.²⁸ A full discussion of the details of model application is presented elsewhere.²⁹

Figures 6 and 7 show two siting scenarios for the New York Power Pool. The base case (Figure 6) premised on a continuation of recent trends, including a 50/50 mix of nuclear and coal for baseload capacity additions, partial implementation of coal conversions under the Energy Supply and Environmental Coordination Act (ESECA), and retirement of old oil capacity at 45 years of age. The high coal electric (Figure 7) case is based on full ESECA implementation, accelerated retirement of oil capacity at 30 years of age (consistent with assumptions under implementation of the oil and gas replacement program of the National Energy Plan), and a 75/25 coal/nuclear mix for baseload additions. These scenarios are discussed more fully in the Coal Utilization Assessment Report.³⁰

One might note that the two scenarios shown exemplify a dispersed, load center siting strategy, since no exogenously specified constraints to force either clustering, mine-mouth (in this case further units in Pennsylvania to augment the already existing NYPP capacity at the Homer City Plant), or off-shore siting were imposed. We note the extensive use of Western coal for the high coal electric case (plants on Lake Erie), reflecting the fact that this particular scenario did not require Best Available Control Technology for SO₂ control on new plants, only the current New Source Performance Standard of 1.21 SO₂/10⁶ Btu.

Figure 6: NYPP Additions 1986-2000, Recent Trends

NOTES

1. See e.g. M. Kennedy "An Economic Model of the World Oil Market" Bell Journal of Economics and Management Science, 5,2 p. 540 (Autumn 74).
2. See e.g. A. Manne "ETA: A Model for Energy Technology Assessment" Bell Journal of Economics, 7,2 p. 379 (Autumn 76) or E. Hudson and D. Jorgenson "U.S. Energy Policy and Economic Growth" Bell Journal of Economics and Management Science, 5,2 p. 461 (Autumn 74).
3. See e.g. Batelle Pacific Northwest Laboratories, "Regional Analysis of the U.S. Electric Power Industry" BNWL-B-415, July 1975 or P.L. Joskow and M.L. Baughman "The Future of the U.S. Nuclear Energy Industry" Bell Journal of Economics, Vol. 7 No. 1, (Spring 1976). Both these studies used Reliability Council Regions as the spatial unit.
4. For discussion of the BNL-University of Illinois Model, see e.g. R. Tessmer et al, "Coupled Energy System--Economic Models and Strategic Planning" Comput and Ops. Res., Vol. 2, p. 213 (1975).
5. See especially P.F. Palmedo "The Incorporation of Environmental Considerations into Energy Policy Analysis" Presented at the AAAS meeting, Jan. 1975 (Published as BNL 19647, Brookhaven National Laboratory, Upton, New York 11967).
6. This is the basic philosophy of the Strategic Environmental Assessment System (SEAS) developed at EPA.
7. See e.g. M. Beller "Energy Systems Studies Program" BNL 50539, Brookhaven National Laboratory, Upton, New York 11967, June 1976.
8. Census regions are used in the Brookhaven Multiregional Energy Systems Model.
9. Reliability Council Regions are used, for example, in the Baughman-Joskow model (note 3, supra).
10. R. Goettle, E.A. Cherniavsky and R.G. Tessmer "An Integrated Multi-Regional Energy and Interindustry Model of the United States", San Francisco TMS/ORSA Joint National Meeting, May 1977.
11. R. Meyers and R. Cederwall "Fossil Pollutant Transport Model Development" P. Palmedo, Editor, in "BNL Regional Energy Studies Program, Annual Report FY 1975", BNL 50478, November 1975.
12. The Electric Power Research Institute (EPRI), in a recent project on regional siting methodologies with the Applied Physics Laboratory of Johns Hopkins University, calls its project not "siting" but "probable

distribution of effluent sources from energy supply and conversion", in order to avoid any misunderstanding concerning its objectives.

13. See e.g. R.L. Church and J.L. Cohon "A Multiobjective Location Model for Regional Energy Facility Siting" ORSA/TIMS Meeting, San Francisco, (May 1977) or, for a more complete exposition, BNL 50567, Brookhaven National Laboratory, Upton, New York.
14. It differs, therefore, to the model of G. Provenzano "Regional Analysis of the Impacts of Energy Production on the Development of Water Resources: A Mathematical Programming Approach", 1976 ORSA/TIMS National Meeting, Philadelphia, (April 1976).
15. National Coal Utilization Assessment Working Paper #4 "A Methodology for disaggregating electric demand to the county level", in preparation.
16. In a problem of, say, 100 counties with an average of 4 types of generation allowed in each county, the saving of 400 variables can be quite significant to computational efficiency.
17. See e.g. U.S. Corps of Engineers, North Atlantic Regional Water Resources Study, Appendix R, Water Supply, p. R-12.
18. Ibid.
19. In view of the demise of the Tocks Island Dam project in the Delaware River Basin, this would also be a not unreasonable subject for examination in the Northeast.
20. See P. Meier and D. Morell, "Issues in Clustered Nuclear Siting" BNL 50560, Chapter 3.
21. E_l is of course a subset of S_l ; the set of non-estuarine counties in the l -th river basin is thus given by $S_l - E_l$.
22. This method of approaching the cost penalties of closed cycle cooling systems in siting models was suggested by F. Moore in a series of unpublished memoranda to the BNL Regional Studies Program, available from the writer of this report.
23. M. Beller, Editor, "Sourcebook for Energy Assessment" BNL 50483, Dec. 1975, Table III-15, p. 56, gives national average values in 1974 dollars of \$520/Kw for nuclear LWR's and \$425/Kw for coal steam electric.
24. E. Rubin and O. Edelston, "The Pennsylvania Energy System", BNL 20782, p. 34.
25. Pennsylvania regulations for the Beaver Valley, Monogahela Valley and Allegheny County air basins are in the range of $0.6-1.0 \text{ lb SO}_2/10^6 \text{ Btu}$, more restrictive than the Federal standard.
26. Lee, "Energy Supply and Demand in the Northeast U.S." BNL 20427, Sept. 1975.

27. The 82 county NEPOOL model has 334 adjacent pairs of (i,j) , almost exactly equal to $4n$.
28. P. Meier, Ed., "A Preliminary Assessment of the Impacts of Increased Coal Utilization in the Northeast", Forthcoming Report, Policy Analysis Division, National Center for the Analysis of Energy Systems, Brookhaven National Laboratory, Upton, New York.
29. P. Meier, M. McCoy, and R. Stern, "County Level Siting Scenarios for Energy Policy Analysis; An Application to the Northeast" Forthcoming Report.
30. It should be noted that even though the maps shown depict the new capacity additions in terms of units of some standard size, the raw output of the LP indicates considerable variation, and we have rounded up and down accordingly. This, to be sure, violates the optimality of the LP solution, and begs the question of why a mixed-integer programming formulation was not used. However, for reasons elaborated earlier in this report, mixed-integer programming is too cumbersome and expensive for the extensive sensitivity analyses to be conducted; beyond which we show elsewhere that the rounding up and down procedure is quite permissible given the uncertainties of other assumptions of analysis.