Section 5

METHODOLOGY ISSUES

INTRODUCTION

When studying the feasibility of incorporating water resources constraints into existing energy models, a number of methodology issues surface. These issues relate to the structure of models, to the way in which the economy is represented by these models, and to a number of points specific to water resources constraints. The ensuing subsections amplify on these issues.

The actual incorporation of water resources constraints is done in a regionalized energy-economic model originally developed at the Brookhaven National Laboratory [Goettle, IV et al. 1977]; how it is to be done also is indicated in an energy model currently operative at the Lawrence Livermore Laboratory [Sussman 1978]. This work, including a comparison between the two models, appears at the end of this section.

The discussion of methodology issues involved in the incorporation of water resources constraints in energy models has an affirmative conclusion: indeed, it is shown how to perform this incorporation in the BNL regionalized energy-economy model, and how the LLL model may be modified to include water resources constraints. The operative conclusion regarding future work relates also to these models. The LLL model with its fully developed software can be used almost immediately for demonstrating the effects of water resources constraints on the energy sector within a dynamic setting. The BNL model, when its input-output submodel will be fully developed, has the capability of being an effective instrument for the evaluation of water resources constraints and their effect within an overall description of the U.S. economy at the regional level.

STRUCTURE OF MODELS

Regionalization

A recent assessment of U.S. water resources [U.S. Water Resources Council 1978a] indicates that the average supply aggregated over the entire country is approximately 1500 Maf/yr, while the total consumptive use requirements in the year 2000 are estimated at 170 Maf/yr. Out of the remaining 1330 Maf/yr of instream flows, the requirements for hydropower generation, navigation, recreation, maintenance of wildlife, etc., amount to 1170 Maf/yr. This indicates that, until the end of the century, there seems to be sufficient water to satisfy all projected requirements. This aggregation, however, masks the significant differences which exist between the various parts of the country regarding estimated supplies of water and projected demands. It follows, therefore, that, in order to integrate meaningful water resources constraints within existing energy models, such models should reflect regional differences.

In the process of regionalization, one can aggregate local units according to two alternative sets of criteria [Glasson 1974] so as to yield either

- formal regions -- geographical areas, each being homogeneous in terms of the defined criteria; or
- functional regions -- geographical areas, each displaying certain interdependence of its parts.

Most regionalized schemes delineate functional regions: such are the regions defined by the U.S. Bureau of Census; those in the National Coal Model [ICF 1976, 1977]; and the regions defined by electric utilities [Reardon 1975]. The U.S. Water Resources Council, on the other hand, delineates formal regions in terms of hydrological basins and subbasins. The integration of water resources constraints into existing energy models seems to require a regionalization scheme based on hydrological criteria. However, since most economic and social activities are seldom confined to the natural boundaries of a watershed, the definitions of hydrobasins should be adjusted for administrative boundaries.

A regionalized energy-economic model of the U.S. with the addition of water resources constraints can serve as a basis for a sequence of models with ever-increasing details at regional and local levels. These models could be related to each other by means of a hierarchical multilevel structure, such as shown in Figure 4-1, pg. 38, where a model at a lower hierarchical level covering a smaller geographical area but in greater detail becomes a component of the model at the next higher hierarchical level.

Regionalized National Models. The purpose of these models is to provide an instrument for assessing the degree at which water resources may be constraining energy-related activities at the regional level. The problem may be formulated in general [Haimes 1977] as follows. The i-th region $(i = 1, 2, \ldots, N)$ will have an objective function f_i which reflects the contribution of the regional outputs $\underline{y}_i$, inputs $\underline{u}_i$, decision variables $\underline{m}_i$, and parameters $\underline{\alpha}_i$. The influence of the other regions is indicated by

$$\underline{x}_i = \sum_{j=1}^{N} C_{ij}\, y_j \quad , \tag{3}$$

where C_{ij} is an interregional coupling element. Then

$$\underline{y}_i = h_i(\underline{x}_i, \underline{u}_i, \underline{m}_i, \underline{\alpha}_i) \ . \tag{4}$$

Also, operating constraints of the form

$$g_i(\underline{x}_i, \underline{u}_i, \underline{m}_i, \underline{\alpha}_i) \leq 0 \tag{5}$$

may be imposed. The general formulation of the regionalized model is

$$\begin{aligned} \text{optimize} \quad z &= \sum_{i=1}^{N} f_i(\underline{x}_i, \underline{u}_i, \underline{m}_i, \underline{\alpha}_i) \\ \text{subject to} \quad & g_i(\underline{x}_i, \underline{u}_i, \underline{m}_i, \underline{\alpha}_i) \leq 0 \ , \\ x_i &= \sum_{j=1}^{N} C_{ij}\, y_j \\ y_i &= h_i(\underline{x}_i, \underline{u}_i, \underline{m}_i, \underline{\alpha}_i) \ . \end{aligned} \tag{6}$$

A particular regionalized energy model which could be modified to incorporate water resources constraints considers the nine regions of the U.S. Bureau of Census [Goettle, IV et al. 1977] using a multiregional I-O model of 30 sectors linked with a multiregional detailed energy model.

Regional Models. The purpose of these models is to quantify the conflicting demands on finite regional water resources which may arise between energy-related processes and other activities (e.g., food production, irrigation, manufacturing, domestic uses). These conflicts will appear in various degrees and at different points in time, depending upon the availability and quality of regional water resources, the relative abundance of primary energy resources, on the level of development of the physical infrastructure, and on the socioeconomic environment. The importance of the regional models is that, because of the greater amount of detail which may be handled (as compared with national regionalized models, for example) without unduly increasing the computational load, it is possible to analyze water-related issues which are normally resolved both in the marketplace and in the political arena.

The only water-energy regional model published so far refers to the Upper Colorado River Basin [Morris 1977, 1978]. This is a static, one-period model in which a number of interrelated I-0 matrices are combined with a linear objective function to yield a linear programming formulation. The objective function is expressed as

$$\max \quad z = \sum_i c_h^i \, x_h^i \,, \tag{7}$$

where

x_h^i is the total gross output of the household sector of the i-th subregion;

c_h^i is a weight coefficient related to the total gross output of the household sector of the i-th subregion.

The regional economy is presented in matrix form, showing at the level of each of the three subregions in which the Upper Colorado River Basin is subdivided.

$$\begin{bmatrix} (I - A^1) & T^{12} & T^{13} \\ T^{21} & (I - A^2) & T^{23} \\ T^{31} & T^{32} & (I - A^3) \end{bmatrix} \cdot \begin{bmatrix} X^1 \\ X^2 \\ X^3 \end{bmatrix} \geq \begin{bmatrix} D^1 \\ D^2 \\ D^3 \end{bmatrix} . \tag{8}$$

Here

$(I - A^i)$ is the Leontief matrix of subregion i, $i = 1, 2, 3$;

T^{ij} is an $n \times n$ matrix of trade coefficients for trade of subregion i to subregion j;

X^i is a column vector of total gross outputs of each of n sectors in subregion i;

D^i is a column vector of minimum final demands for each sector in subregion i.

Subregional Models. These models are useful in screening energy-related alternatives within a geographical subregion, as conditioned by the availability of water resources. An example of such a model is an LP formulation for planning water resources and energy development in Illinois [Brill, Jr. et al. 1976]. In this model, two primary resources (coal and water) supply four categories of demand: coal demand (as coal, mainly for industry), gas, electricity, and water demand (municipal and industrial use). Gas manufacture and electric power generation require a mix of the primary resources. The location of the electric utilities and of the gasification plants has to minimize total transportation costs, and the costs of the resources and of the products (electricity and high-Btu gas). In this way, the model is useful for screening the subregion for locations where it may be desirable to establish large-scale energy facilities.

The parts of a regionalized model -- regions -- must perform a double task. On the one hand, regions are units of analysis of economic activities (production, consumption, transportation, capital formation, etc.). On the other hand, regions may be defined so as to be units of analysis of resources involved in the economic evaluation, such as water, energy resources, minerals, land, and others. This means that regions have to be delineated in such a way that it will emphasize either the problems related to resources development and utilization or the other economic activities. Within the context of water-energy modeling, Table 4-8, page 53, and Figure 4-4, page 54, represent a possible regionalized structure.

Model Components

Models representing decision processes have one or more objective functions and a set of constraints defining the universe within which the decisions are made. Examples of objective functions are maximization of regional income, with or without income distribution effects [Morris 1977]; attainment of a minimum level of income at least cost; maintenance or increase of standard of living, expressed as the average per capita consumption of goods and services [Dantzig et al. 1978].

The constraints should include the following aspects:

- The economic activities of each region should be represented at an appropriate level of detail. One way to do so is by the use of input-output matrices; however, this method raises questions about the values of the technological coefficients in a dynamic model covering a long time span.
- Water-energy models should include detailed information on the regional water resources. This information should be summarized by hydrological basins in the region, and should reflect streamflows (average annual, seasonal, etc.), demands for consumptive use by various activities (including energy-related processes), withdrawals, and projected influences on water quality (surface and groundwater).
- Energy resources and energy-related activities should be shown preferably in each of the hydrological basins defined for the water resources components. This is desirable because, in general, it is easier, i.e., less costly, to transfer energy resources than water from one river basin to another.
- A regionalized model must indicate the relationships existing between the regions. Hence, the interregional flow of goods and services should be represented in adequate form.
- Dynamic models should include driving components, such as population increase, rate of growth of economy, etc., and other relevant details, e.g., capital formation, construction and amortization of production facilities, introduction of new technologies.

Regarding the level of detail that a model may exhibit, there are two aspects to this problem: first, the degree to which the economic data are aggregated; second, whether the same level of detail should be preserved uniformly in all regions.

The degree of aggregation varies from model to model and appears to reflect the personal preferences of the modeler or the modeler's concept of an adequate representation of the economic sector. Thus the Stanford PILOT Energy-Economic model has two versions of input-output matrices: one version of 23 sectors, and a compact version, called Sigma, with 12 sectors [Dantzig et al. 1978]. The Brookhaven regionalized model has 30-sector input-output matrices [Goettle, IV et al. 1977], while the Upper Colorado River Basin water-energy model has I-O matrices with 40 sectors, including 11 sectors of new energy technologies. Another aggregation scheme, following the general approach of the Brookhaven regionalized model, is shown in Table 5-1.

The aggregation scheme should be uniform in all regions of a regionalized model.

Table 5-1

SUGGESTED SECTORS IN I-O MATRICES FOR WATER-ENERGY MODELS

Sector Number	Sector
	Energy Supply Sectors
1	Fuel mining (coal and uranium)
2	Crude oil extraction and oil shale conversion
3	Gas and gas utilities
4	Refined oil products
5	Electric power generation (including combined cycle)
6	Solar energy, geothermal and pumped storage
	Energy Product Sectors
7	Feedstocks (to industry)
8	Motive power
9	Process heat
10	Water heating and cooling
11	Space heat and air conditioning
12	Electric power
	Nonenergy Sectors
13	Agriculture
14	Mining (nonfuel) and construction
15	Energy-intensive manufacturing
16	Energy-nonintensive manufacturing
17	Transportation and warehousing
18	Trade and other financial services
19	Machinery and transportation equiqment

Modeling Techniques

Water-energy models available in the literature [Brill, Jr. et al 1976; Morris 1977] are based on linear programming formulations. Some formulations are in the form of networks; others appear as transportation problems. The LP formulation may also include input-output matrices as representations of the regional economic activities.

Many energy models use linear programming formats [Hoffman 1973, ICF 1978, Dantzig et al. 1978]; others use nonlinear optimization processes [Manne 1977]. Simulation models are also found [Carasso et al. 1975, Cazalet 1976].

One of the crucial issues in the formulation of mathematical models of water-energy models is the preservation of the nonlinearities existing in many energy-related and in most water resources activities. Mathematical representation of nonlinearities avoids simplistic all-or-nothing (either/or) solutions, reflecting more accurately the real life problems.

Water-energy problems are complex issues which can be evaluated in accordance with a number of different engineering, economic, social, political, etc., criteria, not all of which can be expressed in interconvertible units. Hence water-energy models can be single-objective or multiobjective.

Single-objective Models. Almost all energy and water-energy models are single-objective, since all the outcomes are evaluated in economic terms, or in economic equivalents. The underlying assumption of such formulations is that all issues are resolved in the marketplace and that the market (economic) mechanism is the only effective instrument for the resolution of conflicts arising over the use of limited, or scarce, resources.

Multiobjective Models. Problems arising out of multiobjective optimization of large-scale water resources systems have been studied for some time [Haimes et al. 1975]. These problems are generated primarily by the fact that a number of decision makers, each motivated differently, are involved in policy formulations related to water and energy systems; that the several optimization criteria do not have common yardsticks, hence are noncommensurate; and by the uncertainty attached to any projection. The methodology developed for multiobjective optimization was recently reviewed [Charnes and Cooper 1977], with emphasis on quantitative analytical approaches.

The multiobjective formulation of water-energy models enables the detection of trade-offs existing between the different objectives, trade-offs which are negotiated by the political process. Thus a multiobjective model reflects, through the trade-off mechanism, the acceptance, modification, or rejection of the economic solution in the political arena.

The Time Frame

Water-energy models may refer to a single time period, or may cover a longer time span. If the model is single-period (static), the question is what period should be modeled? And if the model is dynamic, how far into the future should it project?

The Illinois water-energy model [Brill, Jr. et al. 1976] is a static model covering one 25-year planning period. The Upper Colorado River Basin regionalized water-energy model is also a one-period formulation, attempting to depict the economic situation in 1980 [Morris 1977]. The Brookhaven regionalized energy model of the U.S. is a one-period static model as well [Goettle, IV et al. 1977].

One of the important issues in dynamic multiperiod models is the specification of conditions at the end of the time span covered by the model, because the outcomes of various policy decisions during this time horizon are greatly affected by the conditions assumed at the end. One method for specifying end conditions, used in the Stanford PILOT Energy-Economic Model, is to extend the analysis over a much longer period of time, using time periods of variable length, then determine the value of the desired variables, such as production capacities of the economic sectors, at a given point in time, fairly close to the beginning of the extended period of analysis [Buras and Dantzig 1978].

REPRESENTATION OF THE ECONOMY

One should recall that large-scale water-energy models reflect primarily economic interactions between these two categories of resources. The main functions of these models are to provide a mechanism for detecting the region, or regions, where water limitations could restrict energy-related activities, given a scenario of development and of final demands for goods and services; to serve as tools in research and development activities; and to aid in the planning process. In all these functions, the way in which economy is represented becomes of great importance. Our main question which arises in this context is whether the model reflects accurately, if at all, the implications of resource scarcity -- limitations on water or energy resources -- with respect to the satisfaction of demands. In other words, is the model sufficiently detailed to be sensitive to price changes? If a model does not have this capability, then it assumes that demand elasticities are zero, while the supply side is infinitely elastic [Patmore et al. 1978].

Another important point is that of the number of economic activities defined in the model. The statistics available in the U.S. define literally hundreds of such activities. Clearly, if all these activities were to be introduced into the model by means of input-output matrices, or in some other form, at the regional level, there is the possibility that the size of the model would increase so as to be unwieldy, thus useless. This point was discussed already, above, and a list of economic sectors was suggested in Table 5-1, page 61.

Finally, one should consider that the economic reality is dynamic. There are changes in demand patterns, spurred by social, political, and other factors, which, if to be met, should be reflected by changes in technologies, in supply capacities, and/or in management practices and in organizational structures. Resources are made available, or are depleted. Capital is formed; plants are constructed to assure growth in supply capacity; older plants are depreciated and finally retired. But there appears to be a fundamental difference between water and energy resources. Whereas energy resources are very diverse (fossil fuels, nuclear energy, solar energy, etc.) and they could probably satisfy demand for a long time to come, provided that appropriate technologies are developed and applied, water has definite physical limitations which will appear as effective constraints to many economic activities, including those related to energy development.

WATER CONSTRAINTS

The water sector in water-energy models should be described at a level of detail commensurate with that usually found in the description of energy-related activities in energy-economic models. The following is a partial list of issues pertinent to this point.

Quantity

Water availability and use patterns at the national levels, by water resources regions and by hydrological basins, are summarized in the reports by the Water Resources Council [U.S. Water Resources Council 1978a, 1978b]. Information may be found also at the regional level for the Western U.S. [Bureau of Reclamation 1975; Water for Energy Management Team 1974, 1975].

Water Storage

Surface reservoirs are factors in determining water availability; hence, it is important to consider their capacities, limitations, and costs involved. Investments in storage facilities may be related to the quantities of water thus made available to users, so that supply curves for water may be developed. Such supply curves were produced for the Upper Colorado and the Upper Missouri River Basins [Buras 1977a, 1977b].

Streamflow Variability

The natural phenomenon which yields streamflows exhibits a great deal of variability. Streamflows vary from year to year, from month to month, from day to day; in fact, they vary continuously. One way to handle this aspect of streamflows is to build and operate storage facilities (dams and reservoirs). The important issues emerging from the stochastic attributes of streamflows with regard to energy-related activities is not only the overall availability of water (see water storage, above), but also to what extent streamflow variability matches the variability in demand for electricity. Water-energy models should indicate whether water would be available also for generating electric power so as to satisfy peak demands.

Groundwater

Available information regarding aquifers* (extent, water quantities, quality, etc.) is not nearly as ample as that related to surface water. In energy-related activities there are two important points to consider:

1. groundwater may be a viable alternative for water supply in areas where surface water is scarce;
2. in some areas of the Western U.S., energy resources (coal and oil shale) are found below the piezometric surface* [Tipton and Kalmbach 1977].

Water Quality

Development of energy resources may affect water quality at least in two ways. First, some conversion processes, particularly oil shale retorting, produce spent material which contains considerable amounts of soluable salts [Probstein and Gold 1978]. Leaching the spent material by natural precipitation can transfer these salts either to surface streams, to aquifers, or to both. Second, diverting substantial amounts of surface water in the upper reaches of a river basin for

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*See Appendix A, glossary.

energy development, such as it may occur in the Colorado River Basin, will decrease the diluting capacity of the river downstream, thus increasing its salinity. There is considerable concern regarding this aspect of the development of energy resources in the Upper Colorado River Basin [Bureau of Reclamation 1975], and there exists at least one study of the salinity control in the entire river basin [Erlenkotter and Scherer 1977].

Legal Constraints

Intrastate allocations of water, interstate compacts, and international treaties form a legalistic framework which may affect strongly water availabilities for energy [Dickinson et al. 1976]. These constraints may be introduced in water-energy models [Morris 1977].

PROPOSED WATER-ENERGY MODELS

A Model Related to BNL's RESOM

As mentioned previously, a national water-energy model has to be regionalized in order to be relevant in the sense of stressing and quantifying conflicting demands on water resources by energy and other activities. With this purpose in mind, a proposed water-energy formulation is based on a multiregional energy and interindustry model developed recently at Brookhaven National Laboratory [Goettle, IV et al. 1977]. This model has two components: a set of interindustry input-output matrices, one for each region; a detailed representation of the energy sector, by resource and by technology, for every region. The solution of the input-output equations yields a demand pattern for energy, which is introduced into the energy sector submodel. This submodel is formulated as a linear programming (LP) model, so that an optimal mix of energy resources and conversion technologies can be derived. The LP solution is also used to modify the coefficients in the I-O submodel, if necessary, so that the overall solution of the model is attained through an iterative procedure. Alternatively, both the I-O and the LP submodels may be combined into a single, compact, linear programming formulation [Dantzig 1974].

The interindustry input-output submodel is formulated as

$$X = C(AX + Y) \quad , \qquad (9)$$

where

- X is a column vector of total production, by industry and by region;
- C is a square matrix of main diagonal submatrices representing the interregional flow of goods and services;
- A is a block-diagonal square matrix of interindustry technical coefficients;
- Y is a column vector of final demands, by industry and by region.

Rearranging equation (9), one obtains

$$(C^{-1} - A)X = Y \ . \tag{10}$$

Define

WR = a column vector of water resources available in each region;

D = a column vector representing the residential uses of water in each region.

The water available for all other economic activities in each region is then represented by the column vector $(WR - D)$. This annual amount of water may be used in industry (manufacturing), M; in food production (irrigated agriculture), F; or in the energy sector, E. The following balance must, therefore, be maintained:

$$E + F + M = WR - D \ , \tag{11}$$

which assumes that all water not used by any other economic activity is available for energy-related activities.

Now, partition X into X^E, a column vector of total energy production, by activity and by region, and X^0, a column vector of total production <u>except</u> energy, by activity and by region. Then the following condition must hold:

$$WX^0 = F + M \ , \tag{12}$$

where

- W is a rectangular matrix of water-use coefficients for all activities except energy, for each region.

The binding constraint, however, is that water used by energy-related activities cannot exceed E, the amount available for this purpose:

$$W^E X^E \leq E , \qquad (13)$$

where

W^E is a rectangular matrix of water-use coefficients for energy activities, by activity and by region.

Introducing the slack variable S (a column vector), inequality 13 may be rewritten as

$$W^E X^E + S - E = 0 . \qquad (14)$$

Finally, partitioning the $(C^{-1} - A)$ matrix (equation 10) into $(C^{-1} - A)^E$ related to energy activities and $(C^{-1} - A)^0$ related to all other activities, and also partitioning the final demand Y into Y^E (final demand for energy) and Y^0 (final demand for all other goods and services), the water-energy regionalized input-output submodel is

$$\begin{bmatrix} (C^{-1} - A)^E & 0 & 0 & 0 \\ 0 & (C^{-1} - A)^0 & 0 & 0 \\ 0 & W & I & 0 \\ W^E & 0 & -I & I \end{bmatrix} \cdot \begin{bmatrix} X^E \\ X^0 \\ E \\ S \end{bmatrix} = \begin{bmatrix} Y^E \\ Y^0 \\ (WR - D) \\ 0 \end{bmatrix} . \qquad (15)$$

Solution of equation 15 yields, in addition to the production vectors X^E and X^0, the amount of water available for energy production in each region E and whatever "slack" S may be generated by equation 14. Since expression 15 is a system of linear equations, its variables are unconstrained in sign. Hence, if $S < 0$ -- "negative slack" -- the indication is that there is a shortage of water in relation to the energy-related activities X^E required by the scenario defined by Y. Therefore, the amount $(E - S)$ is used as the right-hand side of the water constraints of the LP submodel and is denoted there as WRAE(I). If $E - S \leq 0$, the LP submodel may have no feasible solution.

The overall water resources constraints of the LP submodel, one for each region, have the following form:

$$\underbrace{\sum_{RS} SRS \sum_{s} RR(RS)(I)(s)}_{\text{Water use in extracting energy resources}} + \underbrace{\sum_{\substack{J\\ I\neq J}} WSP[RR(RS)(I)T(J)]}_{\text{Water use in transporting energy resources via slurry pipeline from region } I \text{ to region } J} + \underbrace{\sum_{RS}\sum_{IEF} WIEF(RS)(IEF)(I)}_{\text{Water use in converting energy resources to non-electric intermediate energy forms (gasification, liquefaction)}}$$

$$+ \underbrace{\sum_{CS_I} WCS_I[EE(CS_I)(I) \cdot t(CS_I,I)]}_{\text{Water use in electricity generation by technology } CS\text{, transmission efficiency } t\text{, power generated and used in region } I}$$

$$+ \underbrace{\sum_{CS_{IJ}} WCS_{IJ}[EE(CS_{IJ})(I) \cdot t(CS_{IJ},I)]}_{\text{Water use in electricity generation by technology } CS\text{, transmission efficiency } t\text{, power generated in region } I \text{ and used in region } J} + \underbrace{WFC[EE(FC)(I)]}_{\text{Water use in electricity generation by fuel cells}}$$

$$+ \underbrace{WTE[EE(TE)(I)]}_{\text{Water use in electricity generation by total energy systems}}$$

$$+ \underbrace{WPS[ELE(PS)(I) \cdot t(PS,I)]}_{\text{Water use in electricity generation by pumped storage (evaporation), transmission efficiency } t} \leq \underbrace{WRAE(I)}_{\text{Water available for energy-related activities in region } I} \tag{16}$$

where

RS	is energy resource type;
WRS	is water use in extracting energy resource;
RR(RS)(I)(s)	is production level of resource RS extraction by activity RR in region I within the segment s of the supply curve;
WSP	is water use in slurry pipelines;
RR(RS)(I)T(J)	is exports of energy resources from region I to region J;
IEF	is intermediate energy forms;
WIEF	is water-use coefficients for converting energy resources into nonelectric IEF;
(RS)(IEF)(I)	is production of a particular IEF from resource RS in region I;
WCS	is water use in electric power generation;
$EE(CS_I)(I)$	is electricity generation by technology CS_I, installed and used in region I, $CS_I \neq FC,TE$;
$t(CS_I,I)$	is transmission efficiency associated with CS_I;
$EE(CS_{IJ})(I)$	is electricity generation by technology CS_{IJ}, generated in region I and used in region J;
$t(CS_{IJ},I)$	is transmission efficiency associated with CS_{IJ};
WFC	is water use by power generation with fuel cells;
EE(FC)(I)	is electricity generation by fuel cells in region I;
WTE	is water use in power generation by total energy systems;
EE(TE)(I)	is electricity generation by total energy systems;
WPS	is water use in pumped storage (evaporation);
ELE(PS)(I)	is electricity input demand for pumped storage in region I;
t(PS,I)	is transmission efficiency related to PS;
WRAE(I)	is water available for energy-related activities in region I.

The iterative method for solving this model suggested by Brookhaven National Laboratory [Goettle, IV et al. 1977] is shown in Figure 5-1.

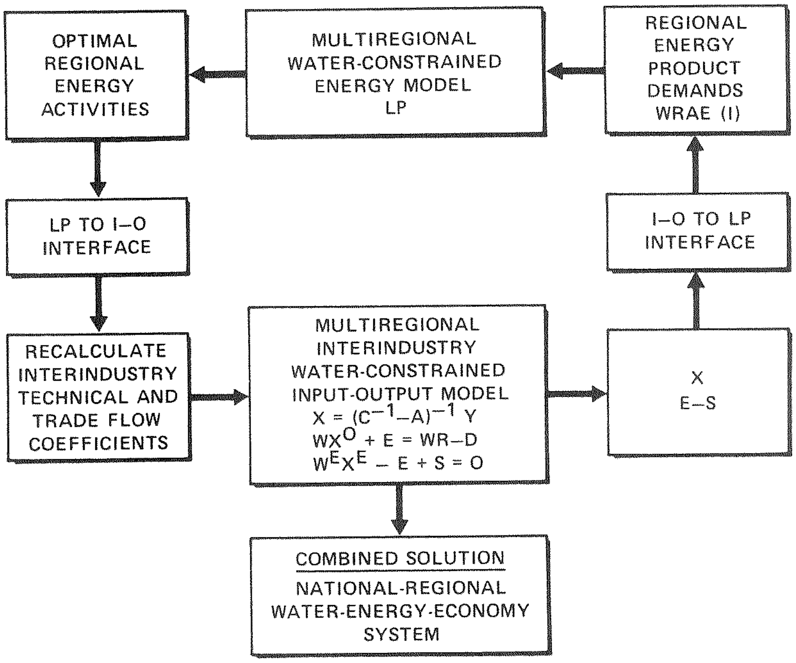

Figure 5-1. The Solution Sequence for the Iterative Method

The electrical sector may exhibit sensitivity to water limitations also in regard to the satisfaction of peak demands for power. These demands appear during short periods of time, yet their satisfaction may require significant amounts of water. The Brookhaven National Laboratory RESOM model expresses this issue in the form that required generation capacity should be at least as large as the peak demand of each season-day period in every region. The water constraint should only indicate that the regional water resources available during the given season-day period should be sufficient to enable the operation of the required peak generating capacity. Thus, defining that

$r(I)$ is the reserve power generation margin in region (I);

$YY(CS_I)(I)$ is capacity equivalent of $EE(CS_I)(I)$;

$YY(CS_{IJ})(I)$ is capacity equivalent of $EE(CS_{IJ})(I)$;

$YY(FC)(I)$ is capacity equivalent of $EE(FC)(I)$;

$WRAE(S)(D)(I)$ is water available for peak power generation in season-day $(S)(D)$ and region I;

the water constraint on peak power generation is

$$[1 + r(I)]^{-1} \left\{ \sum_{CS_I} WCS[YY(CS_I)(I) \cdot t(CS_I, I)] + \sum_{CS_{IJ}} WCS[YY(CS_{IJ}(I) \cdot t(CS_{IJ}, I)] + WFC[YY(FC)(I)] \right\} \leq WRAE(S)(D)(I) \; . \qquad (17)$$

Possible objective functions which may be formulated for the LP submodel, so as to include the water resources element, may be as follows:

- Minimize total annual costs, using either average or marginal cost coefficients and including capital costs, fuel, operating costs, end-use devices, and water storage and distribution costs.
- Minimize total capital requirements, including those related to water resources development.
- Minimize total resource use, including water.

A Model Related to LLL's Energy Policy Model

The Lawrence Livermore Laboratory's Energy Policy Model (EPM), a general equilibrium formulation of the energy sector of the U.S. economy, has the following features [Sussman 1978]:

- Energy transformations from primary resources to end-use sectors are described as a network.
- The selection among energy alternatives is based on prices, such that the lowest-priced alternative captures the bulk of the market. It is, however, possible to activate lags, penalties, etc., that describe non-economic determinants of market share.
- The energy network incorporates technological processes, including new technologies.

- The model is dynamic over the time horizon specified by the scenario under study.
- For each primary resource a supply curve provides marginal costs as a function of quantity already consumed. Pricing is based on these costs.
- Regions are defined for resource extraction, for refineries, and for end-use consumption.

An important contribution of LLL's modeling system is the development of a special purpose computer language for defining general equilibrium models and of the attendant computer software [Sussman and Rousseau 1978a]. The language allows the symbolic specification of the network and of the data base, thus facilitating construction and/or modification of networks and of data sets. The software sequences the network, performs iterative calculations, and organizes the output for tabular or graphical display.

The integration of water resources into the LLL energy model begins with the definition of the water regions, in each of which water availability is described by a supply curve. Figure 5-2 shows the unit investment in 1967 dollars necessary to develop water in the Upper Colorado River Basin with a reliability of supply of 98% [Buras 1977a]. From this information it is possible to derive the marginal costs (dollars per acre-foot) needed for the supply curve. Next, water requirements are introduced into the representation of various energy-related processes: electric power generation, oil shale retorting, coal slurry pipelines, coal gasification. Obviously, the definition of water regions will have to be coordinated with the existing regionalization. Finally, water resources constraints may be added wherever appropriate to the definition of network submodels which group a number of processes in order to satisfy a given final demand.

A somewhat more detailed description of LLL's Energy Policy Model and Economic Modeling System, and of their application in this study is given in Appendix D.

A Comparison between the Two Models

An earlier study of alternative approaches to regional energy modeling [Cohen and Costello 1975] considered three major criteria for evaluating these models: comprehensiveness, especially spatial; the level of detail of economic aspects, in particular the determination of total supply and demand in the economy; capabilities of the model to reflect policy and technology changes. To these criteria we shall add two: the time frame of the model, and the availability of software for their solution. Table 5-2 summarizes the differences between the BNL and the LLL models, according to these criteria.

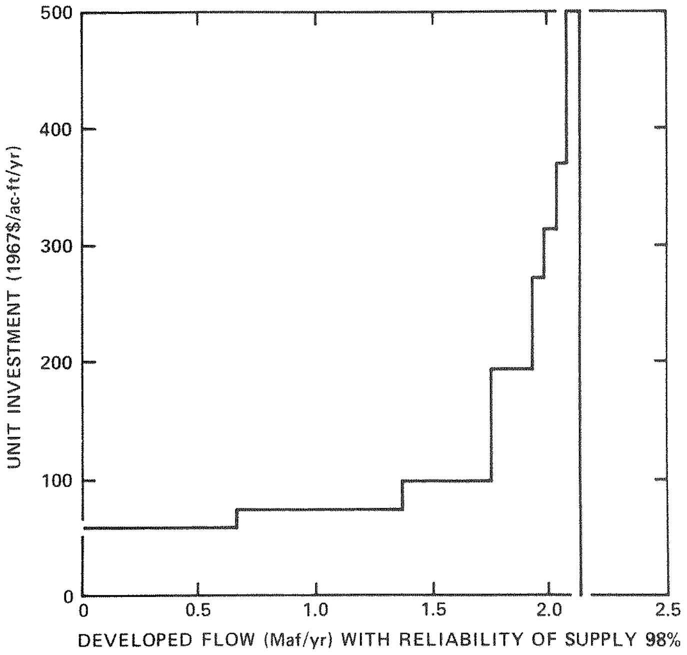

Figure 5-2. Water Supply Function,
Upper Colorado River Basin

This brief comparison indicates that each of the two models has qualities that the other does not have. For example, the BNL model has the capability of representing the entire U.S. economy, by regions, by means of its I-O submodel. On the other hand, the LLL model allows the exploration of policy issues along a time trajectory, thus reflecting, in part at least, the dynamics of the U.S. economy. It appears, therefore, that both models may be useful in determining the feasibility of integrating water resource constraints into energy models. The LLL model, having its software fully developed and readily available, albeit only to be run at the LLL computer center, can be used to demonstrate the effects which water resources constraints may have on the energy sector of the U.S. in a dynamic setting. The BNL model, on the other hand, when fully developed, may provide decision makers with an effective analytical tool for the evaluation of the effects of water resources constraints on the energy sector within the overall framework of the U.S. economy on a regional basis, given an assumed scenario.

Table 5-2

COMPARISON BETWEEN THE BNL AND LLL ENERGY MODELS

Criterion	BNL Model	LLL Model
Regionalization	Nine Census regions	Nine Census regions (demand), 14 supply regions, six refinery regions
Energy supply detail	Seven energy supply sections	19 primary energy resources, 13 secondary energy resources, 38 energy transportation processes
Energy demand detail	Eight types of end use	Twenty-three types of end use
Representation of the rest of the economy	15 nonenergy sectors in a 30-order I-O regional matrix	Exogenously specified
Interfuel competition	LP formulation of the energy sector	Lowest-priced alternative captures the greatest market share
Interregional competition	I-O submodel has interregional trade matrix	Supply and refinery regions compete as in interfuel competition, above
Policy evaluation	By specifying Y, the vector of final demand, in the I-O submodel	By varying the economic parameter in the node of definitions within the network
Evaluation of technological changes	Adjusting the coefficients in the A-matrix in the I-O submodel, and the appropriate coefficients in the LP energy submodel	Adjusting the appropriate parameters the definitions of the processes
Time frame	Single-period static model	Multiperiod dynamic model. Recent runs cover the time span 1975-2020.
Software availability	LP submodel available and currently undergoing adaptation for running on IBM 370/168 system. I-O submodel not available, algorithm not developed and data not assembled	Special computer language developed for this model. Runs may be made only at the computer center of the Lawrence Livermore Laboratory.

Section 6

BRIEF EXPLORATION OF TWO WATER-ENERGY MODELS

THE WATER-RESOM MODEL

As indicated in Section 5, equations and constraints were added to BNL's RESOM model describing water scarcities and/or availabilities, thus producing the current (first) version of WATER-RESOM. The algorithm used for solving it is similarly a modification of the RESOM algorithm, as obtained from the Brookhaven National Laboratory.

The multiregional interindustry input-output component of RESOM is still under development at BNL and the appropriate coefficients are not available yet. The multiregional energy linear programming algorithm, however, is available and a copy of it was received from BNL. This copy included an input file to an LP solver in IBM format, and 1975 data for a test problem. This file together with the MPS III code developed by the Management Science Systems were used in making the exploratory runs.

In order to perform these runs, appropriate software was developed.* Details of the software are given in Appendix E.

After including the water use coefficients for energy-related activities, the LP matrix had 1767 rows, 3589 variables, a total of 9816 nonzero elements yielding a matrix density of 0.15%. The solution, using 1975 data, converged to an optimum in 13' 59.52" following 2791 iterations, yielding a minimum cost of $\$409.813 \times 10^9$ (1975\$).

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*Dr. Alexander I. Simon's major contribution to this project.

A scenario for the year 2000 was developed on the basis of the following assumptions:

- The population will increase by the year 2000 with respect to 1975, as shown in Table 6-1.
- The increase in the per capita energy demand is, on the average, 2% per year, yielding a 64% increase by the year 2000.
- The water available for energy-related activities is estimated from the Water Resources Council data (U.S. Water Resources Council 1978a]. See Table 6-2.

Table 6-1

ESTIMATED PERCENT INCREASE IN POPULATION, 1975-2000

Region	Percent Increase
1. New England	33
2. Mid-Atlantic	24
3. East North Central	26
4. West North Central	11
5. South Atlantic	21
6. East South Central	15
7. West South Central	14
8. Mountain	22
9. Pacific	36

Table 6-2

WATER RESOURCES AVAILABLE FOR ENERGY-RELATED ACTIVITIES

Hydrological Region	1975 (Maf/yr)	2000 (Maf/yr)	2000 (%of 1975)
1. New England	10.2	9.5	93.1
2. Mid-Atlantic	11.44	9.5	83.0
3. South Atlantic-Gulf	53.05	46.86	88.3
4. Great Lakes	9.81	7.43	75.7
5. Ohio	19.59	15.86	81.0
6. Tennessee	2.60	1.71	65.8
7. Upper Mississippi	11.48	0.54	4.7
8. Lower Mississippi	82.83	58.54	70.7
9. Souris-Red-Rainy	2.61	2.96	113.4
10. Missouri	11.36	2.14	18.8
11. Arkansas-White-Red	18.44	10.96	59.4
12. Texas-Gulf	5.99	0.24	4.0
13. Rio Grande	-1.18[a]	0.0	-
14. Upper Colorado	2.27	1.03	45.4
15. Lower Colorado	-6.00[a]	0.0	-
16. Great Basin	2.648	1.86	70.2
17. Pacific Northwest	15.978	11.517	72.1
18. California	16.930	10.396	61.4
Total	277.23	191.04	

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[a] Negative values represent groundwater overdraft, in order to meet current (1975) water demands; they are not included in the total.

Source: U.S. Water Resources Council 1978a.

The estimated increase in demand for energy in the year 2000, as a combination of population growth and increase in per capita use of energy, and the water available for energy-related activities in each of the nine Census regions are shown in Table 6-3.

Table 6-3

ASSUMED SCENARIO FOR THE YEAR 2000

Region	Energy Demand (% of 1975)	Water Available for Energy	
		(Maf/yr)	(% of 1975)
1. New England	218	6.4	74.4
2. Mid-Atlantic	203	7.2	75.0
3. East North Central	207	16.0	75.1
4. West North Central	182	12.7	75.1
5. South Atlantic	199	22.3	74.8
6. East South Central	189	44.9	74.7
7. West South Central	187	36.2	74.9
8. Mountain	200	6.0	75.0
9. Pacific	223	17.4	75.0
Total		169.1	74.9

The year 2000 scenario was run and an optimal solution was obtained in 6 minutes and 17.04 seconds after 1543 iterations. The value of the objective function was \$494.584 × 10^9(1975\$), i.e., when water constraints were integrated into the model, the energy demands were satisfied at a total cost 20.7% higher than in 1975.

A comparison of the 1975 and 2000 runs reveals the following details:

- Coal-steam power generation decreases 65%, from 0.968 quad to 0.343, in Region 3 (East North Central); and 41%, from 0.625 to 0.371 quad, in Region 5 (South Atlantic). It increases 7% in Region 8 (Mountain), from 0.179 to 0.192 quad.

- Oil-steam power increases in Region 1 (New England) 31%, from 0.106 to 0.139 quad.

- Oil refining increases in Region 3 (East North Central) 2%, from 4.353 to 4.452 quads; in Region 4 (West North Central) 2%, from 1.438 to 1.471 quads; in Region 6 (East South Central) 4%, from 1.002 to 1.039 quads; and in Region 9 (Pacific) 7%, from 4.002 to 4.298 quads. It decreases 37% in Region 7 (West South Central), from 9.944 quads to 6.253.

- Coal liquefaction activities appear in the year 2000 in Region 6 (East South Central) and Region 8 (Mountain) with the amounts 0.423 and 0.343 quad, respectively.

- Coal mining, assumed 50% underground and 50% strip mining, diminished 52% in Region 2 (Mid-Atlantic), from 2.02 to 0.97 quads; 35% in Region 3 (East North Central), from 4.72 to 3.09, quads; 22% in Region 6 (East South Central), from 1.90 to 1.48 quads; and 25% in Region 9 (Pacific), from 0.22 to 0.16 quad. It increased 132% in Region 4 (West North Central), from 0.90 to 2.09 quads; 109% in Region 5 (South Atlantic), from 2.38 to 4.98 quads; and 111% in Region 8 (Mountain), from 0.69 to 1.45 As a result, Region 1 (New England) lost its supply of coal, 0.06 quad, from Region 3 (East North Central), but was compensated by shippings, 50% by slurry pipeline, from Region 4 (West North Central), 0.02 quad, and Region 5 (South Atlantic), 0.04 quad. Region 2 (Mid-Atlantic) receives coal shipments in the year 2000, 50% by slurry pipeline, from Region 4 (West North Central), 0.44 quad, and from Region 5 (South Atlantic), 1.07 quads. Region 3 (East North Central) is supplied with coal, 50% by slurry pipeline, also from Region 2 (Mid-Atlantic), 0.42 quad, from Region 4 (West North Central), 0.20 quad, and from Region 5 (South Atlantic), 2.55 quads. Region 5 (South Atlantic) continues to receive 0.10 quad of coal from Region 2 (Mid-Atlantic) in the year 2000, loses its supply of 0.19 quad from Region 3 (East North Central), but is compensated by shipments, 50% by slurry pipeline, from Region 4 (West North Central), 0.87 quad, and from Region 8 (Mountain), 0.81. Region 6 (East South Central) continues to be supplied from Regions 4 (West North Central), 7 (West South Central), and 8 (Mountain) at the same levels as in 1975, 0.39, 0.68 and 0.80 quad, respectively; the shipments from Region 5 (South Atlantic), however, increase from 0.15 to 0.32 quad, 50% of which are by

> slurry pipeline. Region 7 (West South Central) receives in the year 2000 coal shipments, 50% via slurry pipeline, from Regions 5 (South Atlantic) and 8 (Mountain), 0.01 and 0.42 quad, respectively. Finally, Region 9 (Pacific) maintains its coal supply of 0.169 quad from Region 8 (Mountain), but loses that from Region 6 (East South Central), 0.057 quad.

These results should be considered only as indicative of the type of analysis which could be made using water-energy-economy regionalized models, and not as reflecting possible outcomes of a scenario structured in detail.

In conclusion, these exploratory runs on a national linear programming static model regionalize in accordance with the U.S. Bureau of Census, thus not highlighting the possible problems generated by water resources, indicate quite clearly that the introduction of constraints reflecting regional scarcities or availabilities of water has an influence both on the objective function (it costs the economy more to satisfy end-use demands) and on the regional distribution of many energy-related activities.

THE WATER-EPM MODEL*

The Lawrence Livermore Laboratory EPM (Energy Policy Model) was described by Sussman and Rousseau [1978a, 1978b] and by Rousseau et al. [1978], and is presented briefly in Section 5. Data representing water resources availabilities were introduced into one of the supply regions defined by this model, namely the Rocky Mountain Region, which contains both the Upper Colorado and the Upper Missouri River Basins. Since the two river basins were aggregated, a composite supply curve for water was produced (Table 6-4 and Figure 6-1), as well as an aggregated projection for non-energy water use in the entire region (Table 6-5, Figure 6-2). Both the supply curve and the projection of non-energy use refer to amounts of water in addition to those used in 1975. The horizontal lines on Figure 6-2 represent the increasing cost of developed water.

Since Figure 6-2 shows the water availability for energy in quantities above those used already for all purposes in 1975, Figure 6-3 shows a total allocation of water resources in the Rocky Mountain Region projected from 1975 to the year 2025.

The water-use coefficients used in this study are identical with those shown in the summary of Section 3.

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*The cooperation with the Lawrence Livermore Laboratory was suggested by Dr. Stanley Sussman. The computer runs which resulted in Figures 6-4 through 6-8 and in Tables 6-6 and 6-7 were performed by Dr. Mary D. Schrot. Her contribution is gratefully acknowledged.

Table 6-4

SUPPLY CURVE, ROCKY MOUNTAIN REGION

Cumulative flow (M ac-ft/yr)	Cost (1974$/ac-ft)
.798	18
7.598	20
8.228	22
8.543	30
8.771	44
8.999	57
9.146	60
9.246	67
9.451	84
9.593	97
9.635	114
9.656	154
9.934	177
10.000	240

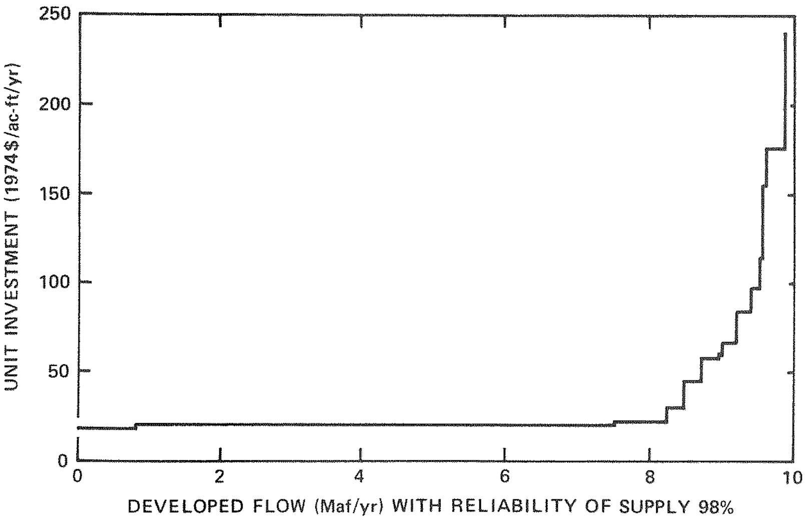

Figure 6-1. Water Supply Function, Rocky Mountain Region (Post 1975)

Table 6-5

PROJECTED WATER USE, ROCKY MOUNTAIN REGION
(million acre-feet per year)

Year	Upper Colorado	Upper Missouri	Total
1980	0.700	1.300	2.000
1985	1.075	2.400	3.475
1990	1.375	3.400	4.775
1995	1.575	4.200	5.775
2000	1.750	4.900	6.650
2005	1.875	5.500	7.375
2010	1.975	6.000	7.975
2015	2.050	6.500	8.550
2020	2.100	6.800	8.900
2025	2.100	7.100	9.200

The results of this exploratory study are shown graphically in Figures 6-4 through 6-8, indicating clearly the influence of the water resources constraints. For example, the power generation in nuclear plants (LWR) in the Rocky Mountain Region begins to drop as early as the year 2000 (Figure 6-6). The amount of coal transported from the Rocky Mountain Region via slurry pipelines (with no return lines) starts in the year 1980, peaks at 0.75 quad in 2005, then drops two-thirds to 0.25 quad in the year 2020 (Figure 6-7). Most other energy-related activities peak in 2010. Fossil-fueled power plants use about 2.5 quads of fuels in 2010, then drop to about 1 quad in 2020 (Figure 6-4). This may be attributed to the scenario under study which specifies that water available for energy decreases while the demand for it increases, and that, at the same time, water which is available for energy is increasingly costlier. Oil shale production rises rapidly from 1985, reaching about 6 quads in 2010 and declining gradually thereafter (Figure 6-8).

The increasing scarcity of water postulated in this scenario is reflected also in the costs related to energy activities. An example of this is shown in Figure 6-5. The sharp rise in costs in the year 2010 is attributed largely to the development and use in the energy sector of high-cost water, probably around $100/ac-ft.

The allocation and use of water in the Rocky Mountain Region under the assumptions of this scenario are shown in Table 6-6.

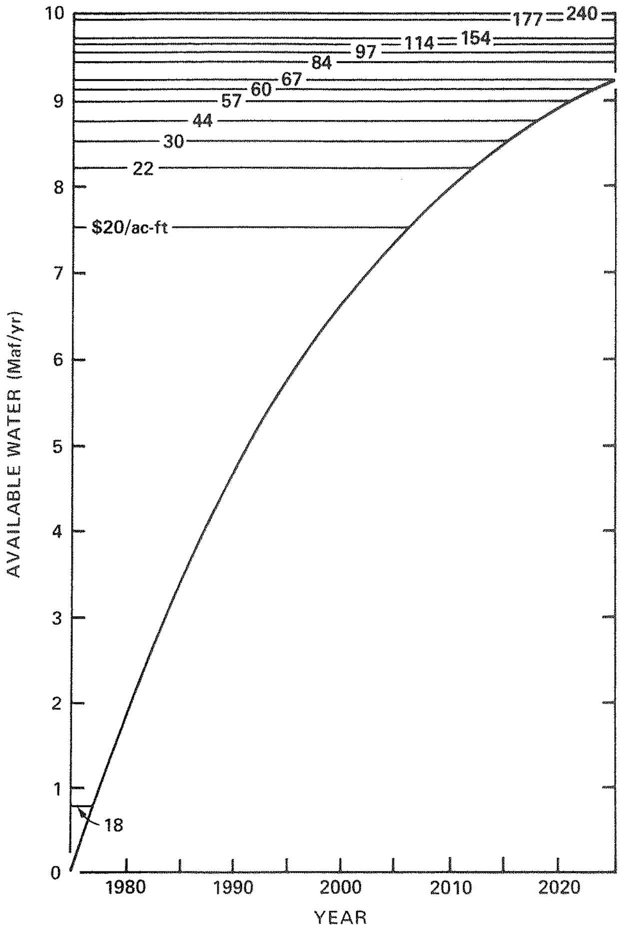

Figure 6-2. Water Availability for Energy, Rocky Mountain Region

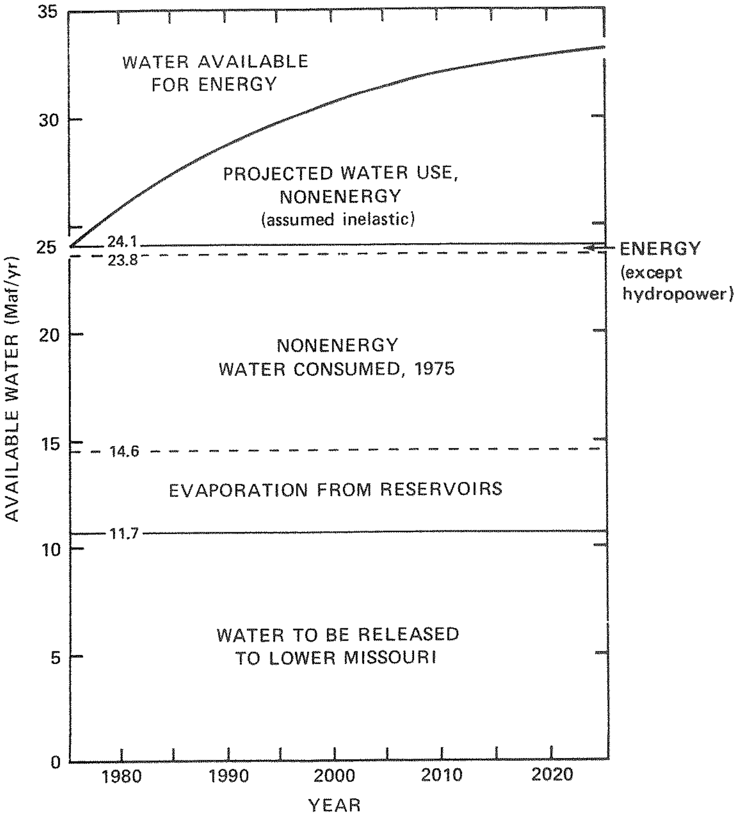

Figure 6-3. Projected Allocation of Water Resources, Rocky Mountain Region

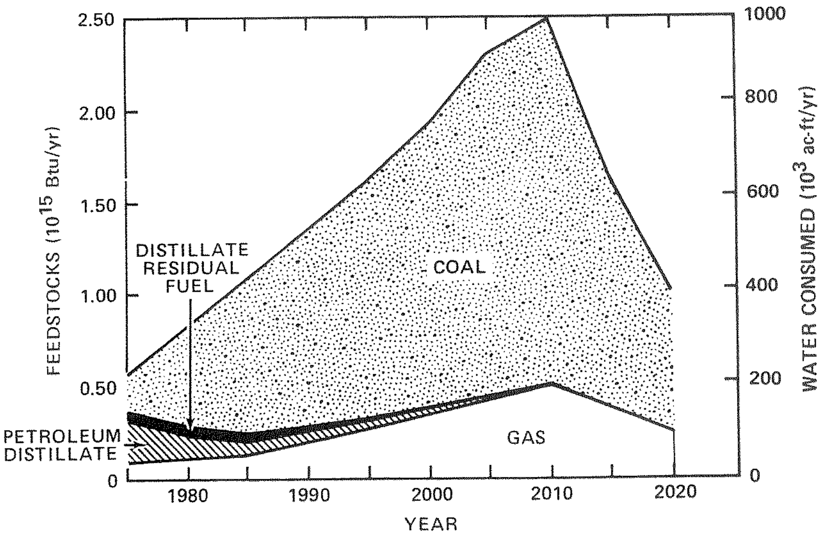

Figure 6-4. Fossil-fueled Power Generation

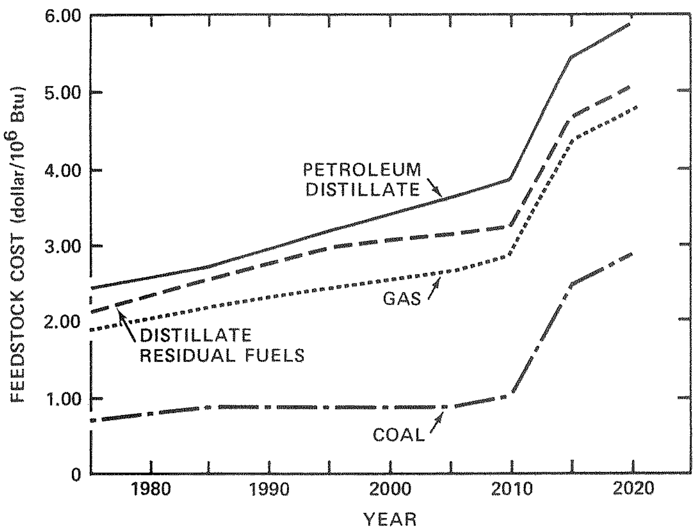

Figure 6-5. Cost of Fossil-fueled Power Generation

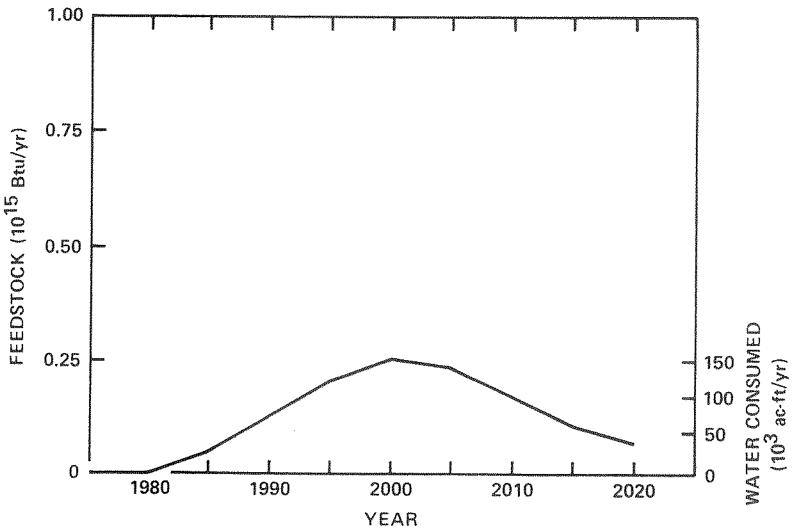

Figure 6-6. Nuclear Power Generation

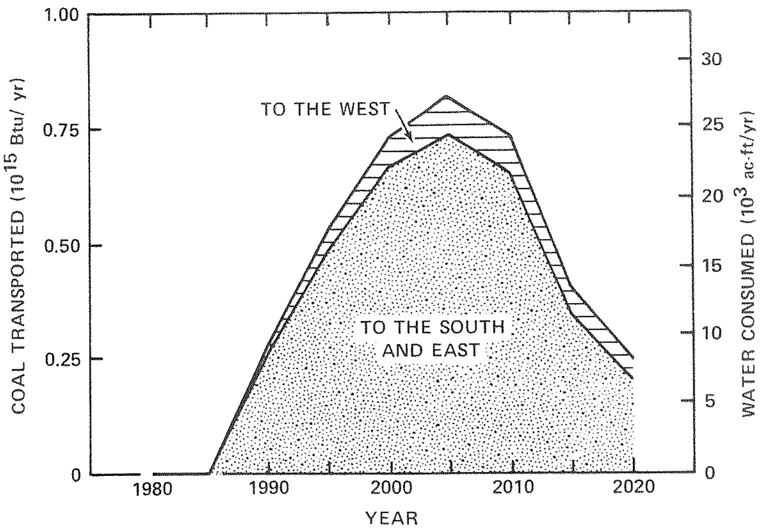

Figure 6-7. Coal Transported by Slurry Pipeline

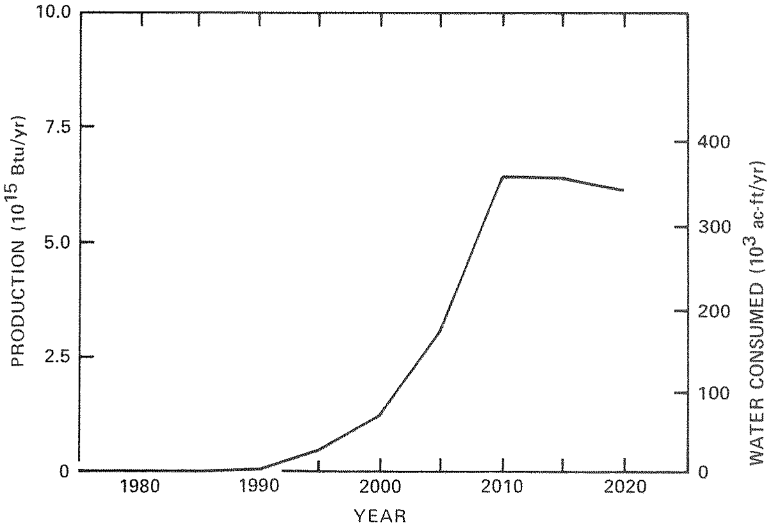

Figure 6-8. Shale Oil Production

Table 6-6

WATER USE, ROCKY MOUNTAIN REGION
(thousand acre-feet)
(Feasibility scenario results, LLL model)

Water for	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020
Slurry pipelines*	0	0	0	9.56	17.0	22.8	27.7	24.9	13.8	8.46
Gas-fired power	37.4	43.1	52.1	77.7	107.0	135.0	168.0	195.0	150.0	97.8
Distillate fuel power	87.7	49.0	27.4	21.8	15.9	11.1	7.61	5.13	3.24	1.96
Residual fuel power	18.6	17.8	14.0	9.99	6.87	4.66	3.13	2.05	1.28	.79
Coal-fired power	78.4	221.0	334.0	423.0	510.0	608.0	735.0	782.0	490.0	303.0
LWR	0	3.50	29.0	76.4	123.0	150.0	140.0	101.0	62.2	38.6
Coal gasification	0	0	0	0	.23	2.59	10.5	28.0	16.4	8.82
Shale	0	0	0	3.35	27.7	77.2	190.0	397.0	395.0	380.0
Coal syncrude	0	0	0	0	.002	.022	.159	.785	1.63	2.55
Total energy**	222.1	334.4	456.5	621.8	1,429.5	1,011.4	1,282.1	1,535.9	1,133.6	842.0
Nonenergy	13,200	14,900	16,700	17,700	18,700	19,700	20,700	21,200	21,800	22,100
Total**	13,400	15,300	17,200	18,300	20,100	20,700	22,000	22,800	22,900	22,900

---

*Non-return water.
**Rounded off.

The primary components of electric power generation -- gas, coal, petroleum distillates, distillate residuals, and nuclear reactors -- in the Rocky Mountain Region, in 10^{12} Btu/yr, are shown in Table 6-7. (Note that hydroelectric power generation, which is quite significant in this region, does not appear in this table.)

As in the case of the WATER-RESOM model, the results of the WATER-EPM runs should be viewed only as a demonstration of an initial capability for analyzing economic interactions of water and energy, and the details shown in Table 6-7 should be viewed in this light. The results presented in this table reflect a modeling situation in which water availability and use were considered only in one resource region (Rocky Mountains), thus tacitly assuming that this region alone is expected to experience in the future water-related problems in the energy sector. This assumption explains, in part, the inordinately rapid increase of base electricity generated in LWR (from zero in 1975, to 1.88×10^{12} Btu in 1980, to 15.69×10^{12} Btu in 1985, to 41.27×10^{12} Btu in 1990), and the growing shortfalls in electricity. This, of course, is unrealistic, but one should re-emphasize that the objective of the study was to determine the feasibility of integrating water resource constraints into energy models, rather than to evaluate quantitatively water-energy interactions. The latter may be the object of a future study.

Table 6-7

PRIMARY COMPONENTS OF ELECTRIC POWER GENERATION, ROCKY MOUNTAIN REGION (trillion Btu output)

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020
Gas-fired boiler -- base	28.11	26.94	21.21	15.06	10.39	7.02	4.72	3.09	1.92	1.18
Gas-combined cycle -- base	0	.05	.10	3.06	5.39	6.06	6.69	8.62	5.39	3.33
Gas-combined cycle -- int.	0	2.58	16.97	51.19	89.23	126.52	167.53	200.10	155.66	100.47
Gas-fired turbine -- peak	4.89	8.41	9.39	8.62	6.94	5.25	3.98	2.83	1.74	1.06
Gas-combined cycle -- peak	0	.31	2.87	9.08	16.46	23.90	32.15	39.09	32.36	22.87
Total gas-fired	33.00	38.29	50.54	87.01	128.41	168.75	215.07	253.73	197.07	128.91
Coal boiler -- base	75.24	189.94	299.98	380.70	458.76	530.14	575.60	479.00	297.56	183.78
Coal-combined cycle -- base	0	0	.04	.75	5.97	29.34	109.55	273.51	170.22	105.16
Coal boiler -- int.	0	19.57	15.03	15.09	13.26	11.89	10.75	8.58	5.38	3.33
Coal-combined cycle -- int.	0	0	0	.01	.08	.57	2.57	7.97	6.86	4.37
Total coal-fired	75.24	209.51	315.05	396.55	478.07	571.94	698.47	772.06	480.02	296.64
Residual fuel boiler -- base	17.81	17.07	13.44	9.54	6.58	4.45	2.98	1.96	1.21	.75
Distillate turbine -- int.	61.98	34.20	18.68	15.56	11.70	8.34	5.88	3.97	2.48	1.53
LWR -- base	0	1.88	15.69	41.37	66.28	81.03	75.43	54.35	33.76	20.85
Regional shortfall in electricity*	0	1.19	2.29	2.59	2.48	2.27	2.33	58.27	399.74	620.72

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*Not practical but due, primarily, to the incorporation of water-related data only in the Rocky Mountain Region.