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DETERMINING THE FEASIBILITY OF INTEGRATING WATER RESOURCE CONSTRAINTS INTO ENERGY MODELS

by

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ABSTRACT

Development of energy sources and generation of electric power require substantial amounts of water. The water is necessary as process water in the production of synthetic fuels, and as cooling water in almost all activities related to the development of energy resources and in thermoelectric power plants. Yet existing energy-economy models do not explicitly take account of the availability of water resources for energy-related activities. The objective of the project was to express, in a general form, the availability of regional water resources and to determine the feasibility of integrating these availabilities into energy models. Following reviews of water resources data bases, of technologies involved in energy development, and of energy models with regional disaggregation, two models were used for the study of this integration: the Regional Energy System Optimization Model (RESOM), currently under development at the Brookhaven National Laboratory, and the Energy Policy Model (EPM), developed at the Lawrence Livermore Laboratory. Water resources constraints were introduced in these models and exploratory computer runs using demonstration scenarios were made. The test scenarios assumed that nonenergy users would make increasing, inelastic demands upon regional water resources, leaving limited amounts of increasingly more expensive water for energy activities. The results of the exploratory runs demonstrate the feasibility of integrating water resources availabilities and water consumption data into energy-economy models.

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The conterminous 48 states of the U.S. have large quantities of energy resources and of surface and groundwater. It is estimated that the average aggregated streamflow[*] is about 1.9 × 10^3 million acre-feet/year,[**] and groundwater within 2500 feet of ground surface amounts to 100 × 10^3 Maf/yr. However, the distribution of water resources does not parallel that of energy reserves and, in areas where water is relatively scarce or where it is already used by other sectors of the U.S. economy, it may influence appreciably the rate at which energy resources could be developed. Hence, the effects of water availability or scarcity are important and should be reflected in models used in energy R&D planning. Also, the availability of water supplies adequate in quantity and in quality ranks as an important criterion for the siting of thermoelectric power plants, alongside the proximity of fuel supply and load (demand) centers.

The use of water in energy-related activities is consumptive, i.e., water cannot be reused by any other user within the same hydrological unit without some treatment -- if, indeed, it can be treated at all. The consumptive use consists of three major components:

1. process water, such as in the case of synthetic fuels and oil derived from shale, where water contributes to the making of the product;
2. evaporation, which removes excess (waste) heat from energy-related processes;
3. waste water, which removes waste matter.

The use of water by energy-related activities is shown below.

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*For a definition of terms, see Appendix A.

**Conversion factors for water-measurement terms are given in Appendix B.

Table S-1

WATER USES IN ENERGY-RELATED ACTIVITIES
(acre-feet per quadrillion Btu of product)

Activity	Process Water	Evaporation	Waste Water	Total	Sources
Nuclear power stations (LWR)	-	537,200	55,600	592,800	(2)[a,b]
Fossil-fueled power stations	-	358,100	37,100	395,200	(4)[c]
Coal gasification, high-Btu gas	32,500	68,100	2,800	103,400	(4)
Oil shale conversion	21,700	32,000	8,000	61,700	(3,4)
Coal gasification, low-Btu gas	1,000	56,000	700	57,700	(1,6)
Coal liquefaction	2,800	36,700	17,500	57,000	(7)
Nuclear fuel processing	-	37,400	3,900	41,300	(2)
Coal slurry pipeline	-	-	-	34,000	(4,9)
Oil refining	-	16,000	6,200	22,200	(2)
Underground coal mining	-	7,700	-	7,700	(5,8)
Strip coal mining, revegetation	-	3,400	-	3,400	(4)
Strip coal mining, no revegetation	-	1,800	-	1,800	(4)

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[a] Numbers refer to the bibliography at the end of this summary.

[b] Equivalent to 0.66 gallons/kWh.

[c] Equivalent to 0.44 gallons/kWh.

Water use numbers in this table are representative of ranges of values, reflecting the variability in conditions which exist at different sites.

Hydropower generation, which is not included in this table, may be considered as a user of water, although water flowing through turbines and generating electricity is readily available for other uses a short distance downstream from the hydropower plant. But plants, other than run-of-the-river, are constructed and operated in conjunction with dams, so that part of the water stored behind them evaporates. However, water storage reservoirs often perform other functions in addition to power generation, such as flood control, flow regulation for water supply, recreation, etc., and there is no agreed method for the allocation of evaporative losses among these functions. For this reason, all these losses are combined into one category of water use called "evaporation from man-made lakes" (see Figure A-1, Appendix A).

Table S-1 shows that water plays a key role in the development and operation of the energy sector in the U.S. In order to study the effects of water availability on a growing energy sector, it appears that water-energy-economy models could be very useful. Furthermore, such models could offer guidelines to policy-makers and managers in the energy sector for decisions related to the acquisition, use, treatment, and discharge of water.

Availability of water resources varies both in space (i.e., geographically) and in time (i.e., seasonally): different regions of the U.S. have different amounts of water which can be made available to users; and in the same region, these amounts of water may vary from season to season. Furthermore, the quantity of water flowing past a given point at any specified time varies from year to year. Hence, one may consider the amount of water flowing in a region as a stochastic variable exhibiting certain probabilistic properties. In this study, however, all water quantities are expressed as expected annual volumes, thus restricting the discussion to deterministic terms. It is hoped that future studies of water-energy-economy interactions will consider the stochastic aspects of streamflows.

Information related to water resources and assembled in a number of data bases refers usually to hydrological units called river basins (see Appendix A, glossary). Boundaries of river basins are determined primarily by topography; they seldom coincide with state, country, or other administrative or political boundaries. Although interbasin transfers of water are feasible, they often entail formidable engineering works in order to overcome topographical obstacles. For example, the California aqueduct conveys water from the Sacramento river basin, through the San Joaquin Valley, over the Tehachapi mountains, to southern California. Water resources models should represent availabilities, uses, and transfers on the basis of river basins water balances.

In order to highlight some of the critical problems likely to arise in water-energy interactions, water-energy-economy models have to be regionalized. Two models, each having the capability of emphasizing regional differences yet integrating the regions within the framework of the entire U.S. economy, were used to explore the feasibility of adding water resources constraints: the Regional Energy System

Optimization Model (RESOM), currently under development at the Brookhaven National Laboratory, and the Energy Policy Model (EPM) of the Lawrence Livermore Laboratory, developed on the basis of the Gulf-Stanford Research Institute model.

The RESOM model is a single-period static formulation, and it has two major components:

1. a multiregional interindustry input-output submodel;
2. a multiregional linear programming submodel representing in detail energy-related activities.

In this study, equations representing the water sector were integrated within the I-O submodel, and constraints showing regional availabilities of water resources were added to the LP model. As of this time, only the LP submodel of RESOM has been developed at the Brookhaven National Laboratory; the regional data for the I-O submodel has yet to be produced. Hence, only the LP submodel was used for testing the feasibility of integrating water resources constraints into RESOM, yielding a matrix of more than 1700 rows and some 3000 columns. Computer runs made using 1975 data indicated, as expected, that in 1975 water was not a constraining element in energy-related activities. Other runs used a scenario for the year 2000 in which the following assumptions were made:

- Population growth and increase in the standard of living will more than double the total end-use energy demands, as compared with 1975.
- Water resources available for energy-related activities will be less than 75% of the 1975 quantities, due primarily to the increase in population, increase in the standard of living, increase in food production through irrigated agriculture, and further industrial expansion.

Results of these demonstration of feasibility runs indicate that the incorporation of water availabilities into the model does affect regional energy-related activities, such as considerable reduction in oil-fired steam-electric generation in the central U.S. One should consider these results, however, only as indicative of the possible effects the constraining availabilities of water resources might have on energy-related activities.

The EPM model of the Lawrence Livermore Laboratory uses a general economic equilibrium formulation of the U.S. energy sector in a dynamic framework. Regions are defined separately for energy resource availability and production (supply), and for energy consumption (demand). The integration of water resources into this model requires primarily that regional water availabilities be described by means of supply curves. As an exploratory exercise, this was done in only one energy supply region, namely the Rocky Mountain Region, which contains both the Upper Colorado and the Upper Missouri River Basins. It was necessary to aggregate the two river basins into one region to correspond to the existing energy supply-based regionalization of the EPM model. Since the two river basins were aggregated, a composite supply curve for water was produced, as well as an aggregated projection for nonenergy water use for the entire region. The aggregation of the two river basins is probably one of the more serious distortions of the formulation, since it implies complete mobility of the available water througout the Rocky Mountain Region (and is less constraining than in reality). Even with this far-reaching assumption, the influence of reduced availabilities of water resources, as assumed for this feasibility demonstration, vis-a-vis the increasing energy demands can be detected as early as the year 2000; for example, the amount of power generated by nuclear plants (LWR) (relatively water intensive) begins to drop at the end of this century.

To attain an assessment of the effects of water resources availability on the energy sector, it is proposed to capitalize on the modeling feasibility demonstrated in this study, primarily by developing an improved water-energy-economy model so as to focus on problems arising out of the water-energy interactions. In this way, regions could be identified where water availability may inhibit significantly the rate at which energy resources could be developed and utilized, and these regions could be ranked on a time scale, thus suggesting priorities for further studies in greater subregional detail.

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Section 1

INTRODUCTION

This is an exploratory study of energy-water resources interactions to determine the feasibility of integrating water constraints into energy models. The Continental U.S. has vast quantities of energy resources and large amounts of surface and groundwater. However, the distribution of water resources does not parallel that of energy resources, and in areas where water is relatively scarce it may influence appreciably the rate at which energy resources could be developed. Availability of water supplies adequate in quantity and in quality ranks, alongside the proximity of fuel supply and the load (demand) centers, as an important criterion for the siting of thermal power stations. Similarly, the rate at which oil shale could be developed in the future will probably be conditioned to a great extent by water availability.

The purpose of this study is to clarify the role which water plays in the development and operation of the energy sector in the U.S., so as to identify some of the critical issues which are likely to arise in water-energy interactions. The study is focused on the integration of water resources constraints within energy models, hereby constructing water-energy-economic models. These models should offer guidelines useful to policymakers and managers in the energy sector, emphasizing the acquisition, use, treatment, and discharge of water.

This study consists of five tasks:

1. review of water resources data base (Section 2);
2. review of technologies involved in energy development and their water use requirements (Section 3);
3. review of energy models, with emphasis on regional disaggregation (Section 4);
4. a feasibility study for the incorporation of water resources constraints in energy models (Section 5);
5. preliminary demonstration runs of energy systems models containing water resources constraints and water consumption data associated with energy technologies (Section 6).

The emphasis in task 4 was on clarifying some methodology issues arising when integrating water resources constraints into existing energy models. The title of Section 5, which summarizes this task, was, therefore, modified accordingly.

Two existing energy systems models were selected for the incorporation of water resources constraints: RESOM (Regional Energy System Optimization Model), developed by Brookhaven National Laboratory; and EPM (Energy Policy Model), of the Lawrence Livermore Laboratory. Data reflecting water resource availability and water use by energy-related activities were included in these models.

Section 2

REVIEW OF WATER RESOURCES DATA BASE

INTRODUCTION

A distinction should be made between data and assessments. A data base is probably unique, at least in the sense of "natural data" [Nunamaker and Pingry 1978]: these are streamflow (discharge) measurements and groundwater table elevations, rainfall and snowpack data. In another sense, these are barely raw numbers, which have to be further processed so as to make them useful for planning, design, or any other purpose. An example of processed hydrological data is a list of average monthly discharges at a given point on a stream, including their probabilistic and statistical characteristics, such as frequencies, expected values, variances, and coefficients of skewness.

If to the natural data is added information regarding technologies, economic factors, legal considerations, water quality standards, and so on, a basis is formed for an assessment of the availability of water resources in a given region for a stated purpose. Thus, an assessment will have two sets of components:

1. nature-related, i.e., streamflows (surface and subsurface) and other hydrological and meterological information;
2. man-related, i.e., economics, technologies, laws, traditions, demands, aspirations, etc.

The first set of components of an assessment indicates the physical limits of the natural resources (water, energy) with which we deal; the second set, however, appears to be less immutable than the first. Nevertheless, the degree and the difficulty with which any single man-related component may be changed varies within a wide range. For example, lifestyles may be rather resistant to change, especially in a direction in which standards of living are reduced. Technology, on the other hand, has manifested at times quantum-like jumps. In general, a specific combination of man-related components of an assessment will define a scenario, which may be used in a quantitative evaluation of decisions and policies relevant to the development of energy resources.

THE DATA BASE ASSEMBLED BY THE EPRI SUPPLY PROGRAM

The EPRI Supply Program is currently engaged in an effort for the assembly of a water supply data base [Nunamaker and Pingry 1978]. The thrust of this effort is threefold:

1. to identify pertinent water resources information at national and regional levels;
2. to design a system which will enable EPRI (and others) to make maximum use of this information;
3. to implement this system on a publicly accessible computer.

The result is an information system which has two components, a "macro" data base and a "micro" data base. Both components are computerized.

The "macro" data base is essentially a bibliographic system in which the information is assembled in lists called "records." There are nine such records: ENTRY, ORGANIZATION, DATA-BASE, KEYWORD, REGION, CONFERENCE, PUBLISHER, JOURNAL, AUTHOR.

ENTRY is a set of bibliographic records, each including full bibliographic reference and an abstract. The following are defined: MONOGRAPH, ARTICLE, CHAPTER, UNPUBLISHED REPORT, PAMPHLET, THESIS, CONFERENCE PROCEEDING, CONFERENCE PAPER.

ORGANIZATION is a list of agencies and other institutions which maintain water information of some kind. There are 10 types of organizations: federal, state, local, university, water research center, private, regional, defunct (e.g., Federal Water Pollution Control Administration), international, other.

DATA-BASE contains information of various types. Each type includes a synonym for use with the "micro" data base, where details may be obtained. Ten types of information are defined: data (computerized), data (manual), bibliographic (computerized), bibliographic (manual), legal (computerized), legal (manual), research collection, directory (computerized), directory (manual), other.

KEYWORD is a list of only two types: legal, and data-base-content.

REGION, CONFERENCE, PUBLISHER, JOURNAL and AUTHOR are self-explanatory.

The "micro" data base is a system capable of storing, maintaining, updating, manipulating, and retrieving information in an EPRI Water Supply Data Base; it can also be used to access external data banks (national, regional, and state) for the purpose of acquiring and displaying a desired piece of information. Thus the "micro" system consists of two main subsystems:

1. software for describing and reporting information from sources external to the EPRI Water Supply Data Base;
2. a data base management subsystem for storing these descriptions and reports.

The "micro" data base has two major characteristics:

1. it is capable of handling queries about external water supply data banks;
2. it is capable of storing descriptions of contents of these banks.

The major data banks to which the "micro" data base has access are those assembled by the United States Geological Survey (USGS) and by the Environmental Protection Agency (EPA).

DATA BASES COMPILED BY USGS

The United States Geological Survey is the governmental agency which collects, on a continuous basis, hydrological data and assembles a great deal of other information pertinent to water resources. Much of its work is accomplished through cooperation with other agencies -- regional, state, and local. The information so acquired is accessible through two computerized data banks: NAWDEX and WATSTORE.

NAWDEX (National Water Data Exchange) [Edwards 1977, 1978] is an instrument for identifying sources of hydrological information and for connecting users of this information with those who acquire it. It is a confederation of water-oriented organizations cooperating to provide convenient access to their data located at the USGS National Center in Reston, Virginia. This program performs two major tasks:

1. it maintains a directory of organizations that collect water data;
2. it maintains a master water data index which contains over 80,000 sites at which measurements are made throughout the United States.

In addition, NAWDEX can provide direct access to the daily values file of the National Water Data System of the USGS, so that this minutely detailed information can be retrieved and displayed.

WATSTORE (Water Data Storage and Retrieval) is a large-scale computerized system which is capable, in addition to data processing, storage, and retrieval, of performing statistical analyses of data and displaying their results by means of tables and graphs. It consists of a number of files, which contain the following information:

- quantitative and qualitative measurements of surface and groundwater on a daily or continuous basis;
- annual peak values for streamflow (surface) stations;
- chemical analyses of surface and groundwater;
- geologic information regarding groundwater;
- index of sites for which data are stored in the system;

The daily values file contains currently about 120 million items of information, including streamflow discharges, river stages, reservoir contents, water temperatures, specific electric conductance values, sediment discharges, sediment concentration, and groundwater levels.

The annual peak file contains also computer software for the calculation of flood frequencies and their associated curves.

The water quality file contains results of analyses which describe water quality in terms of chemical, biological, physical, and radiological parameters, as defined by the Environmental Protection Agency.

The groundwater file is cross-referenced to both the daily values and to the water quality files.

DATA BASE COMPILED BY EPA

The Environmental Protection Agency is the governmental body which collects water quality information. This information is handled by STORET (Storage and Retrieval), a computerized data bank which has capabilities for storing and retrieving information, as well as for processing and analyzing the data [U.S. Environmental Protection Agency 1977]. The information handled refers to

- water quality,
- water quality standards,

- point sources of water pollution (municipal and industrial waste discharge),
- fish kills caused by pollution,
- waste abatement needs,
- implementation schedules and costs.

The software may be divided into two main categories:

1. water quality data programs, which include water quality analysis in terms of chemical, physical, and biological parameters (about 2000 in all, 187 of which cover about 85% of the data);
2. waste discharge inventories related to about 24,000 locations.

STORET does not have an explicit effluent discharge file.

WATER RESOURCES ASSESSMENT BY WRC

The Water Resources Planning Act of 1965 (P.L. 89-90) directs the Water Resources Council to maintain a continuing study of the adequacy of the U.S. water resources to meet current and future requirements for these resources. The first assessment was published in 1968. The second assessment uses 1975 as a base year for purposes of analysis and makes projections for 1985 and 2000.

The second national water assessment has undergone a number of revisions [U.S. Water Resources Council 1977] and it is still in draft form [U.S. Water Resources Council 1978a, 1978b]. This assessment involved three major phases:

- Phase one: A nationwide analysis was carried out by the Council's member agencies* reflecting their current and future requirements, their perceptions of problems related to the use of water, and their possible implications.
- Phase two: Specific problems were analyzed in each of the 21 water resources regions (18 in the 48 conterminous states, Alaska, Hawaii, and the Caribbean) reflecting state and regional existing and future water-related problems, conflicts arising out of meeting state and regional objectives, and identifying issues needing resolution.

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*Member agencies: U.S. Departments of Agriculture, Army, Commerce, Energy, Housing and Urban Development, Interior, Transportation, and EPA. Observers: Attorney General's Office, Office of Management and Budget, Council on Environmental Quality, Interagency Committees, and River Basin Commissions.

- Phase three: A national problem analysis includes

  --an evaluation of results of the first two phases;

  --identification of the nation's most serious water resources problems;

  --documentation of analysis results.

The second national water assessment will be published as a series of reports and accompanying appendixes. The following is a list of reports currently contemplated.

- Summary -- is an overview of the final report, including a resume of water supply conditions, water use appraisal, identifies critical problems, and draws conclusions of the second assessment.
- Part I, Introduction -- outlines the purpose of the assessment and presents an historical perspective.
- Part II, Water Management Problem Profiles -- identifies 10 most critical issues and their implications.
- Part III, Functional Water Uses -- presents national perspectives regarding existing (1975) and future (1985, 2000) requirements for water to meet offstream, instream, and flow management needs for major functional uses.
- Part IV, Water Supply and Water Quality Considerations -- focuses on the adequacy of freshwater supplies to meet existing and future requirements.
- Part V, Regional Summaries -- analyzes conditions in each of the 21 water resources regions and recommends state-regional scenarios regarding planning, research, data needs, and cooperation with federal agencies.
- Statistical Appendix, A-1 -- presents economic, social, and environmental data for 1975, 1985, and 2000 on which water supply and use projections are based.
- Statistical Appendix, A-2 -- contains streamflow information, reservoir storage capacity, groundwater data, interbasin imports and exports, and instream flow estimates for 1975, 1985, and 2000.
- Statistical Appendix, A-3 -- contains annual streamflow depletion analyses for average and dry years; annual water use-supply analyses for average and dry years; summaries of monthly and annual streamflow depletion analyses for average and dry years; monthly water use-supply analyses for average and dry years; average annual water supply analysis. All these analyses are presented in aggregated form at regional level and in detail for each subregion.

WATER RESOURCES ASSESSMENTS BY THE BUREAU OF RECLAMATION

The Bureau of Reclamation of the U.S. Department of the Interior is charged with the planning of water resources development west of the Mississippi River. One of its major activities is the assembly of relevant information and the assessment of available water resources for specific uses. Traditionally, the Bureau of Reclamation was concerned primarily with the development of irrigated agriculture in the Western United States. Lately, however, it began a series of studies related to future development of energy resources [Water for Energy Management Team 1974, Water for Energy Management Team 1975, Bureau of Reclamation 1975]. This effort still continues, and there appears to be a substantial degree of cooperation with the Water Resources Council [Kauffman 1978, Davenport 1978].

The assessments of the Bureau of Reclamation seem to embody the outlook of the bureau: all future scenarios are oriented heavily toward continuous development of irrigated agriculture in the West at a fairly high rate, without much discussion of the availability of land areas suitable for such intensive cultivation. However, the usefulness of the USBR assessments resides in their estimates of water availability, i.e., water currently not utilized for any purpose (domestic, irrigation, industrial use, energy, recreation, etc.). These estimates have focused primarily on the Upper Colorado River Basin and the Upper Missouri River Basin, where significant energy resources are found (primarily coal and oil shale) and where water resources are limited.

Estimates of the mean annual flow of the Colorado River vary, but most of them are around 15.1 Maf* (million acre-feet) [Wollman and Bonem 1971]. The U.S.-Mexico Treaty of 1944 guarantees Mexico an annual amount of 1.5 Maf, leaving about 13.6 Maf/yr for the United States. The seven states which share the Colorado River Basin -- Wyoming, Utah, Colorado, Nevada, New Mexico, Arizona, and California -- signed in 1922 an agreement known as the Colorado River Compact, which divided the basin into an upper and a lower basin, and which apportioned to each of the two basins in perpetuity 7.5 Maf/yr. Clearly, the Colorado River Compact predated the U.S.-Mexico Water Treaty and could not anticipate obligations of the U.S. towards Mexico. Furthermore, the quantity of 15.1 Maf/yr (average total flow) was based on data accumulated during a period of relatively abundant flows. Therefore, revised estimates of the Bureau of Reclamation [Water for Energy Management Team 1974]

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*1 ac-ft = 1233.6 m^3

consider that only 5.8 Maf/yr would be available for consumptive use in the upper basin. Of this amount, the consumptive use in 1974 was in excess of 3.7 Maf/yr, as shown in Table 2-1, leaving 2.1 Maf/yr unused [Buras 1977a].

Table 2-1

CONSUMPTIVE USES OF WATER, UPPER COLORADO RIVER BASIN, 1974

Use	Thousand Acre-feet/Year	Percent of Total
Irrigation	2,154	58.1
Transbasin exports	754	20.3
Evaporation from reservoirs	520	14.0
Livestock ponds	79	2.2
Recreation, fishing, and wildlife	77	2.1
Mining	48	1.3
Municipal and industrial	38	1.0
Thermal power plants	38	1.0
Total	3,708	100.0

Source: Water for Energy Management Team 1974.

The Upper Missouri River Basin is defined by the watershed which contributes to the flow of the Missouri River at Sioux City, Iowa [Water for Energy Management Team 1975]. The estimated mean annual flow at Sioux City is 28.3 Maf/yr. The consumptive use (depletion) in 1970 was 6.5 Maf/yr, as shown in Table 2-2, leaving an availability of 21.8 Maf/yr on the average.

Table 2-2

CONSUMPTIVE USES OF WATER, UPPER MISSOURI RIVER BASIN, 1970

Use	Thousand Acre-feet/Year	Percent of Total
Irrigation	4,200	64.6
Evaporation from reservoirs	1,900	29.2
Other uses	400	6.2
Total	6,500	100.0

Source: Water for Energy Management Team 1975.

The minimum water requirements downstream from Sioux City for hydropower generation and navigation require an annual release into the Lower Missouri River Basin of 11.7 Maf/yr on the average [Buras 1977b]. This leaves in the upper basin an amount of 21.8 - 11.7 = 10.1 Maf/yr available for use.

The state engineer of the state of Utah has recently reviewed the Bureau of Reclamation figures relevant to the Upper Colorado River Basin [Hansen 1976]. His estimate of the amount of water apportioned to the Upper Colorado River Basin is higher than that of the Bureau of Reclamation -- 6.3 Maf/yr. However, the total consumptive use in 1975 was 3,647,000 acre-ft. The amount of unconsumed water in 1975 is, therefore, between 2.153 and 2.653 Maf/yr.

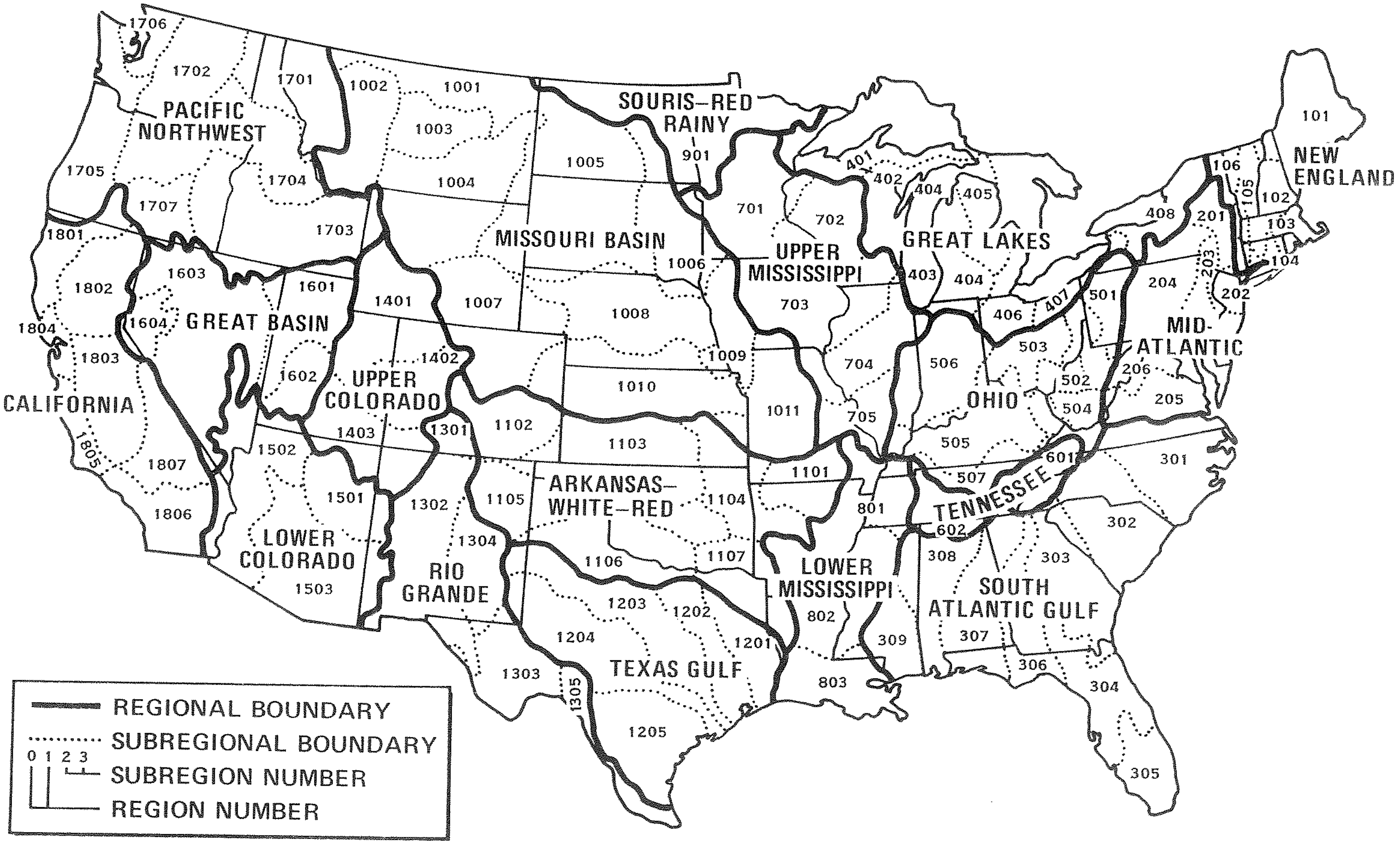
Recently, the water availability in the Upper Missouri River Basin has been estimated at 11.3 Maf/yr [Gibbs 1976].

OTHER ASSESSMENTS

A recent study [Harte and El-Gasseir 1978] shows the mean annual runoff (surface flow) and the 1975 consumptive use of water for each of the regions defined by the Water Resources Council. (See Figure 2-1.) The data relevant to the 48 counterminous states is shown in Table 2-3. The point of this assessment is that, although current consumptive uses of water aggregated over the entire United States appear to be of the order of only 10% of total mean annual runoff, the actual supply and demand for water are highly variable across time and space. Therefore, depending upon the development scenario used, one can estimate at which point in time water availability may become a constraining factor in any given region.

USE OF DATA BASES AND ASSESSMENTS IN WATER-ENERGY MODELS

The usefulness of a water-energy model -- or, for that matter, any model -- is greatly dependent on the reliability of its data base. On the other hand, the usefulness of the details contained in a data base depends upon the level of analysis which uses the information. For example, the detailed information contained in the USGS data base WATSTORE or in the EPA bank STORET would be most useful to planning organizations or even for the detailed design of specific components of water resources systems.



Source: U.S. Water Resources Council 1977

Figure 2-1. Water Resources Regions and Aggregated Subregions of the United States

Table 2-3

REGIONAL RUNOFF AND 1975 CONSUMPTIVE USE OF WATER
(Million acre-feet per year)

Region	Mean Annual Runoff	Consumptive Use
New England	75.4	0.49
Mid-Atlantic	97.3	1.78
South Atlantic Gulf	219.0	4.14
Great Lakes	81.1	1.22
Ohio	137.9	1.38
Tennessee	46.2	0.36
Upper Mississippi	73.0	1.05
Lower Mississippi	81.1	6.16
Souris-Red-Rainy	7.0	0.14
Missouri	60.8	19.46
Arkansas-White-Red	81.1	12.98
Texas-Gulf	35.7	10.54
Rio Grande	5.6	4.87
Upper Colorado	14.6	2.76
Lower Colorado	3.6	8.11
Great Basin	8.1	4.46
Pacific Northwest	235.2	14.60
California	69.7	27.57
Total	1,320.4	122.03

Source: Harte and El-Gasseir 1978.

For the purpose of the present study, because of the regional differences of water availability, the basic information should be regionalized in a meaningful way. An adequate regionalization, with some modifications, would be that of the Water Resources Council. One modification which seems obvious is to separate the Upper Missouri River Basin, because of the important coal deposits found in it.

The regionalization of the data bases and of models should enable the ranking of regions in accordance with the degree at which water may become a constraining element in the development of regional energy resources, including electric power generation. The ranking will then provide a priority scale for the overall research effort. This concept is illustrated graphically in Figure 2-2. Suppose that the entire U.S. is divided into two regions. For each region one can estimate the long-term average of annually available water with a given probability. Considering development scenarios for these regions which translate into monotonically increasing demands for water, the demand function will intersect the availability

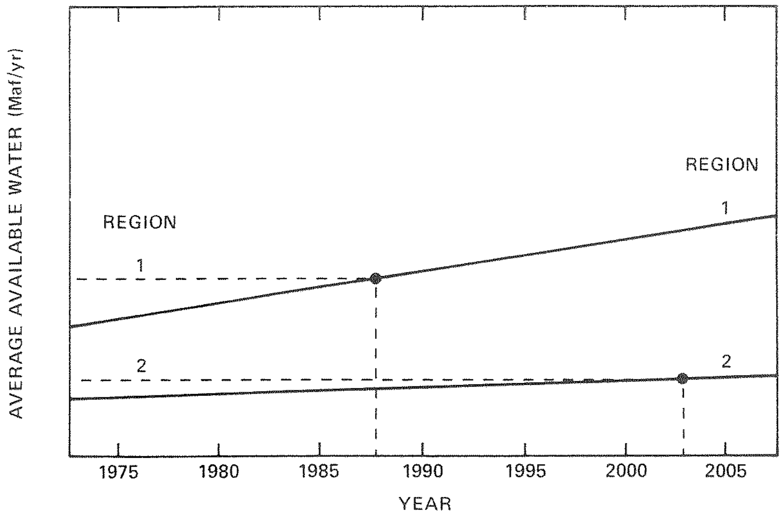


Figure 2-2. A Hypothetical Example of Regional Development Reaching Limits of Water Availability

limit at a certain point in time. In this way, one could forecast the time period when water-related problems will arise in each region, given a development scenario and the technology of water utilization. According to these hypothetical examples, water-related problems will appear around 1987 (Region 1), and 2002 (Region 2).

The various data bases and assessments could also be used to define scenarios to be tested by means of the water-energy models. The importance of evaluating the possible outcomes of different scenarios (also sometimes called "alternative futures") has been stressed in many recent papers [Committee on Water Resources Planning 1976]. To paraphrase Schoeffler [Wismer 1971], optimizing only the energy sector of a national (or regional) economy without regard to the effects of interactions may lead to degraded performances in the other sectors, such as water, land, etc., so that overall process performance is worse than without optimization. A regionalized water-energy model based on regionalized data and assessments will, hopefully, avoid this pitfall.

Section 3

REVIEW OF TECHNOLOGIES INVOLVED IN ENERGY DEVELOPMENT

INTRODUCTION

In this review, emphasis is placed on the amounts of water required by the different technologies. Water requirements have two components: withdrawal, and consumption. Water withdrawn is water abstracted from a supply source but not necessarily consumed: part of it may return to the same supply source. Water consumed is water which becomes unavailable for further uses. For example, the once-through cooling of thermal power plants requires the withdrawal of large amounts of water; however, only a relatively small proportion of it is evaporated, thus becoming unavailable for any other use. Our concern in this review is primarily with the consumptive uses of water by the different energy-related technologies.

Consumptive use of water has quantitative as well as qualitative aspects. The quantitative aspect is clear, especially if we refer to the example presented above. The qualitative aspect involves the removal of waste products of energy-related activities, particularly material wastes, thus rendering the water highly polluted. Almost always the waste water is unsuited for any further use, thus becoming part of the consumptive use of the production process. Reclamation of waste waters to a certain degree is possible and wherever this is done the consumptive use can be reduced by the amount reclaimed.

The following technologies involved in energy development are briefly discussed:

- coal liquefaction,
- coal gasification,
- thermal electric power generation,
- oil shale conversion,
- fuel refining,
- coal slurry pipelines,
- coal mining.

COAL LIQUEFACTION

For some time, coal liquefaction was considered to be the least advanced of the technologies involved in energy development [Dickinson et al. 1976]. Yet liquefaction is one method by which coal may be effectively upgraded so as to meet stringent environmental criteria, by reducing sulfur content and by a more complete ash removal [McNamee et al. 1978].

Early estimates of water requirements by coal liquefaction [Davis and Wood 1974] used as a rule of thumb 0.2 ac-ft/yr per barrel of fuel oil equivalent per day production capacity. This meant that a "standard" 100,000 bbl/day plant may use consumptively 20,000 ac-ft of water per year. A later assessment [Gold et al. 1977] evaluated water consumption by coal liquefaction plants, each having a capacity of 100,000 bbl/stream-day,* at four different locations in the Western United States. The following categories of water consumption were considered:

- the coal conversion process itself;
- evaporation for process cooling;
- flue gas desulfurization, where required;
- coal mining operations and land revegetation;
- disposal of solid waste and other uses within the mine liquefaction plant complex.

The results are summarized in Table 3-1.

Table 3-1

WATER CONSUMED BY COAL LIQUEFACTION[a]

Location	Water Consumption (ac-ft/yr)
Beulah, N. Dak.	10,090
Colstrip, Mont.	10,300
Gillette, Wyo.	9,230
Navajo-Farmington, N. Mex.	11,750

[a] Plant capacities, 100,000 bbl/stream-day

Source: Gold et al. 1977.

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*The ratio of stream-day to calendar-day is 0.9.

The variation in water consumption reflects local differences.

The most recent evaluation of water requirements by coal liquefaction technology [McNamee et al. 1978] considers plants having an output of 50,000 bbl/day fuel oil equivalent.[*] The typical plant receives the coal washed, so that the water requirements represent only the consumptive uses within the coal liquefaction plant itself.

Two types of liquefaction processes are considered: the solvent refined coal process (SRC), and the catalytic hydroliquefaction (CHL). Two cases were examined for each type: a case of normal operating conditions, and a case of more severe operating conditions, so as to lower the sulfur content of products. Some characteristics of the four cases are shown in Appendix C.

The items related to water requirements are divided into two categories: raw water, and waste water.[**] About 70% of raw water is being consumed (evaporated), and about 30% leaves the plant carrying waste material (waste water).

The raw water requirements and the waste water generated by a 50,000 bbl/stream-day coal liquefaction plant are summarized in Table 3-2.

Table 3-2

SUMMARY OF RAW WATER REQUIREMENTS AND WASTE WATER GENERATED
(thousand acre-feet per year)

Item	Case 1 (SRC)	Case 2 (CHL)	Case 3 (SRC)	Case 4 (CHL)
Raw water				
Process water	0.320	0.332	0.327	0.378
Boiler makeup	1.109	1.423	0.324	1.934
Cooling-tower makeup	9.225	11.898	10.373	15.694
Potable water	0.161	0.161	0.161	0.161
Total	10.815	13.814	11.185	18.167
Waste water				
Nonoily wastes	0.084	0.108	0.024	0.147
Boiler blowdown	0.399	0.518	0.452	0.678
Cooling-tower blowdown	2.689	3.420	2.996	4.482
Sanitary sewage	0.121	0.121	0.121	0.121
Total	3.293	4.167	3.593	5.428

Source: McNamee et al. 1978.

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[*] 1 bbl fuel oil equivalent = 6.3×10^6 Btu [McNamee et al. 1978].

[**] See Appendix A, Glossary.

If electric power is not generated at the coal liquefaction plant but is purchased from other sources, the overall thermal efficiency of the SRC process under normal operating conditions (Case 1) will increase from 71.8% to 84.1%. Such an alternative was examined under two variants:

1. steam in excess of process requirements is used to generate electric power, thus satisfying some of the power demand -- Case 1A;
2. use of the excess steam directly in process drivers -- Case 1A1.

A comparison of power and capital requirements of these two variants with Case 1 (SRC) -- the least-cost case of the four alternatives examined above -- is shown in Appendix C. The raw water requirements and the generated waste water are identical in both variants; the comparison with Case 1 (SRC) is given in Table 3-3.

Table 3-3

RAW WATER REQUIREMENTS AND WASTE WATER GENERATED, CASES 1, 1A, 1A1
(thousand acre-feet per year)

Item	Case 1 (SRC)	Cases 1A, 1A1 (electric drive, steam drive)
Raw water		
Process water	0.320	0.320
Boiler makeup	1.109	0.530
Cooling-tower makeup	9.225	5.548
Potable water	0.161	0.161
Total	10.815	6.559
Waste water		
Nonoily wastes	0.084	0.084
Boiler blowdown	0.399	0.190
Cooling-tower blowdown	2.689	1.618
Sanitary sewage	0.121	0.121
Total	3.293	2.013

Source: McNamee et al. 1978.

Table 3-3 indicates that electric power generation at the coal liquefaction plant requires 4256 ac-ft of water per year (579 ac-ft for boiler feedwater makeup and 3677 ac-ft for cooling-tower makeup); and it will generate 1280 ac-ft of waste water per year (209 ac-ft of boiler blowdown and 1071 ac-ft of cooling-tower blowdown).

COAL GASIFICATION

Gasification of coal produces a low-Btu fuel gas (less than 400 Btu/scf),* which may be used directly in a combined-cycle system for electric power generation, or be further processed to attain pipeline quality (954 Btu/scf). The further processing involves methane synthesis and the product is often called syntane.

There are three main types of coal gasification technologies:

1. moving-bed,
2. fluidized-bed,
3. entrained-bed.

The first two involve high pressure processes (340 psig);** the other may be carried out also at atmospheric pressure. Each gasification technology can use either air or oxygen as oxidant.

There are two major variants in the moving-bed technology: (1) the Lurgi process, and (2) the BGC (British Gas Corporation) slagger. The entrained-bed technology has three major variants: (1) high pressure, (2) low pressure, and (3) Texaco process. In the Texaco process, the coal is fed to the gasification plant by means of a slurry (and its water can be used for the chemical processes and for cooling), or as a dry powder. Table 3-4 indicates the energy content of the gas produced by the different technology alternatives [Kimmel et al. 1976, Chandra et al. 1978].

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*scf, standard cubic foot

**psig, pounds per square inch gage

Table 3-4

ENERGY CONTENT OF COAL GASIFICATION TECHNOLOGIES

Technology	Symbol	Btu/scf
Moving-bed		
Lurgi, air	MACW	189
Lurgi, oxygen	MX	302
BGC slagger, oxygen	MXSC	379
Fluidized-bed		
air	FA	158
oxygen	FX	323
Entrained-bed		
air, high pressure	EAHC	174
oxygen, high pressure	EXHC	315
air, low pressure	EALC	113
oxygen, low pressure	EXL	312
oxygen, Texaco process	EXTC	281

Sources: Kimmel et al. 1976, Chandra et al. 1978.

The water consumption of a Lurgi coal gasification process followed by methane synthesis to yield high-Btu gas (954 Btu/scf) in a plant producing 250 Mscf/day is estimated as follows [Davis and Wood 1974]:

	ac-ft/yr	% of total
evaporative cooling	4,143	35.3
process water	3,075	26.2
coal mining	1,817	15.5
evaporation from waste ponds	1,258	10.7
losses within the plant	1,174	10.0
wet ash	266	2.3
Total	11,733	100.0

Most of the water (83.4%) has to be made up by exogenous supplies (river, groundwater, etc., 9784 ac-ft/yr). The moisture in the coal supplies is 9.1% of the required water(1069 ac-ft/yr); and the H_2O generated during the methane synthesis forms the remaining 7.5% (880 ac-ft/yr).

The synthane process, which yields synthetic gas of pipeline quality, consumes nearly twice as much water as the Lurgi process, which produces low-Btu gas, as seen in Table 3-5 [Gold et al. 1977].

Table 3-5

WATER CONSUMED BY COAL GASIFICATION TECHNOLOGIES[a]
(acre-feet per year)

Location	Lurgi (low-Btu)	Synthane (high-Btu)
Beulah, N. Dak.	3,310	7,670
Colstrip, Mont.	4,610	7,810
Gillette, Wyo.	4,210	7,780
Navajo-Farmington, N. Mex.	5,640	8,670

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[a] Plant yield, 250×10^6 Mscf/stream-day; load factor, 0.9
Source: Gold et al. 1977.

Recent analyses of coal gasification processes are based on plant capacities of 10,000 tons of coal per day [Kimmel et al. 1976]. Some of the plant characteristics are shown in Appendix C. These plants produce, in addition to low-Btu gas, liquid hydrocarbons which may also be used as fuels. Some of the steam generated in these plants, as well as some heat derived from exchange processes, may be used to generate electric power as a by-product.

Water consumption by low-Btu coal gasification processes is shown in Table 3-6.

Recent studies consider low-Btu coal gasification as part of combined-cycle systems for electric power generation [McElmurry 1977, Chandra et al. 1978]. The size of the power plants is 1000-1300 MW, and some of their characteristics are shown in Appendix C.

The consumptive use of water, in acre-feet per year/1000 MW electric, is summarized in Table 3-7. In the case of the EXTC-SF process, the water-coal ratio in the slurry feed is 0.503, by weight.

THERMAL ELECTRIC POWER GENERATION

The overall thermal efficiency of fossil-fueled power plants is less than 38%; that of nuclear plants is approximately 31% [Davis and Wood 1974]. This means that fossil-fueled plants must dispose of 1.6 MWh of waste heat for every megawatthour of electricity produced. One way to do so is to use the waste heat beneficially, either in industry or for space heating in commercial and residential buildings. Another way is to reject the waste heat by means of cooling. Most cooling methods

Table 3-6

WATER CONSUMED BY LOW-Btu COAL GASIFICATION PROCESSES[a,b]
(acre-feet per year)

Water Use	MACW	MX	FA	FX	EALC	EXL
Steam vented to atmosphere	3	3	3	3	3	3
Blowdown	97	172	103	71	73	51
Process water	3,845	5,985	1,532	1,435	69	72
Cooling water[c]	6,118	4,830	6,405	4,379	5,313	4,025
Total	10,063	10,990	8,043	5,888	5,458	4,151

Source: Kimmel et al. 1976.

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[a] Plant capacities, 10,000 tons of coal per year.

[b] For a key to symbols, see Table 3-4.

[c] Additional cooling water makeup is obtained from treated process condensate, except in EALC and EXL processes.

involve evaporation of water. When one kilogram (2.2 lbs) of water is evaporated, i.e., it passes from liquid to vapor, it loses its latent heat of vaporization of 2.5×10^6 joules (2370 Btu).

Four methods of cooling are considered:

1. once-through cooling,
2. cooling-pond,
3. wet-cooling towers,
4. dry-cooling towers [Hirsch et al. 1977].

Combinations of wet- and dry-cooling towers may also be possible [Gold et al. 1977].

Once-through cooling involves pumping water from a river, lake, or ocean, and passing it across the steam condensers. The cooling water thus heated is returned to the same river, lake, or ocean, where it mixes with the existing water. The locally increased temperature of the natural water body due to the inflow of cooling water increases its evaporation rate, and this increase should be attributable to the power plant. Once-through cooling has the advantage of lower rates of water

Table 3-7

WATER CONSUMPTION BY LOW-Btu COAL GASIFICATION COMBINED-CYCLE SYSTEMS FOR ELECTRIC POWER GENERATION[a]
(acre-feet per year/1,000 MWe)

Water Use	MACW	MXSC	EAHC	EXHC	EALC	EXTC-SF	EXTC-DF
Process water	3,553	1,343	800	1,660	253	583	1,726
Cooling tower	9,174	9,470	9,861	9,665	11,977[b]	12,217	11,681
Slurry feed	---	---	---	---	---	1,292	---
Total	12,727	10,813	10,661	11,325	12,230	14,092	13,407

Sources: McElmurry 1977, Chandra et al. 1978.

[a] For a key to symbols, see Table 3-4. SF indicates slurry feed of coal; DF direct (dry) feed of coal.

[b] If product gas is further compressed so as to increase steam turbine power at generator terminals from 307 MW to 422 MW, thus reducing the net heat rate from 8959 Btu/kWh to 8951 Btu/kWh, the cooling-tower water consumption will rise to 12,630 ac-ft/yr.

consumption, lower capital costs, and higher generating efficiency. Its main disadvantage is that it involves the withdrawal of very large quantities of water.

The cooling-pond method overcomes most of the disadvantage of the once-through cooling. After an initial filling of the pond from a river or lake, water from the pond is used to cool the power plant. The evaporation losses from a pond are 50% larger than for once-through cooling, because it includes the natural evaporation from the pond as well as that induced by waste heat rejection. This evaporation loss is made up by water from the stream or lake. However, if the makeup water would equal exactly the evaporation loss, the dissolved solids which exist in any natural water body would accumulate, increasing the salinity of the cooling water. Beyond a certain concentration, the increased salinity may cause corrosion of heat exchanging surfaces, or deposit scale on them. In order to prevent this occurrence, the makeup water is increased by about 10% and the excess is released from the cooling pond back to the river or lake, carrying with it some of the accumulated salts (blowdown). The cooling-pond method has the great advantage of requiring a much smaller amount of withdrawal (as compared with once-through cooling), but its major disadvantage is that it requires substantial land areas for the cooling pond.

Wet-cooling towers reject waste heat as the cooling water comes into close contact with moving air. The air is driven either by fans or by natural buoyancy. The makeup water must replenish also the losses caused by blowdown, which are about 10% of the evaporation loss. The main disadvantages of wet-cooling towers are additional capital costs, loss of power plant efficiency due to the energy requirements of the fans and of the pumps, and a certain loss of thermodynamic efficiency due to higher cooling water temperatures.

Dry-cooling towers reject waste heat only by the conduction of sensible heat. (No latent heat of vaporization is involved.) The principle is similar to a car radiator, where a fan blows air across finned tubes through which the cooling water circulates. The dry-cooling system is much more expensive than the other three, since it involves a radiator-type structure constructed of thin-walled metal tubing. In addition, the loss in plant efficiency due to the fan and pump requirements is quite substantial. Similarly, losses of thermodynamic efficiency can be substantial when the ambient air temperature is high.

Table 3-8 shows a comparison of the four cooling methods for a 1000 MWe fossil-fueled (coal-fueled) power plant operated at about 38% efficiency and a load factor of 83%, located in the Colorado River Basin at 6000 ft altitude.

Table 3-8

COMPARISON OF FOUR COOLING TECHNOLOGIES

Item	Once-through	Cooling-pond	Wet-tower	Dry-tower
Water withdrawal (ac-ft/yr)	537,500	11,425	11,100	0
Water consumption (ac-ft/yr)	6,950	10,375	11,100	0
Electricity generated (kWh/yr)	8.15×10^9	8.15×10^9	8.10×10^9	7.58×10^9
Electricity generated (once-through = 100)	100	100	99	93

Source: Hirsch et al. 1977

Many estimates of water consumption by thermal electric power generation published recently refer to coal-fired plants with wet-cooling towers. Incidentally, it is estimated that nuclear plants consume 50% more water than conventional facilities [Davis and Wood 1974]. The water consumption estimates refer to generating plants of 1000 Mwe capacity.

An earlier estimate [Davis and Wood 1974], considering 38% overall thermal efficiency for fossil fueled plants (1000 MWe), is as follows:

	ac-ft/yr
evaporation loss	14,475
blowdown	3,619
Total makeup water (consumption)	18,094

A detailed study [Gold et al. 1977] of six specific locations in the Western United States (Beulah, N. Dak.; Colstrip, Mont.; Gillette, Wyo.; Kaiparowits/Excalante, Utah; Navajo/Farmington, N. Mex.; Rifle, Colo.) considers coal-fired plants of 35% efficiency at 70% load factor. The water consumption averaged over the six locations is given below:

	ac-ft/yr	
evaporative cooling	7,662	(7,183- 7,941)
blowdown	1,443	(778- 1,998)
boiler makeup	338	
Total	9,443	(8,299-10,277)

A coal-fired power plant with flue gas desulfurizer of 34.4% efficiency [McElmurry 1977] yields the following estimate:

	ac-ft/yr
evaporative cooling	7,457
cooling-tower blowdown	4,379
water in scrubber sludge	615
Total	12,451

A recent estimate relating to a coal-fired power plant with gas scrubber having an efficiency of 34.4% at a 70% load factor [Chandra et al. 1978] indicates total raw water makeup at 22,773 ac-ft/yr.

Thus, the water consumption for a 1000 MWe coal-fired power plant using wet-tower cooling is estimated between a low value of 9443 ac-ft/yr [Gold et al. 1977] and a high of 22,773 ac-ft/yr [Chandra et al. 1978]. The higher value is related to a power plant having a gas scrubber.

OIL SHALE CONVERSION

The oil shale deposits of the Green River Formation in Colorado, Utah, and Wyoming contain probably the largest known oil resource in the world [Weeks et al. 1974], estimated at about 600×10^9 bbl. This quantity is found in deposits more than 10 ft thick and averaging 25 gal of oil per ton.* If deposits of same thickness but averaging at least 15 gal/ton are considered, the oil resource is estimated at 1800×10^9 bbl.

Retorting the oil shale in order to extract from it the kerogen -- an organic compound which is subsequently upgraded to yield an oil-like substance called syncrude -- can be done either on surface, i.e., after the oil shale has been mined, or <u>in situ</u>. It appears that <u>in situ</u> retorting consumes considerably less water than surface processes, but the technology is yet in the initial stages of development [Smith 1978]. The surface retorting technologies are of two kinds: hot solids-to-solids heating, and gas-to-solids heating [Dickinson et al. 1976]. The first kind involves the use of ceramic balls for heating crushed oil shale, and this process is called TOSCO II. The second kind has two variations:
(1) internal gas combustion, used by the Paraho Development Corporation;
(2) external heat generation, used by Petrobras, the Brazilian National Oil Company.

The TOSCO II process, named after the Oil Shale Corporation, is probably the most advanced technology of oil shale conversion in the sense that it is ready for commercial application, and all details regarding water requirements below will refer to it. To be sure, oil shale conversion using the TOSCO II process requires large amounts of resources.

For example, a plant producing syncrude at the rate of 100,000 bbl/day will require the following [Dickinson et al. 1976]:

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*As estimated by the Fisher assay.

capital	750×10^6 1973$
oil shale	54×10^6 ton/yr or 140,000 ton/day
water	16,000 ac-ft/yr
electric power	170 MWe
labor	1,700 people

The mining operation supplying this plant will be larger than the largest mine in the U.S. -- the Bingham Canyon open-pit copper mine, which yields 110,000 ton/day -- and 10 times larger than the largest underground coal mine.

An additional environmental problem related to oil shale conversion is that of the spent shale. The spent shale volume is on the average 50% greater than the original mined shale [Gold et al. 1977] and its compaction and settlement require large amounts of water. For example, it is estimated that the spent shale of 100,000 bbl/day plant will produce every day a pile about 1000 ft long, 120 ft wide, and 25 ft high.

Estimates of water consumptive uses for a 100,000 bbl/day plant using the TOSCO II process vary from a low of 13,073 ac-ft/yr [Gold et al. 1977] to a high of 30,250 ac-ft/yr [Gardner et al. 1976]. The details of the low estimate are given below. The plant, which has a nominal capacity of 100,000 bbl/day at 90% load factor, has the following output:

fuel oil	94,000 bbl/day
liquefied petroleum gas	8,660 bbl/day
coke	1,600 ton/day

Consumptive water uses are estimated as follows:

			ac-ft/yr
mine-dust suppression			1,016
revegetation			203
crusher-dust suppression			653
dust control on processes shale			726
retorting:			
shale crushing		261	
preheating and ceramic balls circulation scrubber		900	
miosturizer scrubber		44	
moisturizer:			
from dust suppression	319		
makeup water	1,423		
		1,742	
			2,947
upgrading:			
hydrogen plant		1,619	
steam used in upgrading		639*	
wash water, gas treating unit		523*	
steam to coker		87*	
boiler blowdown		377**	
			3,245
cooling tower:			
evaporation		2,903	
blowdown		871**	
			3,774
fire, service, drinking water			436*
losses in water treatment plant			73
Total			13,073

The processed shale which exits the plant carries with it 3920 ac-ft/yr of water. This amount is made up of the cooling-tower blowdown, the boiler blowdown, and other quantities of water involved in the retorting and upgrading phases of the process. Thus, if one combines the cooling-tower blowdown (871 ac-ft/yr) with the

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*These amounts of water, totaling 1685 ac-ft/yr, may be partly reclaimed and reused. Assuming 75% reclamation efficiency, a saving of 1264 ac-ft/yr, or 9.7%, may be attained.

**These amounts are further used in retorting and upgrading.

consumptive uses of retorting and upgrading (2947 and 3245 ac-ft/yr, respectively), yielding a total of 7063 ac-ft/yr, and subtracts from it the water content of the spent shale (3920 ac-ft/yr), the balance of 3143 ac-ft/yr represents the actual amount of water which becomes part of the product (fuel oil, liquified petroleum gas, and coke). Thus, product water amounts to 24% of total consumptive use, while the spent shale carries with it 30% of the water consumption. Evaporation losses from the cooling tower form 22.2% of the total water consumed by the TOSCO II process.

FUEL REFINING

Nuclear Fuel

The estimated water demands for nuclear fuel to be supplied to a 1000 MWe light water reactor generating electricity at 80% load is as follows [Davis and Wood 1974]:

	ac-ft/yr
uranium ore milling	200
uranium enrichment, evaporative cooling	277
production of uranium hexafluoride	12
reprocessing of reactor products	11
Total	500

The generation of power used in the uranium enrichment processes requires, in addition, 490 ac-ft/yr for evaporative cooling.

Oil

In general, the refining of one barrel of oil uses consumptively one barrel of water [Davis and Wood 1974]. A refining operation of 10^6 bbl/day will use the following amounts of water:

	ac-ft/yr	% of total
evaporative cooling	33,416	71
boiler water feed	12,237	26
sanitary and other uses	1,412	3
Total	47,065	100

COAL SLURRY PIPELINES

Water used to transport coal by means of slurry pipelines usually leaves the hydrological unit where it occurs naturally, or where it is developed, and cannot be reused for other purposes in the same river basin. Hence, from a regional point of view, water for coal slurry pipelines is a consumptive use, unless there is a return water pipeline.

Water is used in coal slurry pipelines for two purposes. First, water is used to wash the coal before it is shipped. The water so used can be reclaimed through a settling tank for reuse. The amount of water involved in coal washing is relatively small and may be neglected. Second, water is used as a transport medium. At the terminal of the pipeline, the powdered coal is separated from the water in the slurry through flocculation and the water so reclaimed can be used for cooling.

In general, water makes up 50% of the slurry, by weight [Gold et al. 1977], i.e., in order to transport 10^6 tons of coal, it is necessary to use 730 ac-ft of water. A more detailed analysis [Palmer et al. 1977] indicates that, in order to move 12.5×10^6 tons of coal per year over a distance of 1000 mi (e.g., from Wyoming to Houston, Texas), the optimum (minimum cost) coal-to-water ratio is 52-48. The costs considered were those related to the size of the pipeline and those related to the energy necessary to overcome frictional resistance in the pipe. The greater the coal-to-water ratio, the smaller the diameter pipe is required; hence, the pipe-related costs decrease. However, the viscosity of the slurry increases, requiring greater energy input. The optimum ratio, as mentioned, is in the neighborhood of 52-48. This means that, in order to move 12.5×10^6 tons of coal per year over 1000 mi in a slurry containing 48% water, by weight, 8500 ac-ft of water per year are consumed, or 680 ac-ft/10^6 tons of coal. For comparison, the amount of 8500 ac-ft is equivalent to the annual water supply to a city of about 75,000 inhabitants. In order to transport the same amount of coal (12.5×10^6 tons) by rail, 1250 unit trains are required, or one unit train every seven hours approximately on the average.

Comparing a coal slurry pipeline with other coal-based energy-related activities, it uses one-third as much water as coal gasification and only one-fifth of the water required for on-site electric power generation. Regarding transportation of energy (a distance of 1000 mi), energy losses are 4.6% of the potential electrical output of coal transported by slurry pipeline; 4.2% of that of coal transported by unit train; and 6.5% of the electric power generated on site and transmitted over high-voltage (600 kV)dc transmission lines.

COAL MINING

The indirect effects of coal mining on regional water resources may be more significant than direct consumption of water by mining-related activities. Surface coal mining in the Western United States will disturb, at least temporarily, the groundwater conditions and will affect surface hydrology [Fluor Utah, Inc. 1975]. One should consider that coal seams are often water bearing (aquifer) formations, and that strip mining can produce topographic depressions where "dead" lakes may trap water and prevent it from reaching natural streams.

In general, water use for coal mining is relatively low: 25-175 ac-ft/10^6 ton [James, II and Steele 1977]. However, since the planned capacity per mine in Montana and Wyoming averages 50-75% more than the production in the largest mine existing in the United States in 1974 [Nehring et al. 1976], the aggregate effect of coal mining in the West may be substantial.

The consumptive use of water in coal mining falls within the following categories:

- mine, road, and embankment dust control;
- dust control in handling and crushing coal;
- service and fire water;
- sanitary and potable water;
- water for revegetation;
- coal washing.

Since coal is not uniform in its qualities, the amount of water consumed per Btu mined will vary from location to location. Recent work [Gold et al. 1977] investigated the consumptive uses of water in coal mining at six different locations in the Western United States: Beulah, N. Dak.; Colstrip, Mont.; Gillette, Wyo.; Kaiparowits/Escalante, Utah; Navajo/Farmington, N. Mex.; Rifle, Colo. All sites involved strip mining, except for Kaiparowits-Escalante in Utah, where underground mining is considered. Table 3-9 summarizes the information, in acre-feet/10^{15} Btu mined.

Table 3-9

CONSUMPTIVE USE OF WATER IN COAL MINING[a]
(acre-feet/10^{15}Btu mined)

Use	Beulah, N. Dak.	Colstrip, Mont.	Gillette, Wyo.	Navajo, N. Mex.	Rifle, Colo.	Kaiparowits, Utah
Mine dust control	1,340	730	360	1,010	790	2,630
Crushing, dust control	1,080	860	870	890	570	420
Service and fire	70	60	70	100	80	80
Sanitary and drinking	10	10	10	20	30	80
Revegetation[b]	---	---	---	1,360	---	50
Coal washing[c]	---	---	---	---	---	4,440
Total	2,500	1,660	1,310	3,380	1,470	7,700

Source: Gold et al. 1977.

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[a] Strip mining at all locations, except Kaiparowits, Utah

[b] Revegetation requires water where precipitation is less than 10 in/yr.

[c] Necessary only for coal mined underground

SUMMARY OF WATER USES

Energy-related activities consume the following estimated amounts of water, acre-feet/10^{15} Btu output:

Nuclear power stations (LWR)*	592,800
Fossil-fueled power stations*	395,200
Coal gasification, high-Btu gas	103,400
Coal gasification, low-Btu gas	57,700
Oil shale conversion	61,700
Coal liquefaction	57,000
Nuclear fuel processing*	41,300
Coal slurry pipeline	34,000
Oil refining	22,200
Underground coal mining	7,700
Strip coal mining, revegetation	3,400
Strip coal mining, no revegetation	1,800

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*1 kWh = 3412 Btu

Section 4

REVIEW OF ENERGY MODELS WITH REGIONAL DISAGGREGATION

REGIONALIZED MODELS

One has to make the distinction between regional and regionalized models. A regional model refers to a portion of a larger geographic entity, defined in accordance with some criteria. A regionalized model should, ordinarily, represent the interrelationships between the regions within the larger geographic entity. Both types of models imply a hierarchical structure; however, only regionalized models can have this structure explicitly expressed. A schematic representation of a regionalized model is shown in Figure 4-1. The point stressed in this figure is that constraining conditions on energy resources (e.g., import quotas on oil and gas, nuclear power development) are easier to define at the national level, while water resources and environmental restrictions can be defined meaningfully only at the regional level.

Models related to regions can be classified into three groups:

1. national models which may be applied to regional energy planning [Hoffman 1973];
2. regional energy models, e.g., the Rocky Mountain States [Bullock-Webster 1974]; the State of Illinois [Brill, Jr. et al. 1976]; the Upper Colorado River Basin [Morris 1977];
3. regionalized models.

The models considered in this section are Battelle, ICF, Gulf-SRI, Bechtel, Brookhaven, ETA-MACRO, and Upper Colorado.

The discussion which follows will focus on regionalized models and will include the model developed by Morris for the Upper Colorado River Basin. Morris' model, although restricted in extent to one region, subdivides it into three subregions, thus developing an interesting methodology for approaching hierarchically structured regionalized models.

An earlier review of regional energy modeling [Cohen and Costello 1975] specifies the following criteria for model evaluation:

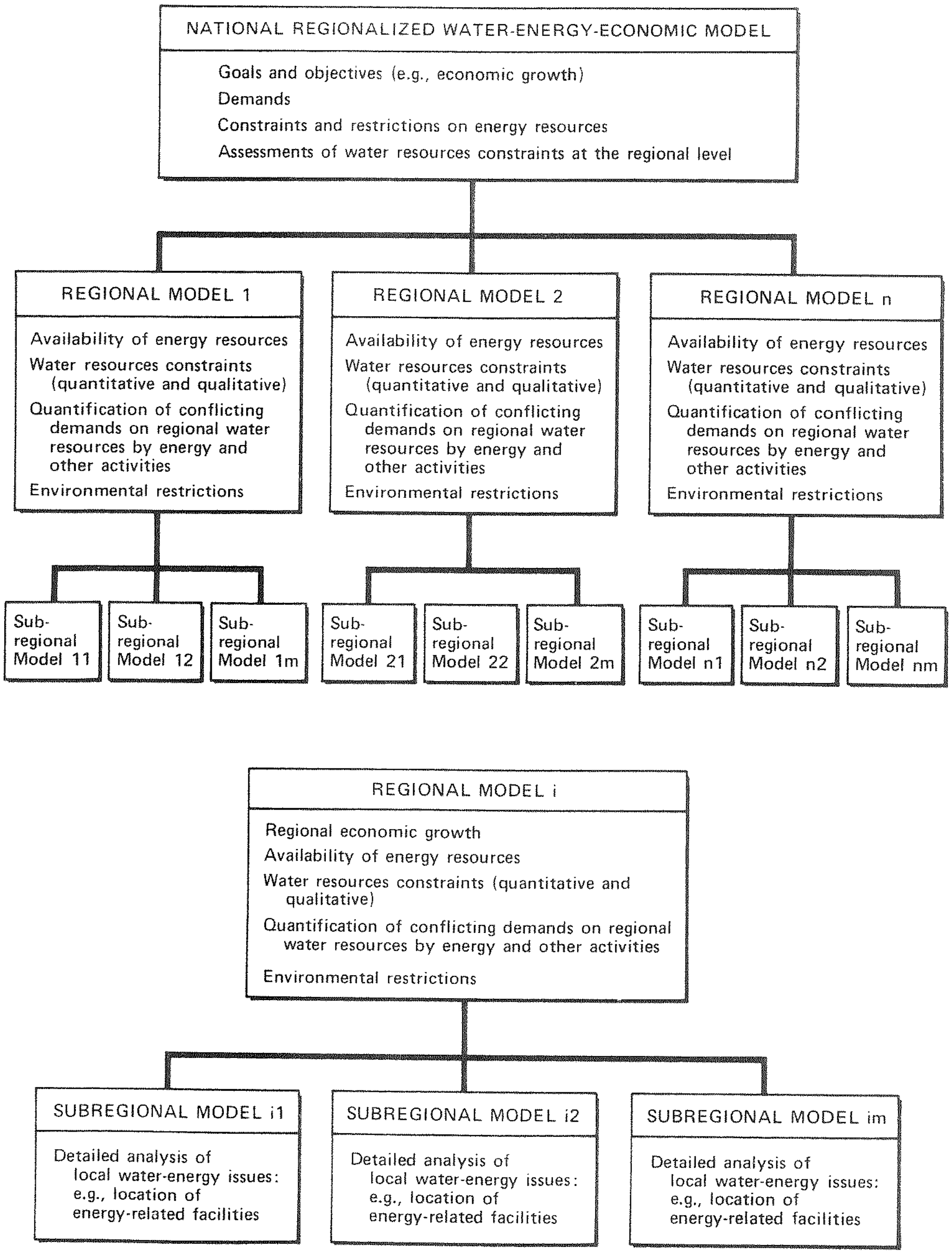


Figure 4-1. An Outline of Regionalized Water-Energy-Economic Models Showing a Hierarchical Multilevel Structure

- their comprehensiveness regarding detail (spatial, i.e., regions, energy supply sources, energy demand sectors);
- economic aspects included in the models (determinants of total supply and demand, such as prices and incomes, interfuel competition, interregional competition);
- their capabilities to reflect policy changes (e.g., import quotas, conservation measures) and technology changes, such as the introduction of solar energy.

Nine models were reviewed by Cohen and Costello, but only three were found to include relevant regional disaggregation: the Battelle Columbus-EPA Energy Quality Model, the Energy Management Simulation and Analysis System (EMSAS), the Project Independence Evaluation System (PIES). The first model is restrictive in the sense that it focuses primarily on air quality requirements in each of 238 air quality control regions and it omits important details in the demand sectors (e.g., no transportation sector). The second model (EMSAS), a simulation model, does not allow for interregional competition. The PIES model, structured by Census regions, allows for interdependence among them. The model reflects competition between producing and consuming regions, as well as interfuel competition. Its main disadvantages include lack of production constraints, omission of environmental costs, and an underestimated market share of coal.

A regionalized model of the electric power industry alone [Reardon 1975] refers to the nine regions defined by the National Electric Reliability Council (NERC). The model uses a linear programming formulation to optimize the long-range development of the U.S. electric generating industry. Regionally dependent characteristics, such as coal and oil prices, availability of alternate energy sources (hydro, geothermal), energy demands and systems loads, are processed by means of submodels and then used as inputs to a linear programming model formulated at the national level. The thrust of the model is to determine the minimum present value of the costs of building and operating all power plants in the U.S. between 1968 and 2000, with special emphasis on nuclear power generation. Because of this emphasis, all variables related to the nuclear fuel cycle are considered to be regionally independent and are, therefore, represented adequately at the national level. As mentioned before, all regional characteristics are dealt with in submodels, only to appear as constraining conditions on the national scale. Because of its emphasis on only one energy-related activity, this model was not used in the more general study of integrating water constraints into energy models.

Another regionalized model restricted to only one part of the energy sector is the National Coal Model [ICF 1977, ICF 1978]. This is a detailed linear programming model which has 40 different coal types, 35 demand regions, 30 supply regions, and six consuming sectors. This formulation yields equilibrium solutions reflecting the impact of various scenarios on the supply of and demand for energy; thus, it is price-sensitive. The model is static, but it can be used to study arbitrarily chosen "case years." For example, Table 4-1 summarizes a sensitivity analysis of the western coal produced in 1990. The analysis shows that the western coal production in 1990 will increase significantly (22.6% above base case) if there is a surge in the growth rate of the electric power generation (sensitivity run No. 3). On the contrary, coal production in the West in 1990 will be depressed by 17.4% if rail transportation rates will increase 50% by 1985 (run No. 11). (Coal slurry pipeline was not considered as an alternative.) The western coal production in 1990 also is sensitive to low severance tax (as opposed to actual state severance taxes in the base case), to low rates of growth of electric power generation, to the absence of sulfur removal from the western coal, and to the 2% annual escalation in labor costs. In all other sensitivity runs (No. 1, 5, 6, 7, 10, and 12), the results were within ±10% of the base case. The model is insensitive regarding the quantities of western coal used in 1990 for synthetic fuel production. In all cases, the western coal consumption for this purpose was 0.625 quad. Being restricted to only one energy source -- coal, the ICF model was not used in this study.

The SRI energy model is described by a network [Cazalet 1976] which has 14 resource regions, six refinery regions, nine demand regions, and three groups of end-use locations (residential-commercial, industrial, transportation). The network has a hierarchical structure in the sense that the flow is generally from a resource region to a refinery region, to a demand region, to end-use locations. An important exception is that transportation may be allowed between locations at the same level in the hierarchy. Thus, interregional transportation networks reflect transportation processes of western and/or eastern coal, via unit trains or by slurry pipeline.

Given end-use energy demands in each of the nine demand regions, the Gulf-SRI model indicates the market share of different energy resources and technologies satisfying these demands. The model is dynamic in character, covering a span of fifty-one years (1975-2025), which can be divided into a number of timeperiods. Different mixes of energy sources and technologies may be obtained for the satisfaction of end-use demands, depending upon different scenario assumptions. A version of the Gulf-SRI model developed by the Lawrence Livermore Laboratory was used in this study.

Table 4-1

WESTERN COAL PRODUCTION, 1990

Sensitivity Run		Production	
No.	Description	10^6 tons	Index
0	Base case	652.1	100.0
1	Coal severance tax: 30%, except in Arizona	612.4	93.9
2	Coal severance tax: 5%, except in Arizona	763.1	117.0
3	Electricity growth rate: 5.8%/yr (1975-1985) 5.0%/yr (1985-1990)	799.6	122.6
4	Electricity growth rate: 3.8%/yr (1975-1985) 3.0%/yr (1985-1990)	572.5	87.8
5	Oil price: $20/bbl (1985); $30/bbl (1990)	668.4	102.5
6	Oil price: $13/bbl (1985 and 1990)	596.9	91.5
7	Sulfur removal requirements: 90%	640.6	98.2
8	Sulfur removal requirements: 1.2 lb/10^6 Btu (no scrubbing for western coal)	721.9	110.7
9	Labor cost escalation: 2%/yr	722.6	110.8
10	Labor cost escalation: none	627.6	96.2
11	Rail transportation costs: increase 50% by 1985	538.9	82.6
12	New combined-cycle oil-fired plants included	642.7	98.6

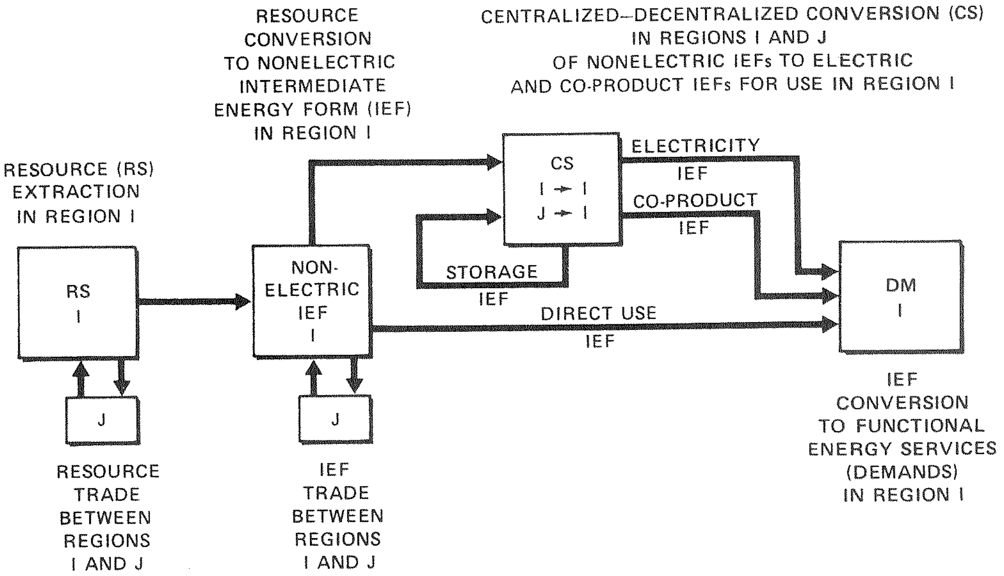
Sources: ICF 1977, ICF 1978.

The Bechtel Energy Supply Model [Carasso et al. 1975] simulates the capital, labor, materials, and industrial production capacity required for the construction and operation of energy supply and transportation facilities within the 1975-1995 time frame. The simulation can be performed so as to analyze alternative energy policies and their impacts on a national and regional scale. The model has 14 regions, including three which refer to the continental shelf (Atlantic Coast, Gulf of Mexico, Pacific Coast) and converts a specified scenario into direct annual requirements for facilities and resources. The level of detail may be regional or national. An important aspect of this model is that future energy mixes for any year of interest within the time frame are considered to be matters of policy and have to be specified. These specifications are inputs to a submodel which generates a fuel mix. The fuel mix is input to national and regional energy facilities generators which output energy facilities schedules. These schedules are input to a further submodel which generates interregional fuel allocation and transportation facilities schedules. The transportation facilities, the energy facilities, and the facility resource data are input to national and regional resource requirements generators which output the final result -- the resource requirement schedules. These may be exhibited on a yearly basis, or cumulatively for the entire time horizon. The Bechtel model was considered too cumbersome for this exploratory study.

A detailed multiregional energy and interindustry model was developed recently at the Brookhaven National Laboratory [Goettle, IV et al. 1977]. This model allocates optimally energy resources produced regionally, and indicates the optimal mix of energy supply, conversion, and demand technologies, in accordance with a specified criterion (e.g., least-cost). The linear programming formulation of this model links the nine Census regions by interregional energy and industrial flows. It allows for intraregional interfuel substitution and preserves the dependence of the energy sector on the broader regional economic system of which it is a part. The model is static, single-period, yet may be used for multiobjective analyses. A schematic representation of a regional energy system is shown in Figure 4-2. The regional energy submodel is fairly detailed and includes the following components:

- regional resource extraction activities, represented with the aid of step-function approximations of concave supply curves;
- renewable energy resources (hydro, geothermal, solar);
- regional resource availability, distinguishing between interregionally tradeable (coal, crude oil, shale oil, uranium ore) and interregionally nontradeable resources, thus allowing for interregional imports and exports of energy resources;
- regional resource conversion to nonelectric intermediate energy forms (IEF) via appropriate conversion technologies;
- regional production of nonelectric IEFs, which sums up, for each IEF, the yields of the conversion processes defined in the previous paragraph;
- regional nonelectric IEF availability, which distinguishes between interregionally tradeable and nontradeable IEFs;
- regional use of available nonelectric IEFs, for the generation of electricity and co-product IEF, and/or to satisfy interregional end-use demands;

- regional end-use demands, specified exogenously as nonsubstitutable quantities (e.g., Btu of residential space heat);
- the regional electric sector, reflecting details such as baseload, electric space heat, or off-peak load;
- additional components, showing capacity constraints on conversion activities and technologies, export-import limitations, environmental effects, etc.



Source: Goettle, IV et al. 1977

Figure 4-2. A Generalized Diagrammatic View of a Regional Energy System

The interindustry part of the model is represented by a multiregional input-output model of the form

$$X = C(AX + Y) \quad , \qquad (1)$$

where

X is a column vector of total production, by industry and by region;

Y is a column vector of final demands, by industry and by region;

A is a block-diagonal square matrix of interindustry technological coefficients;

C is a square matrix of main-diagonal submatrices of trade flow coefficients.

The energy sectors are represented in this structure by the resource, supply, and conversion activities, as well as by end-use demands for energy. This model was used for studying the integration of water constraints.

The ETA-MACRO energy-economy model [Manne 1977] represents a dynamic nonlinear optimization process, combining an assessment of energy technology with a macroeconomic growth model. This is not a truly regionalized model, since all activities are described at the national level. However, the model does specify explicitly production of synthetic fuels and shale oil conversion. If one can assume that these activities are restricted to the western part of the United States, then ETA-MACRO can be considered as a two-region (East-West) model. This model is too aggregated to be useful in a study of integrating water constraints.

The Upper Colorado River Basin was modeled as a regionalized model consisting of three regions: the upper main stem of the Colorado; the Green River; the San Juan River [Morris 1977]. The model has an interregional input-output scheme imbedded into a linear programming framework. The formulation allows for two alternative objective functions: either the maximization of the regional income, or the specification of the level of activities which will yield a given minimum regional income. The objective function of the first alternative is expressed as

$$\max \quad Z = \sum_i c_h^i x_h^i \quad , \tag{2}$$

where

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

c_h^i is a weight coefficient applicable to the total gross output of the household sector in region i.

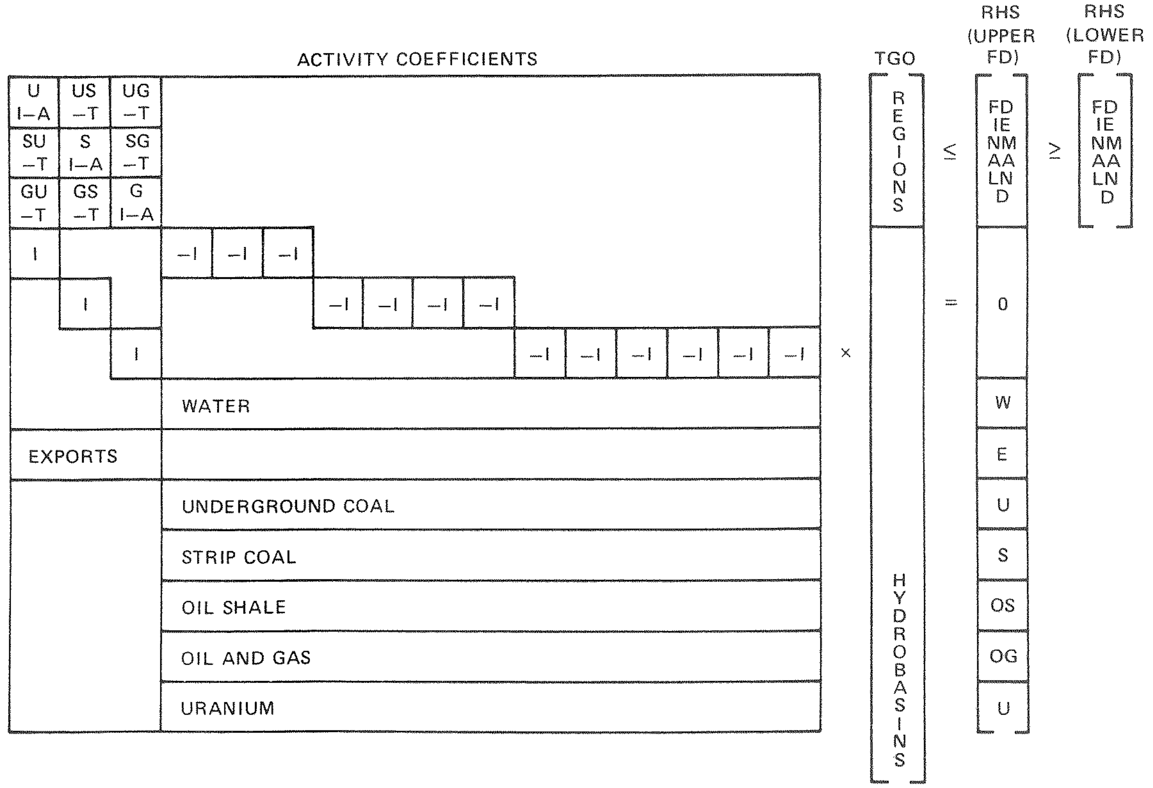
Observe that, by omitting the coefficients c_h^i from the objective function, interregional income distribution effects are ignored. The constraints of the model are represented schematically in Figure 4-3.

The notation which is not clear in the documentation is as follows:

TGO -- total gross output
FD -- final demand
-- food production
IE -- industry
NM -- mining

AA -- all other services
LN -- local government
D -- new energy technologies
U -- upper main stem of Colorado region
-- underground coal
-- uranium availability
S -- San Juan River region
-- strip coal
G -- Green River region
I-A -- Leontief matrix
T -- a square matrix of estimated trade coefficients for trade between region i and region j
W -- water availability
E -- exports
OS -- oil shale
OG -- oil and gas

The model is one-period static, with all coefficients estimated for 1980. It is too restricted in area to be useful in this study.



Source: Morris 1977

Figure 4-3. Schematic Diagram of the Upper Colorado River Basin Policy Optimization Model

REGIONAL WATER SUPPLY AND DEMAND PROJECTIONS

These projections refer to regions defined by the Water Resources Council. The 48 conterminous states are divided into 18 regions, roughly hydrologic boundaries [U.S. Water Resources Council 1977]. These regions are further divided into subregions, as shown on the map in Figure 2-1 (page 12).

When considering demand projections, distinction should be made between withdrawal and consumption requirements.* To illustrate this distinction, the total water withdrawal in the U.S. in 1975 was 371.6 Maf, the consumptive use was 115.1 Maf (31% of the withdrawal), leaving a return flow of 256.5 Maf.

An important factor in estimating surface water supply is the storage capacity of the various reservoirs. Due to the mismatching in time between supply and demand, and because of the stochastic characteristics of the hydrological phenomena, storage facilities are necessary for the development of surface water resources. In order to supply every year with certainty an amount of water equal to the long-term average annual flow, an infinitely large reservoir is necessary. The aggregate storage available in 1975 in the U.S. enables the supply of 30% of the long-term average annual flow 95% of the time. Table 4-2 shows regionally aggregated streamflows, their mean values and select values of their probability distribution. The 5% exceedance values indicate that once in 20 years, on average, a flow of the specified magnitude, or larger, will occur; such flows may cause flooding. The 95% exceedance values indicate the levels of water shortages which may occur, on average, once in 20 years [U.S. Water Resources Council 1978a].

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*For definitions of terms, see Appendix A.

Table 4-2

STREAMFLOW ANALYSIS
(million acre-feet per year)

Region	Mean	Percentage Exceedance 5%	50%	80%	95%
New England	87.6	120.6	86.7	70.2	54.1
Mid-Atlantic	88.7	128.9	87.1	68.5	54.2
South Atlantic-Gulf	255.4	300.4	245.5	183.8	136.4
Great Lakes	81.4	116.4	80.3	64.2	50.3
Ohio	199.4*	284.5*	199.4*	157.9*	117.6*
Tennessee	45.7*	64.8*	45.7*	40.2*	35.2*
Upper Mississippi	135.5*	211.7*	135.5*	102.8*	73.1*
Lower Mississippi	485.0	847.8	485.0	315.8	226.2
Souris-Red-Rainy	6.7	12.8	6.3	3.8	2.0
Missouri	49.4*	83.2*	48.4*	33.5*	19.7*
Arkansas-White-Red	70.1*	135.2*	66.2*	41.9*	24.2*
Texas-Gulf	31.7	69.9	25.6	13.8	7.1
Rio Grande	1.3	4.9	0.7	0.3	0.2
Upper Colorado	11.2*	17.4*	11.2*	7.8*	4.4*
Lower Colorado	1.8	1.9	1.8	1.6	1.3
Great Basin	2.9	21.3	11.0	7.5	5.2
Pacific Northwest	285.9	386.1	284.8	238.9	201.3
California	53.1	99.3	50.6	34.0	22.4
Total	1,381.4	2,191.7	1,356.2	996.1	756.3

---

*These numbers are not included in total because they are inflows to another region.

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

Table 4-2 illustrates the variability of annual streamflow, expressed in terms of flow that is expected to be exceeded in a specific percentage of years. The differences between mean annual flows and flows with 50% probability of exceedance reflect the asymmetry of streamflow probability distributions. Mean annual flows are only part of the water supply generated in a region. Estimated water supply figures are shown in column "Runoff" of Table 4-7.

Groundwater is an important water resource in the U.S. It is estimated that within 2500 feet below ground surface there are about 100 × 10^9 ac-ft, half of which can be economically extracted. (To give an idea of this enormous water resource, note that the total amount of water in Lake Michigan is about 4 × 10^9 ac-ft; and the entire amount of water discharged by the Mississippi into the Gulf of Mexico during the last 200 years is approximately 94 × 10^9 ac-ft.) Table 4-3 summarizes the groundwater supplies, as estimated in 1975.

Table 4-3

GROUNDWATER SUPPLIES, 1975

	Current Withdrawals		Currently in Storage		
Region	Total (Maf/yr)	In excess of recharge* (Maf/yr)	Less than 2500 ft deep (Maf)	Feasible** to withdraw (Maf)	Depletion of amount feasible to withdraw, at current rate (years)
New England	0.7	0	na	na	?
Mid-Atlantic	3.0	0.03	4,946	1,271	424
South Atlantic-Gulf	6.2	0.3	na	13,692	> 2,000
Great Lakes	1.3	0.03	na	801	616
Ohio	2.0	0	4,295	1,176	588
Tennessee	0.3	0	na	1,627	> 2,000
Upper Mississippi	2.7	0	14,239	6,886	> 2,000
Lower Mississippi	5.4	0.4	7,970	3,905	723
Souris-Red-Rainy	0.1	0	2,158	528	> 2,000
Missouri	11.6	2.8	3,432	1,366	118
Arkansas-White-Red	9.9	6.2	2,038	1,532	155
Texas-Gulf	8.1	6.3	8,605	4,402	543
Rio Grande	2.6	0.8	49,221	5,753	> 2,000
Upper Colorado	0.1	0	3,236	239	> 2,000
Lower Colorado	5.6	2.7	1,753	na	?
Great Basin	1.6	0.7	2,898	525	328
Pacific Northwest	8.3	0.7	4,227	553	67
California	21.5	2.5	1,004	252	12

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*Seepage into aquifers from rain, snow, and surface water bodies.

**From aquifers of reasonable thickness, making pumping of groundwater economically attractive.

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

The projections for water withdrawal and consumption are given in Tables 4-5 and 4-6. Table 4-4 summarizes the situation in 1975. From these tables, we can see that in the year 2000 withdrawals will be only about 90% of their 1975 value. The consumptive use, however, will increase in the same interval by about 26%. In these tables, the withdrawals and consumptive uses are detailed in the following categories:

- Municipal and domestic: Average withdrawal is 107 gal per capita per day; consumption is 87 gal per capita per day. The difference is mainly water for city parks, street cleaning, etc. The average per capita withdrawal and consumption is not expected to change substantially during this century.

- Industrial use: 25% of the work force generates 27% of total earnings. By the year 2000, gross water requirements, including saline water, will increase 230%, yet total withdrawal will decrease about 52% due to recycling of water, about 20 times. Fresh water withdrawals will decrease 62%, from 56.9 Maf in 1975 to 21.8 Maf in 2000.

- Mining requirements: Include metals, nonmetals, and fuels; fuel mining uses about 62% of total mining consumptive use.

- The energy sector: Total energy use in 2000 is estimated at 162 quads, 45% of which will be converted to effective work. The remaining 55% will have to be dissipated, requiring substantial amounts of cooling water. Water withdrawals will decrease about 10%, from 99.3 Maf in 1975 to 89.4 Maf in 2000, although electricity use may grow 400% during the same period because of technologies using higher consumption/withdrawal ratios.

- Irrigation: Total cropland in the U.S. is about 460×10^6 acres, of which 42×10^6 are irrigated. Agricultural exports in 1975 are valued at over $\$20 \times 10^9$. Irrigation consumptive use is expected to drop from 83% of total consumptive use in 1975 to 71% in the year 2000, due to some increase in irrigation efficiency, to a decrease of withdrawals from groundwater because of depleted aquifers, and to higher consumption/withdrawal ratios in non-agricultural sectors.

Water supply and requirements in 1975, 1985, and 2000 are summarized in Table 4-7.

Table 4-4

FRESH WATER WITHDRAWAL AND CONSUMPTION, 1975
(million acre-feet per year)

Region	Withdrawal						Consumptive Use					
	Municipal and domestic	Industrial use	Mining (including fuels)	Steam-electric generation	Irrigation	Total	Municipal and domestic	Industrial use	Mining (including fuels)	Steam-electric generation	Irrigation	Total
New England	1.7	2.4	0.1	1.4	0.04	5.64	0.2	0.2	0.01	0.02	0.03	0.43
Mid-Atlantic	5.2	6.1	0.5	8.4	0.3	20.5	0.9	0.7	0.1	0.1	0.2	2.0
South Atlantic-Gulf	3.2	4.6	1.3	14.3	3.9	27.3	1.1	0.7	0.2	0.2	3.1	5.3
Great Lakes	4.8	14.8	0.8	27.3	0.2	47.9	0.7	1.6	0.2	0.2	0.1	2.8
Ohio	2.6	12.2	0.6	23.5	0.1	39.0	0.5	0.9	0.1	0.4	0.04	1.94
Tennessee	0.4	2.3	0.1	5.4	0.02	8.22	0.1	0.2	0.02	0.05	0.01	0.38
Upper Mississippi	2.2	2.3	0.4	8.6	0.2	13.7	0.4	0.3	0.05	0.1	0.2	1.05
Lower Mississippi	0.9	4.7	0.9	4.7	5.1	16.3	0.4	0.4	0.2	0.06	3.4	4.46
Souris-Red-Rainy	0.1	0.1	0.01	0.1	0.1	0.41	0.01	0.01	0.003	0.003	0.04	0.066
Missouri	1.4	0.7	0.3	4.0	35.4	41.8	0.4	0.2	0.1	0.08	15.9	16.68
Arkansas-White-Red	1.1	0.8	0.5	0.2	11.2	13.8	0.4	0.2	0.2	0.1	7.9	8.8
Texas-Gulf	1.7	2.2	1.2	0.8	12.9	18.8	0.6	0.6	0.6	0.1	10.5	12.4
Rio Grande	0.4	0.02	0.2	0.04	6.4	7.06	0.2	0.01	0.1	0.02	4.4	4.73
Upper Colorado	0.1	0.004	0.1	0.1	7.2	7.504	0.03	0.002	0.05	0.04	2.5	2.622
Lower Colorado	0.6	0.1	0.2	0.1	8.9	9.9	0.3	0.1	0.2	0.07	4.5	5.17
Great Basin	0.4	0.1	0.2	0.04	7.8	8.54	0.2	0.03	0.03	0.003	3.6	3.863
Pacific Northwest	1.2	2.6	0.1	0.3	37.2	41.4	0.3	0.4	0.02	0.01	12.3	13.03
California	3.8	0.9	0.3	0.03	38.8	43.83	1.6	0.3	0.2	0.03	27.2	29.33
Total	31.8	56.9	7.8	99.3	175.8	371.6	8.3	6.9	2.4	1.6	95.9	115.1
Percent	8.6	15.3	2.1	26.7	47.3	100.0	7.2	5.9	2.1	1.4	83.4	100.0

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

Table 4-5

FRESH WATER WITHDRAWAL AND CONSUMPTION, 1985
(million acre-feet per year)

Region	Withdrawal						Consumptive Use					
	Municipal and domestic	Industrial use	Mining (including fuels)	Steam-electric generation	Irrigation	Total	Municipal and domestic	Industrial use	Mining (including fuels)	Steam-electric generation	Irrigation	Total
New England	1.8	1.1	0.1	1.2	0.05	4.25	0.3	0.4	0.02	0.02	0.03	0.77
Mid-Atlantic	5.8	2.8	0.6	8.0	0.4	17.6	1.0	1.0	0.1	0.3	0.3	2.7
South Atlantic-Gulf	3.8	3.8	1.7	14.5	4.5	28.3	1.4	1.4	0.3	0.8	3.6	7.5
Great Lakes	5.3	4.6	0.9	25.4	0.2	36.4	0.7	1.9	0.2	0.6	0.2	3.6
Ohio	2.9	3.7	0.7	23.5	0.1	30.9	0.5	1.2	0.1	0.7	0.1	2.6
Tennessee	0.5	0.9	0.2	6.4	0.02	8.02	0.1	0.3	0.02	0.3	0.02	0.74
Upper Mississippi	2.4	1.0	0.5	7.1	0.3	11.3	0.4	0.3	0.1	0.4	0.3	1.5
Lower Mississippi	1.0	1.8	1.1	10.4	5.1	19.4	0.4	0.6	0.3	0.1	3.6	5.0
Souris-Red-Rainy	0.1	0.05	0.01	0.03	0.2	0.39	0.03	0.02	0.003	0	0.1	0.153
Missouri	1.5	0.3	0.4	6.5	44.1	52.8	0.4	0.1	0.2	0.3	19.7	20.7
Arkansas-White-Red	1.2	0.5	0.5	1.1	11.7	15.0	0.4	0.3	0.2	0.3	8.4	9.6
Texas-Gulf	1.9	2.9	1.3	1.1	10.5	17.7	0.6	1.1	0.7	0.3	8.5	11.2
Rio Grande	0.4	0.05	0.2	0.02	6.2	6.87	0.2	0.02	0.1	0.01	4.4	4.73
Upper Colorado	0.1	0.002	0.2	0.2	8.1	8.602	0.03	0.001	0.1	0.1	3.0	3.231
Lower Colorado	0.7	0.1	0.3	0.2	8.2	9.5	0.3	0.06	0.2	0.2	4.4	5.16
Great Basin	0.5	0.1	0.2	0.1	6.9	7.8	0.2	0.05	0.05	0.05	3.5	3.85
Pacific Northwest	1.3	1.5	0.2	0.2	38.8	42.0	0.3	0.6	0.02	0.1	15.0	16.02
California	4.3	0.9	0.4	0.2	39.0	44.8	1.8	0.4	0.3	0.1	28.2	30.8
Total	35.5	26.1	9.5	106.2	184.4	361.6	9.1	9.8	3.0	4.7	103.3	129.9
Percent	9.8	7.2	2.6	29.4	51.0	100.0	7.0	7.5	2.3	3.6	79.6	100.0

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

Table 4-6

FRESH WATER WITHDRAWAL AND CONSUMPTION, 2000
(million acre-feet per year)

Region	Withdrawal						Consumptive Use					
	Municipal and domestic	Industrial Use	Mining Including fuels)	Steam-electric generation	Irrigation	Total	Municipal and domestic	Industrial Use	Mining (including fuels)	Steam-electric generation	Irrigation	Total
New England	2.0	0.9	0.2	0.4	0.1	3.6	0.3	0.6	0.02	0.2	0.04	1.16
Mid-Atlantic	6.7	2.2	0.8	5.2	0.5	15.4	1.1	1.5	0.1	0.7	0.4	3.8
South Atlantic-Gulf	4.8	3.7	2.3	15.6	5.1	31.5	1.7	2.8	0.4	2.1	4.0	11.0
Great Lakes	5.9	3.2	1.2	18.0	0.3	28.6	0.8	2.3	0.2	1.6	0.3	5.2
Ohio	3.3	2.6	0.9	11.8	0.1	18.7	0.6	2.0	0.2	1.9	0.1	4.8
Tennessee	0.6	0.8	0.2	5.1	0.02	6.72	0.1	0.6	0.03	0.5	0.02	1.25
Upper Mississippi	2.7	0.8	0.6	4.0	0.4	8.5	0.4	0.6	0.1	1.2	0.4	2.7
Lower Mississippi	1.1	1.5	1.5	18.7	5.0	27.8	0.4	1.2	0.5	0.3	3.7	6.1
Souris-Red-Rainy	0.1	0.03	0.01	0	0.2	0.34	0.03	0.03	0.003	0	0.4	0.463
Missouri	1.7	0.3	0.5	5.5	40.6	48.6	0.4	0.2	0.2	0.7	19.7	21.2
Arkansas-White-Red	1.3	0.5	0.6	1.1	10.9	14.4	0.5	0.4	0.2	0.5	8.0	9.6
Texas-Gulf	2.2	2.7	1.4	2.5	8.3	17.1	0.7	2.1	0.7	1.1	6.8	11.4
Rio Grande	0.4	0.04	0.3	0.01	5.5	6.25	0.2	0.03	0.2	0.01	4.0	4.44
Upper Colorado	0.1	0.002	0.4	0.2	7.5	8.202	0.04	0.002	0.2	0.2	3.1	3.542
Lower Colorado	0.9	0.2	0.3	0.2	7.1	8.7	0.4	0.1	0.3	0.1	4.2	5.1
Great Basin	0.6	0.1	0.3	0.1	6.5	7.6	0.2	0.1	0.1	0.1	3.6	4.1
Pacific Northwest	1.4	1.3	0.2	0.6	33.6	37.1	0.3	1.0	0.03	0.4	14.8	16.53
California	4.9	0.9	0.4	0.4	38.9	45.5	2.1	0.6	0.2	0.3	29.5	32.7
Total	40.7	21.8	12.1	89.4	170.6	334.6	10.3	16.2	3.7	11.9	103.0	145.1
Percent	12.2	6.5	3.6	26.7	51.0	100.0	7.1	11.2	2.6	8.2	70.9	100.0

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

Table 4-7

SUMMARY OF U.S. WATER SUPPLIES AND REQUIREMENTS, 1975, 1985, 2000
(million acre-feet per year)

Region	Year	Stream* Inflow	Supply			Requirements			Remaining Stream Outflow	Instream Flow[d] (approx.)
			Runoff[a]	Imports	Mined ground-water	Consumed	Evaporation[b]	Exports		
New England	1975	0	88.0	0	0	0.5	0	0	87.5	77.3
	1985	0	88.0	0	0	0.7	0	0	87.3	
	2000	0	88.0	0	0	1.2	0	0	86.8	
Mid-Atlantic	1975	0	90.1	0.5	0.04	2.1	0	0	88.54	77.1
	1985	0	90.1	0.5	0	2.8	0	0	87.8	
	2000	0	90.1	0.5	0	4.0	0	0	86.6	
South Atlantic-Gulf	1975	0	260.45	0	0.38	5.45	0	0	255.38	202.33
	1985	0	260.45	0	0	7.59	0	0	252.86	
	2000	0	260.45	0	0	11.26	0	0	249.19	
Great Lakes	1975	0	84.29	0.02	0.03	2.90	0	0	81.44	71.63
	1985	0	84.29	0.02	0	3.69	0	0	80.62	
	2000	0	84.29	0.02	0	5.26	0	0	79.05	
Ohio	1975	45.70	155.68	0	0	2.01	0	0	199.37	179.78
	1985	45.33	155.68	0	0	2.83	0	0	198.18	
	2000	44.81	155.68	0	0	4.85	0	0	195.64	
Tennessee	1975	0	46.05	0	0	0.35	0	0	45.70	43.10
	1985	0	46.05	0	0	0.72	0	0	45.33	
	2000	0	46.05	0	0	1.24	0	0	44.81	
Upper Mississippi	1975	49.39	85.15	2.31	0	1.28	0.05	0	135.52	124.04
	1985	41.92	85.15	2.31	0	1.79	0.05	0	127.54	
	2000	40.18	85.15	2.31	0	3.01	0.05	0	124.58	
Lower Mississippi	1975	404.99	84.01	0	0.46	4.51	0	0	484.95	402.12
	1985	388.64	84.01	0	0	5.10	0	0	467.55	
	2000	382.82	84.01	0	0	6.17	0	0	460.66	
Souris-Red-Rainy	1975	0	6.87	0	0	0.13	0.02	0	6.72	4.11
	1985	0	6.87	0.06	0	0.23	0.02	0	6.68	
	2000	0	6.87	0.72	0	0.50	0.02	0	7.07	
Missouri	1975	0	68.90	0.46	2.86	17.32	5.51	0	49.39	38.03
	1985	0	68.90	0.55	0	21.51	5.96	0.06	41.92	
	2000	0	68.90	0.56	0	22.30	6.27	0.72	40.17	
Arkansas-White-Red	1975	0	75.82	0.18	6.11	9.03	2.93	0.03	70.12	51.68
	1985	0	75.82	0.23	0	9.82	3.26	0.03	62.94	
	2000	0	75.82	0.26	0	9.93	3.48	0.03	62.64	
Texas-Gulf	1975	0	39.90	0.03	6.25	12.61	1.91	0	31.66	25.67
	1985	0	39.90	0.03	0	11.45	2.10	0	26.38	
	2000	0	39.90	0.03	0	11.79	2.23	0	25.91	
Rio Grande	1975	0	5.95	0.26	0.74	4.75	0.82	0	1.38	2.56
	1985	0	5.95	0.22	0	4.84	0.85	0	0.48	
	2000	0	5.95	0.22	0	4.50	0.88	0	0.79	
Upper Colorado	1975	0	15.60	0	0	2.73	0.80	0.90	11.17	8.90
	1985	0	15.60	0	0	3.38	0.81	1.10	10.31	
	2000	0	15.60	0	0	3.62	0.82	1.23	9.93	
Lower Colorado	1975	11.17	-0.68	0.02	2.70	5.15	1.35	5.02	+1.69	7.69
	1985	10.31	-0.68	0.04	0	5.33	1.37	4.61	-1.64[c]	
	2000	9.93	-0.68	0.04	0	5.27	1.38	4.40	-1.76	

Table 4-7 Cont.

Region	Year	Stream Inflow	Supply			Requirements			Remaining Stream Outflow	Instream Flow[a] (approx.)
			Runoff	Imports	Mined groundwater	Consumed	Evaporation	Exports		
Great Basin	1975	0	15.63	0.12	0.66	4.23	0.37	0.002	11.808	9.16
	1985	0	15.63	0.200	0	4.215	0.371	0.002	11.242	
	2000	0	15.63	0.283	0	4.518	0.373	0.002	11.020	
Pacific Northwest	1975	0	300.737	0.053	0.702	13.334	2.256	0	285.902	269.924
	1985	0	300.737	0.053	0	16.369	2.302	0	282.119	
	2000	0	300.737	0.053	0	17.016	2.333	0	281.441	
California	1975	0	77.187	5.023	2.461	29.833	0.749	0.053	54.036	37.106
	1985	0	77.187	4.610	0	31.280	0.760	0.053	49.704	
	2000	0	77.187	4.399	0	33.263	0.768	0.053	47.502	
Total	1975	0	1499.77	3.00	23.40	118.22	16.75	0	1391.20	1165.40
	1985	0	1499.77	3.00	0	133.62	17.86	0	1351.29	
	2000	0	1499.77	3.00	0	149.67	18.61	0	1334.49	

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*See Appendix A, glossary.

[a] Estimated water supply generated within each region. Negative values indicate that evaporation and transpiration are greater than rainfall in the region.

[b] From manmade reservoirs, including those supplying water to hydropower plants. If precipitation exceeds evaporation, the value is zero.

[c] Negative values show the amount of excess water use without groundwater overdraft.

[d] Estimates prepared by the U.S. Fish and Wildlife Service for optimal fish and wildlife habitat conditions.

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

In two of the 18 water resources regions covering the conterminous 48 states, there will probably arise serious water resources constraints before the end of this century [Green and Skold 1976]: the Upper Colorado (Region 14) and part of the Missouri Basin (Region 10). In Region 10, only some of the aggregated subareas (ASA) forming the Upper Missouri Basin will probably exhibit significant water constraints [Gertsch et al. 1977]: 1001, 1002, 1003, 1004, and 1005.

A PROPOSED REGIONAL SCHEME

From the foregoing discussion, it is quite clear that, in order to determine the feasibility of integrating water resources constraints into energy models, formulations at the national level are too aggregated to be meaningful. Constraining conditions imposed by water resources on energy-related activities will appear in different parts of the country at different times in the future. It seems appropriate, therefore, to study water-energy interactions on the basis of a regionalized scheme.

There are many different ways in which to regionalize the United States. Some of the models reviewed in this section refer to regions defined by the U.S. Bureau of Census; other models use coal regions, or regions delineated by electric utilities. If one were to use any of these formulations, one would have difficulties in estimating streamflows and water availabilities within these arbitrarily defined regions. It is proposed, therefore, to use a scheme based on water resources regions, as defined by the U.S. Water Resources Council. (See Figure 2-1, page 12).

The regionalized scheme proposed for this study is based on Census regions, yet emphasizes major areas where water restrictions may inhibit significantly the rate at which energy resources could be developed using currently available technologies. The proposed scheme combines the nine Census regions and the 18 water resources regions to form eight new regions. The proposed regions and their relation to those of the U.S. Bureau of Census are shown in Table 4-8. They are shown schematically in Figure 4-4.

Table 4-8

A PROPOSED REGIONALIZED STRUCTURE FOR MULTIREGIONAL WATER-ENERGY MODELS

Water-Energy Regions	Census Regions and States	Water Resources Regions and Subbasins[a]
1. Eastern States	1,2,3,5,6	Regions 1,2,3,4,5,6 Subbasins 702,704,705
2. Central States	4,7	Regions 8,9,12 Subbasins 701,703,1005, 1006,1008,1009,1010,1011, 1101,1103,1104,1105,1106, 1107,1303,1305
3. Upper Missouri	Montana, Wyoming	1001,1002,1003,1004
4. Eastern Rockies	Wyoming, Colorado New Mexico	1007 1102,1301,1302,1304
5. Upper Colorado	Wyoming, Utah, Colorado	Region 14
6. Lower Colorado	Arizona	Region 15
7. Great Basin	Idaho, Utah, Nevada	Region 16 1701,1703,1704
8. Pacific	Washington, Oregon California	1702,1705,1706,1707 Region 18

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[a] Defined in U.S. Water Resources Council 1978

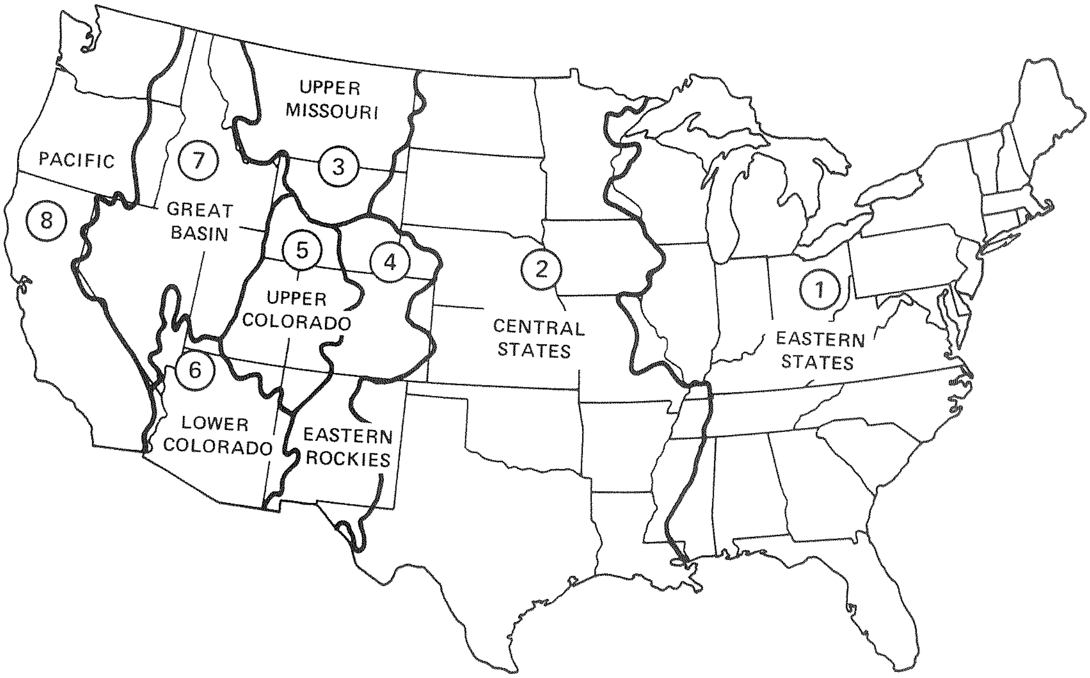

Figure 4-4. Proposed Water-Energy Regions in the United States

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, ..., 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-O 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:

$$W^E X^E \leq E , \tag{13}$$

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

$$W^E X^E + S - E = 0 . \tag{14}$$

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

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

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:

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

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

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

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

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

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.

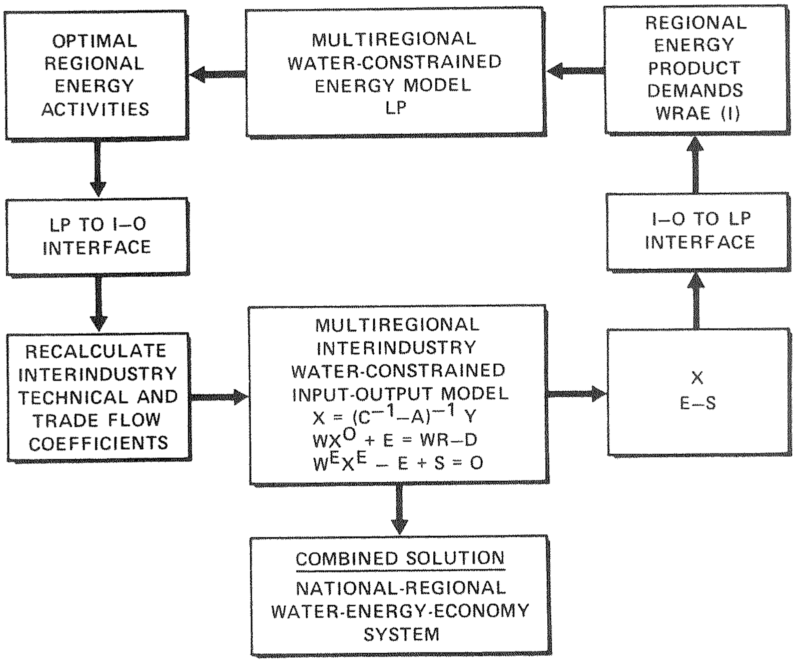

Figure 5-1. The Solution Sequence for the Iterative Method

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

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

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.

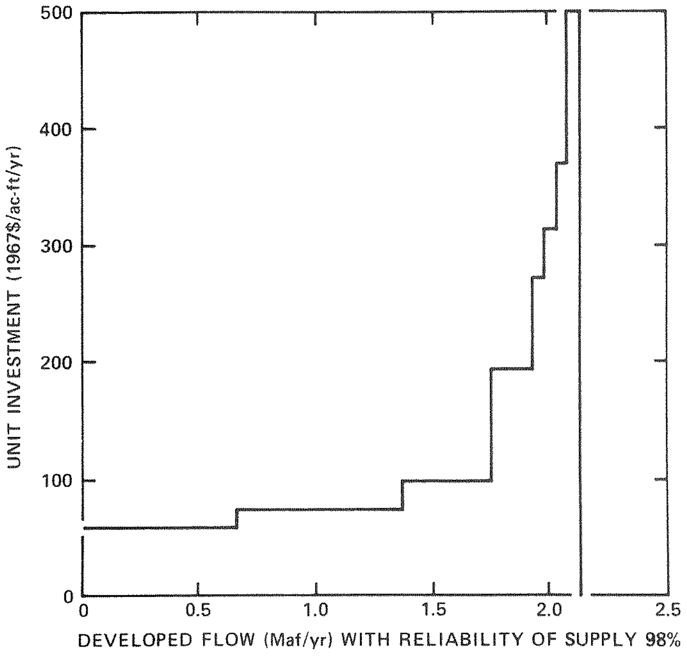

Figure 5-2. Water Supply Function, Upper Colorado River Basin

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

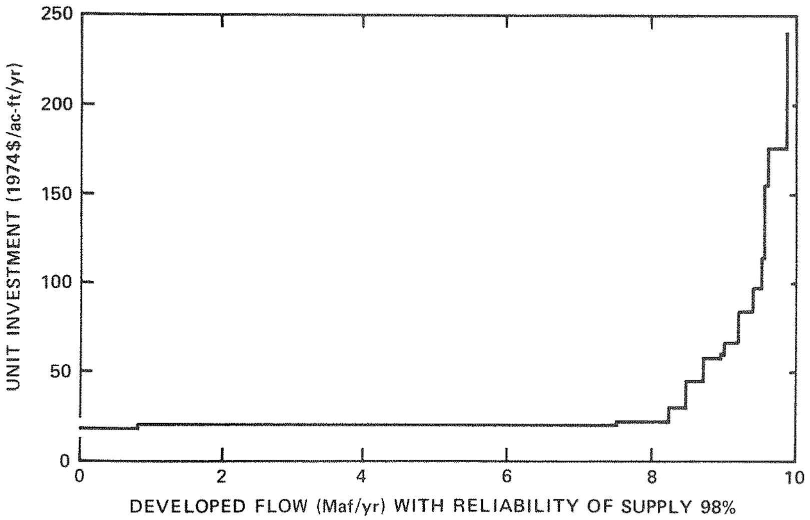

Figure 6-1. Water Supply Function, Rocky Mountain Region (Post 1975)

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.

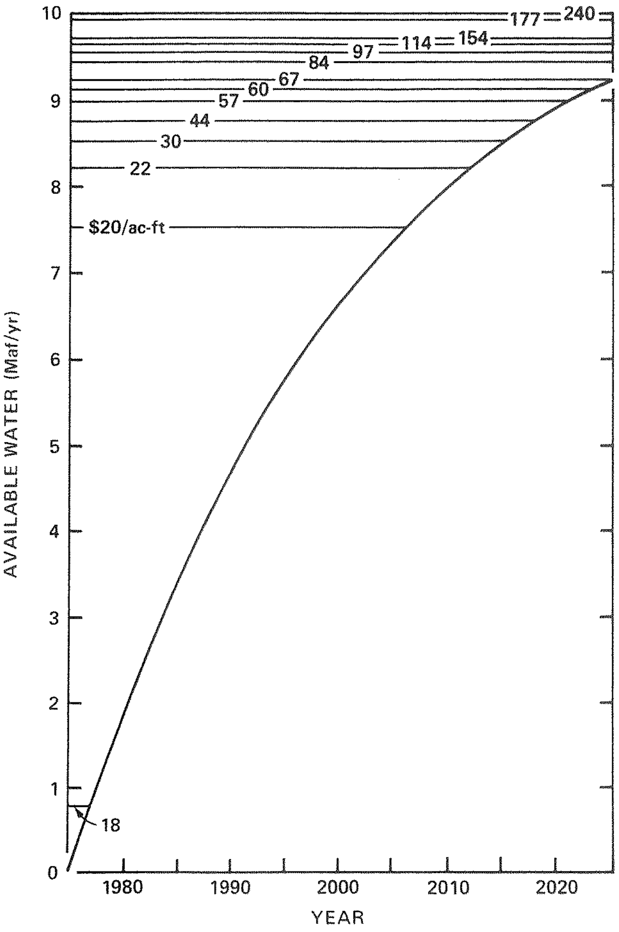

Figure 6-2. Water Availability for Energy, Rocky Mountain Region

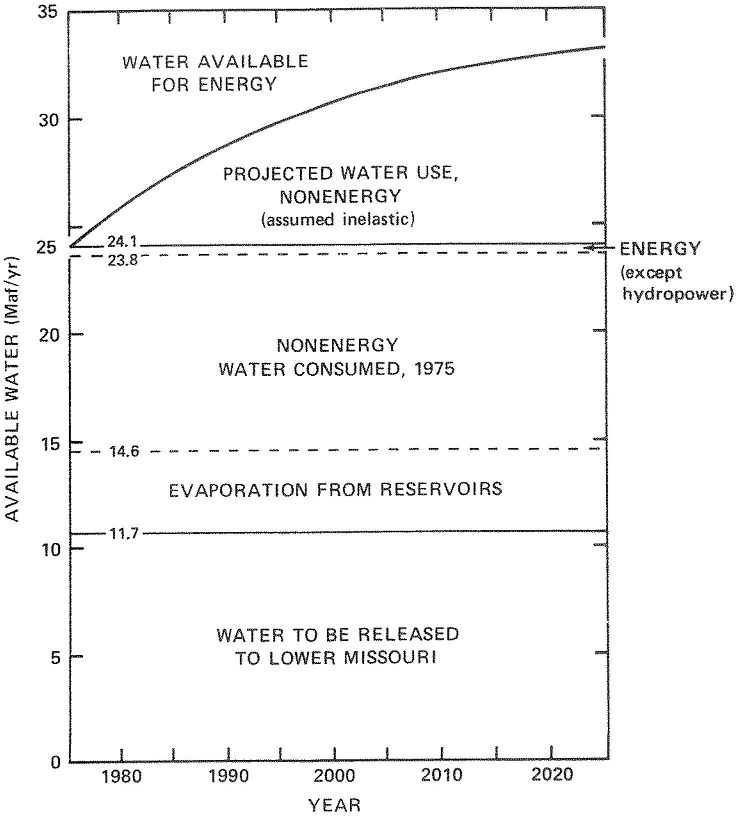

Figure 6-3. Projected Allocation of Water Resources, Rocky Mountain Region

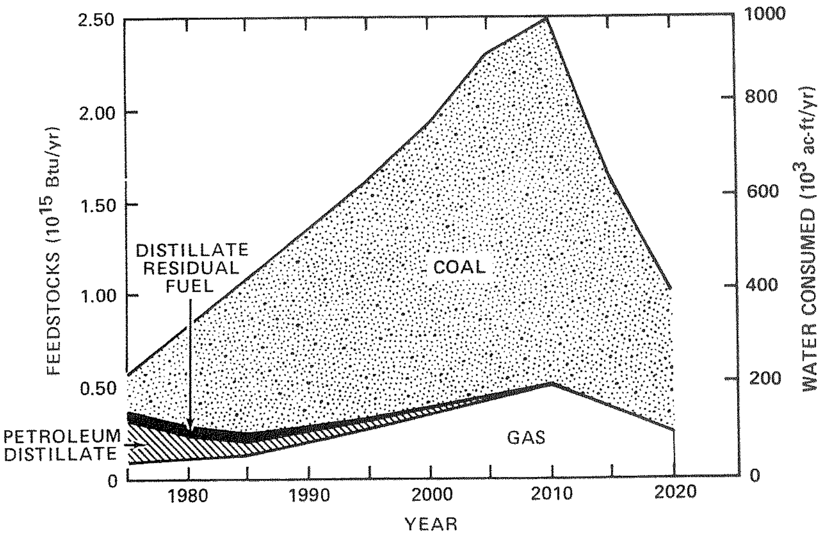

Figure 6-4. Fossil-fueled Power Generation

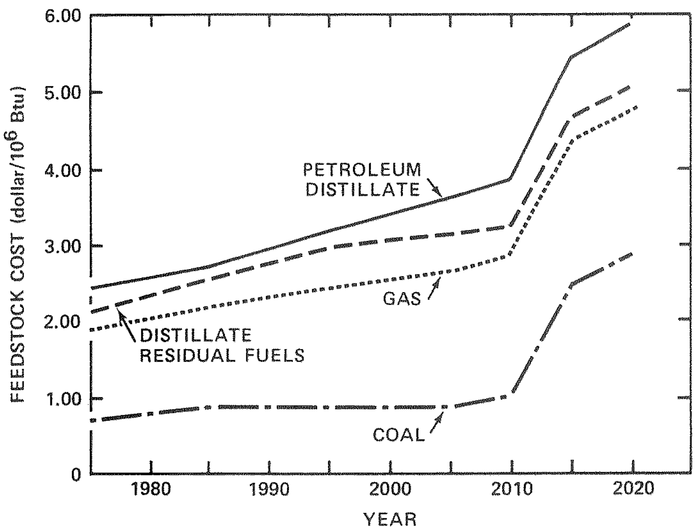

Figure 6-5. Cost of Fossil-fueled Power Generation

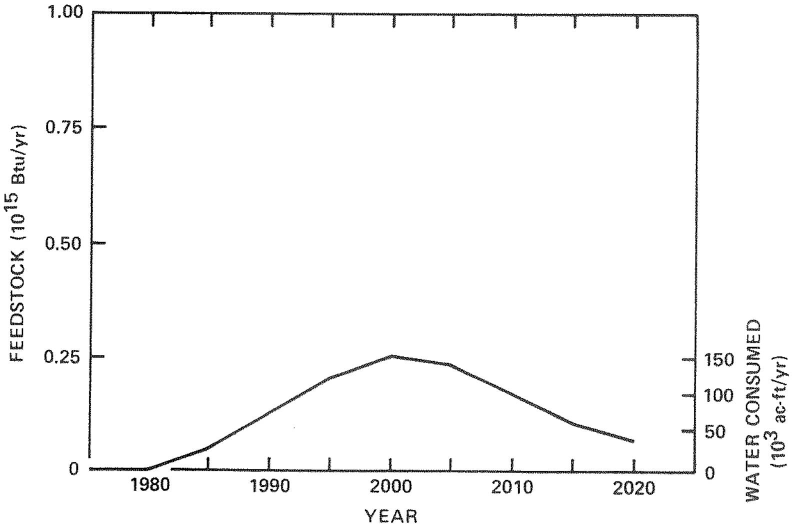

Figure 6-6. Nuclear Power Generation

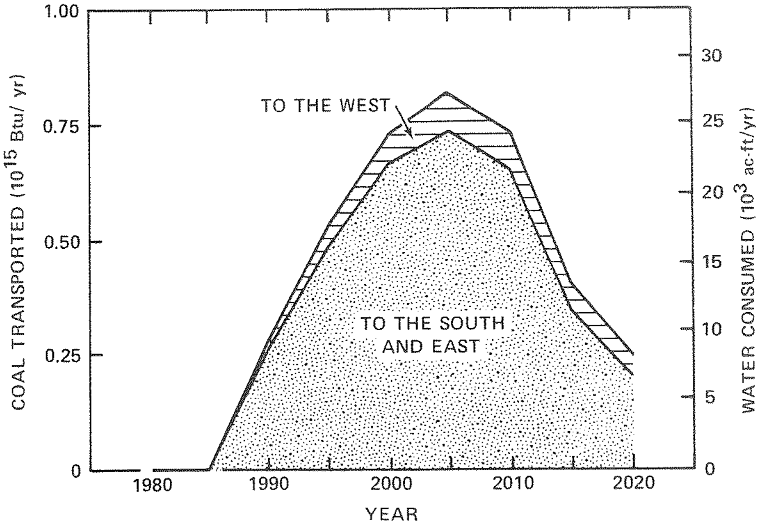

Figure 6-7. Coal Transported by Slurry Pipeline

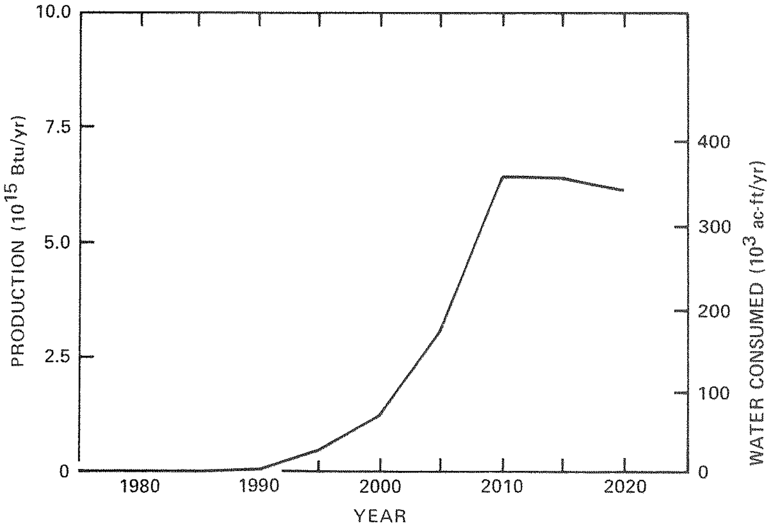

Figure 6-8. Shale Oil Production

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

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*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.

Section 7

CONCLUSION

This exploratory study into the feasibility of integrating water resources constraints into energy models may be summarized as follows:

- In order to represent in a meaningful way the potential interactions between the energy and water sectors of the U.S., it is necessary to use a model aggregated at most to the regional level. For this reason, the BNL model, RESOM, was selected and was modified to yield the WATER-RESOM variant. Similarly, the EPM model of LLL was adjusted so as to beocme WATER-EPM.
- Integration of water constraints into regionalized energy-economy models is both relevant and feasible. Models including representations of water availability and coefficients of water uses may be useful for studying potential interactions between the energy and water sectors of the U.S., and for evaluating the effects of such interactions on the rest of the economy.
- It appears that future studies of the water-energy interface in the U.S. should focus on more accurate regionalized models, so as to estimate the time when, under certain conditions water-energy issues may become acute in a given region, and to rank the regions in this fashion. Following this ranking process, the effort could be concentrated in the regions where these problems will arise sooner, so as to quantify the issues involved in the energy-nonenergy conflicting requirements for a finite amount of water, and to derive alternative policies for the management and use of these important resources.
- Future studies of water-energy interactions should include analyses and evaluations of policy alternatives available in the various regions regarding the development, allocation, and use of water resources. One such study could focus for example, on water transfers from current users in the nonenergy sector to potential users in the energy sector, and the economic, political, and social implications of such transfers.
- The current study related only to water quantity. Water quality management may become, in specific areas, a major issue since it could be affected considerably by energy-related activities.
- A strictly deterministic point of view was adopted in this study. The stochastic aspects of streamflow and water availability need to be included in the analyses of policy options regarding the development, allocation, and use of water within water-energy-economy modeling efforts.

- The effect of technolgy improvements, in water production (e.g., saline water desalination), in nonenergy water use (e.g., more efficient irrigation), and in energy-related activities (e.g., water-saving cooling techniques), need to be considered when looking at water constrained futures.

- This exploratory study restricted itself to deterministic representations of water resources. A more realistic approach is to consider the stochastic aspects of water availability and to include them in analyses of policy options.

- Water quantity alone was considered in this study. However, water quality may become a central issue in specific areas, as a consequence of energy-related activities.

Section 8

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Appendix A

GLOSSARY

Aquifer. A geological formation bearing and conveying water. Water contained in an aquifer is called groundwater. Groundwater saturates the pore space of the aquifer. The upper boundary of the saturated zone of an aquifer is called water table. Aquifers may be overlaid with impervious material (e.g., clay layers) and the water contained in them connected with water bodies at higher elevations. Under these conditions, the aquifer is confined and groundwater is under pressure. The level to which groundwater would rise if the pressure were released defines the piezometric surface. When the piezometric surface is higher than ground surface, the aquifer is artesian.

Blowdown. River, lake, and groundwater contain dissolved salts. Use of these waters in evaporative processes tends to increase salt concentration in the remaining water. Removal of the resulting brine is blowdown.

Consumptive use. Use of water so that it becomes unavailable for further uses within the same hydrological unit. Water is consumptively used when incorporated in a product (e.g., canning fruit and vegetables), when evaporated for removal of waste heat, or when removing waste material (waste water). Thus consumptive use may result in a decrease of water quantity and/or degradation of water quality.

Groundwater. See aquifer.

Groundwater overdraft. Water may be pumped from aquifers in a groundwater basin at various rates. The amount of water which can be withdrawn annually without causing an undesirable influence in the basin (e.g., lowering water tables below a given elevation) is called safe yield. Pumping of groundwater in excess of safe yield is overdraft.

Instream flow. Includes flow requirements for navigation, hydroelectric power generation, conveyance to meet downstream treaty and compact commitments, fish and wildlife habitat maintenance, waste assimilation, recreation, sediment transport and fresh water inflow to estuaries (see Figure A-1).

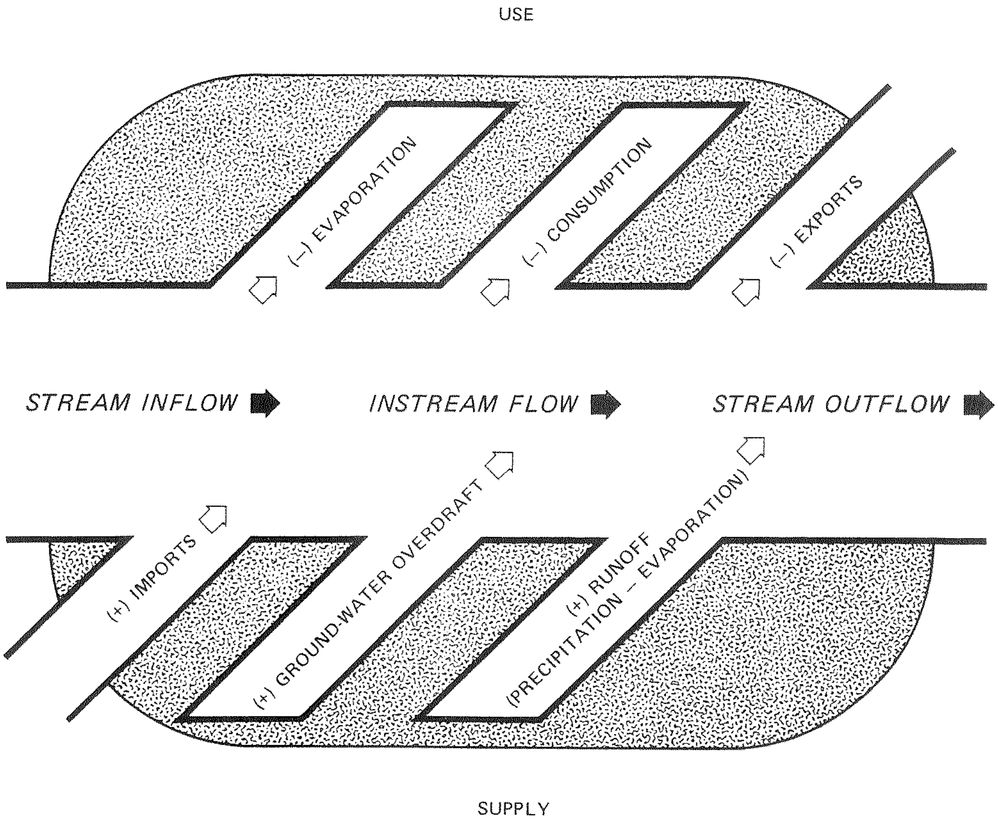

Figure A-1. Schematic Representation of Regional Water Balance

Makeup water. 1. Water added to steam generating facilities to replace steam which escaped or was wented to atmosphere (boiler makeup). 2. Water added to evaporative cooling facilities using water.

Piezometric surface. See aquifer.

Potable water. Water of drinking water quality with respect to physical, chemical and bacteriological properties. Usually it includes water for drinking, cooking, washing, bathing, laundering, and toilet flushing.

Process water. Water incorporated in a product, either wholly (i.e., the entire water molecule), or partially (e.g., the hydrogen of the water molecule is used in the hydrogenation of synthetic fuels). See also consumptive use.

Raw water. Total amount of water supplied to an industrial plant or to a steam-electric generating facility. Often raw waters are treated chemically (e.g., softened), to make them suitable for use. Some water losses may occur in this treatment.

Return flow. See withdrawal.

River basin. A geographical area enclosed by a fictitious line such that all precipitation falling within it and flowing on its surface reaches the lowest point of the ground surface. Also called drainage basin, or catchment area. See also runoff.

Runoff. Precipitation less natural evaporation from land surfaces, less plant evapotranspiration, less percolation to groundwater. Runoff is usually expressed quantitatively in relation to a river basin.

Stream inflow. Amount of water entering a water resources region through a river (or rivers).

Streamflow. Amount of water flowing in a river.

Streamflow frequency. Variations in annual streamflow are expressed in terms of flow that is expected to be exceeded in a specific percentage of years. For example, a flow of 5-percent exceedance represents a very high flow that will be exceeded in only 5 out of 100 years, on the average.

Waste water. See consumptive use.

Water balance. A regional accounting of water inflows, outflows, uses, and changes in storage, so as to reflect the law of conservation of matter.

Water table. See aquifer.

Withdrawal. Water abstracted from a supply source (surface or groundwater). Part of the withdrawal water is consumed; part may evaporate without an apparent beneficial use; and part may reappear in streams (or aquifers) as return flow.

Appendix B

CONVERSION FACTORS

Water Measurement

Quantity

1 acre-foot = 325,851 gallons
= 43,560 cubic feet

1 million gallons = 3.07 acre-feet

1 cubic foot = 7.48 gallons

Flow

1 million gallons per day (mgd) = 694.4 gallons per minute (gpm)
= 1.55 cubic feet per second (cfs)
= 1,120 acre-feet per year (ac-ft/yr)

1 billion gallons per day (bgd) = 1.12 million acre-feet per year (Maf/yr)

1 cubic foot per second = 1.98 acre-feet per day

Energy

1 British thermal unit (Btu) = 1.05506 kilo Joules (kJ)

1 kilowatt-hour (kWh) = 3,600 kilo Joules (kJ)

Water and Energy

Million acre-feet per 10^{15} (quad) Btu = 1.11174 gallons per kilowatt-hour

Appendix C

ESTIMATED CHARACTERISTICS OF SOME ENERGY-RELATED TECHNOLOGIES

Table C-1

COAL LIQUEFACTION PROCESSES

Required power generated at the liquefaction plant

Characteristic	Case 1 (SRC)	Case 2 (CHL)	Case 3 (SRC)	Case 4 (CHL)
Overall thermal efficiency[a] (%)	71.8	67.7	69.9	65.0
Electric power requirements (MW)	182	238	205	317
Capital requirement (10^6 1976$)	1,510	1,690	1,612	1,985
Operating manpower	204	213	209	226
Production costs (1976$/$10^6$ Btu)	4.54	5.32	4.79	5.87

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[a] Fuel products/total coal feed

Source: McNamee et al. 1978

Table C-2

COMPARISON OF POWER AND CAPITAL REQUIREMENTS FOR COAL LIQUEFACTION: REQUIRED POWER GENERATED AT THE PLANT OR PURCHASED OUTSIDE

Characteristic	Case 1 (SRC)	Case 1A (electric drive)	Case 1A1 (steam drive)
Electric power (MW)			
Generated	182	86.86	0
Purchased	0	102.14	99
Total	182	189.00	99
Capital (10^6 1976$)	1,510	1,345	1,268
Production costs (1976$/$10^6$ Btu)	4.54	4.44	4.26

Source: McNamee et al. 1978.

Table C-3

COAL GASIFICATION PLANTS[a]
10,000 tons coal per day

Characteristic	MACW	MX	FA	FX	EALC	EXL
Net fuel gas (10^6 Btu/day)	134,375	131,880	184,872	201,432	185,664	196,920
Liquid hydrocarbons (10^6 Btu/day)	23,168	22,738	31,874	34,730	32,011	33,952
Power by-product (MW)	76.4	63.7	72.5	50.2	106.0	---
Potential power from products (MW)	723.6	712.0	885.9	932.6	859.6	911.7
Total power (MW)	800.0	775.7	958.4	982.8	965.6	911.7
Capital (10^3 1975$)						
70% operating factor	521,501	625,241	409,123	398,271	363,260	346,059
90% operating factor	526,087	629,729	413,562	402,514	367,951	349,927
Operating labor per shift (people)	56	60	48	51	47	46
Production costs (1975$/$10^6$ Btu)						
70% operating factor	3.78	4.42	2.79	2.61	2.48	2.69
90% operating factor	3.19	3.71	2.40	2.26	2.13	2.38

Source: Kimmel et al. 1976.

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[a] For a key to symbols, see Table 3-4.

Table C-4

LOW-Btu COAL GASIFICATION COMBINED-CYCLE SYSTEMS FOR ELECTRIC POWER GENERATION[a]

Characteristic	MACW	MXSC	EAHC	EXHC	EALC	EXTC-SF	EXTC-DF
Overall efficiency (%)	35.0	40.6	40.5	38.5	38.1	38.7	38.2
Capital (1976$/kW)	905.67	711.12	705.15	738.55	930.67	816.53	854.00
Net power (MW)	988	1,212	1,214	1,149	1,138	1,157	1,142
Operating labor per shift (people)	36	30	27	28	27	28	28
Coal (ton/day)	13,900	10,000	10,000	10,000	10,000	10,000	10,000
Production costs (1976 mills/kWh)							
Coal ($\$1/10^6$ Btu)	41.20	32.79	32.53	34.05	41.35	37.21	38.25
Coal ($\$2/10^6$ Btu)	51.38	41.57	41.32	43.30	50.69	46.47	47.56

Sources: McElmurry 1977, Chandra et al. 1978.

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[a] For a key to symbols, see Table 3-4. SF indicates slurry feed of coal; DF direct (dry) feed of coal.

Appendix D

EPM -- AN ENERGY POLICY MODEL

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Energy & Resource Planning
Lawrence Livermore Laboratory

The Lawrence Livermore Laboratory (LLL) uses its Energy Policy Model (EPM) not only to project equilibrium prices and quantities over a long-term horizon (usually 50 years) under free market conditions, but also to exhibit the effects of government policies and other constraints on free market economics. Like the SRI-Gulf Model, from which much of its structure is derived, EPM is a dynamic regionalized model of the energy sector of the U.S. economy in which energy flows are conceptualized as a network with resource nodes at the bottom and end-use nodes at the top. Energy flows upward through a variety of process and transportation nodes. A sample network branch is shown in Figure D-1.

The regionalization in EPM requires distinct nodes for all processes (oil refining, power generation, etc.) and all materials (coal, gasoline, etc.) in every region, as well as for various forms of interregional transport of materials. End-use demands for transportation, space heat, etc. are aggregated by U.S. census regions while resource regions are defined where needed for coal, crude oil, shale deposits, etc. Input data include or imply supply curves at production nodes, demand curves at end-use nodes, and parameters for determining costs and efficiencies at process and transportation nodes.

The use of EPM in a study usually requires the development of a problem-specific version reflecting a suitable base-case scenario. This development may include modification of the network to provide more detail in a sector, such as transportation, or a region, such as New England. Once a basic version has been run, additional scenarios can be designed to reflect assumptions about the economics of any process, e.g., power generated by a coal-fired boiler, about government policies regarding price controls or import limitations, about the dates on which new technologies will be available, etc. The implementation of alternative

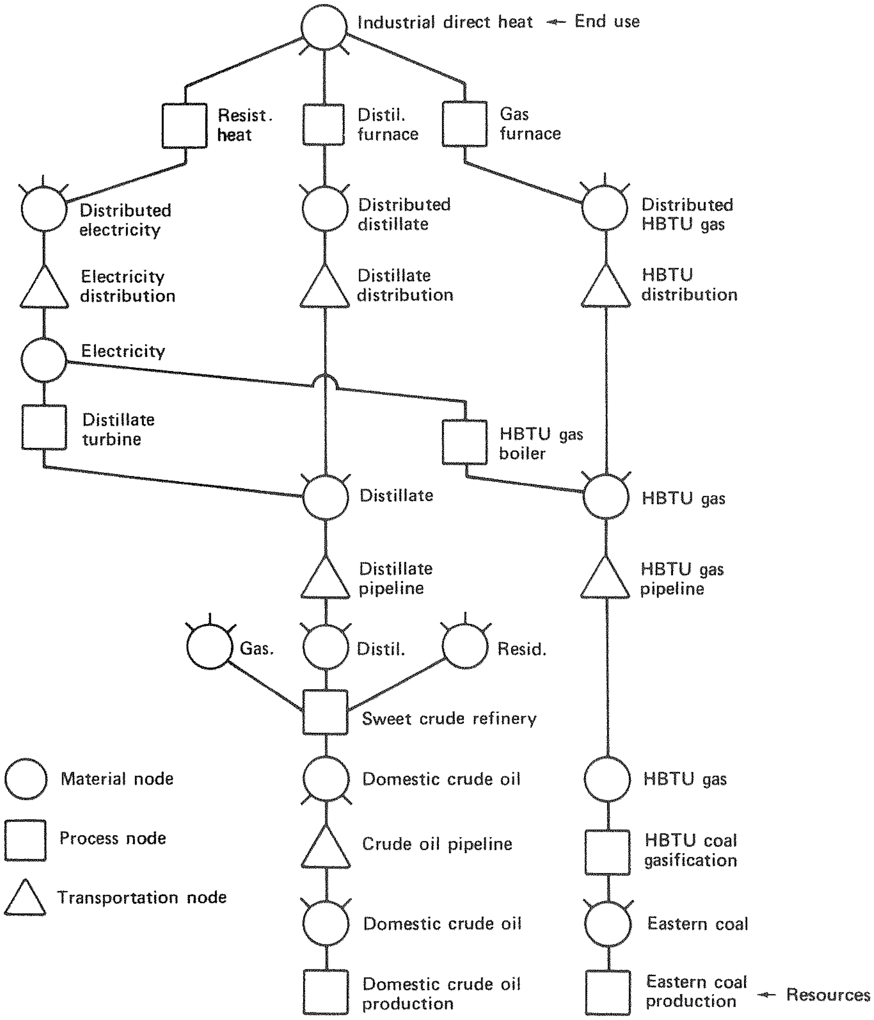


Figure D-1. A Sample Network Section Showing Energy Plan From Resources to End-uses scenarios is accomplished by changing the appropriate parameters in the base version and re-running the model. In any run of EPM, market clearing prices and quantities for a network of several thousand nodes are determined dynamically over a 50-year time horizon.

In order to facilitate the construction and use of EPM, LLL developed an Economic Modeling System (EMS), which consists of four distinct computer programs, INPUT, SOLVE, PRINT, and PLOT along with a specialized modeling language. The program INPUT requires two files -- a network file and parameter file -- to produce an initial market structure. The network file describes energy flows in the symbolic language that INPUT recognizes, while the parameter file provides all necessary data. INPUT generates a market structure, a sequenced network of market, process, and transportation nodes with fully specified calculational routines attached to the nodes. This preliminary market structure, which is dumped as the work file WORKA, contains only initializations, usually zero, of the prices and quantities that will appear in all subsequent market structures.

Program SOLVE takes WORKA, which includes initializing estimates of the volume of resource production, and works up the network from resources to end-uses computing prices, and then down again computing quantities. It thus produces a new market structure which includes prices and quantities at all market nodes. Each such round-trip through the network constitutes an iteration. If SOLVE has been asked to run 10 iterations, it will write over each market structure except the 10th, which it will dump as WORKB. If it is then re-started and run for 20 iterations, it will output the 30th market structure as WORKC. Techniques to drive toward an equilibrium of market clearing prices and quantities are built into SOLVE.

To illustrate the basic iterative process that leads to equilibrium, let us telescope a section of the network and hypothesize a process (Figure D-2a) with constant costs and efficiency:

- A is a resource material with a supply curve S_A exhibiting the quantity q_A of A that will be supplied at price p_A;
- A2B is a process transforming A to B with efficiency e $(0 < e < 1)$ at a cost of c dollars/10^6 Btu of product;
- B is an end-use material with demand curve D_B showing the quantity q_B which users will purchase if the price is p_B.

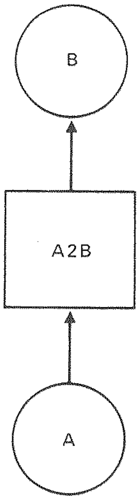


Figure D-2A. Feedstock A is Processed into Product B with Efficiency e and Cost of c Dollars per 10^6 Btu of Product

The supply curve S_A induces S_B (Figure D2b), a supply curve for B showing what may be thought of as the marginal costs (or the selling prices) of various quantities of B in a case where the owner of feedstock A also owns the A2B processor and thus supplies B rather than A. A point (q_A, p_A) on S_A maps into a point (q_B, p_B) on S_B as follows: When feedstock q_A is processed by A2B, which has efficiency e, the output q_B is $e \cdot q_A$. The price p_B will reflect the cost of the feedstock, which is p_A/e per unit of product, plus the processing cost c. Thus $q_B = e\, q_A$ and $p_B = c + p_A/e$.

Similarly, D_B induces D_A, a demand curve on the amounts of A needed to meet requirements on B. It may be thought of as describing the amounts of A that would be purchased at various prices by end users who could process it into B themselves with efficiency e and cost c.

If the mappings from S_A to S_B and from D_B to D_A are well-behaved, as is certainly the case with e and c assumed constant, then the equilibrium points (q_A, p_A) and (q_B, P_B) shown in Figure D-3 are equivalent. A highly simplified and static conceptualization of the iterative process leading to the equilibrium will now be described.

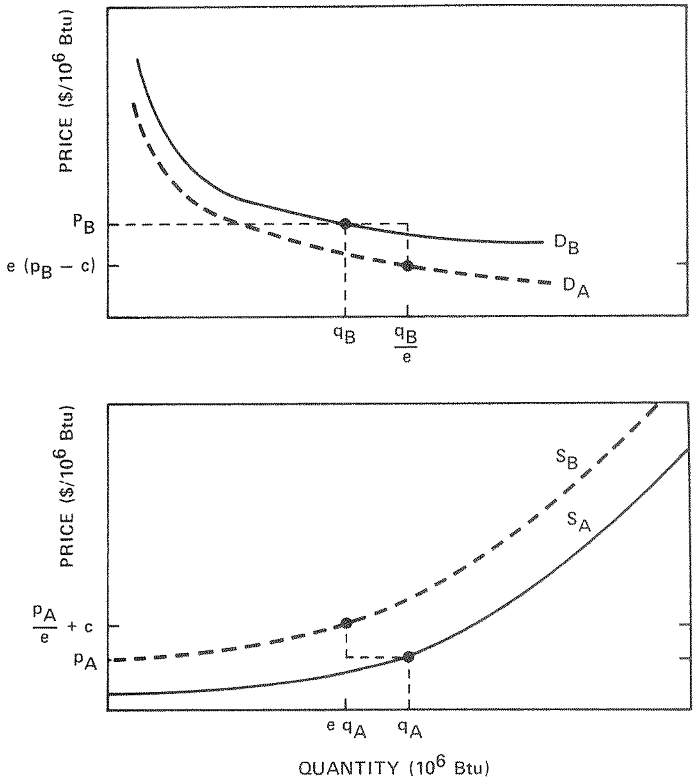


Figure D-2B. The Demand Function for the Product (D_B) Induces a Demand Function for the Feedstock. Likewise the Supply Function for the Feedstock (S_A) Induces a Supply Function for the Product

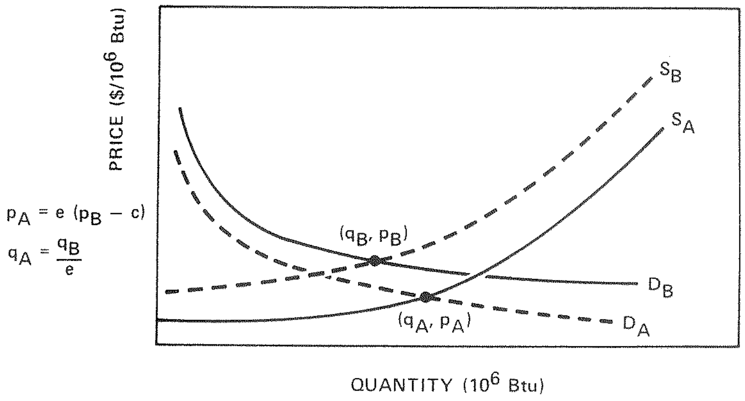


Figure D-3. The Feedstock Equilibrium ($\underline{q}_A \cdot \underline{p}_A$) corresponds to the Product Equilibrium ($\underline{q}_B \cdot \underline{p}_B$)

The process is initialized with an estimate q_A of the production volume of the resource material A. The curve S_A then determines a price p_A, which is transformed during the upward portion of an iteration into a price $p_B = c + p_A/e$.

As prescribed by D_B, this price p_B determines a product demand quantity q_B, which is then transformed down the network to $q_A = q_B/e$, the quantity of feedstock demanded at price p_A. This concludes the first iteration. If, after some iteration, q_A' equals q_A, then the equilibrium point where D_A and S_A intersect has been found. In actual practice, one iterates until prices and quantities are sufficiently stable. This is done by setting $q_A = q_A'$ and repeating the process of determining p_A from S_A, working up to (q_B, p_B), etc.

Any work file can be passed to program PRINT or program PLOT, each of which transforms the market structure prices and quantities into a file suitable for displaying results.

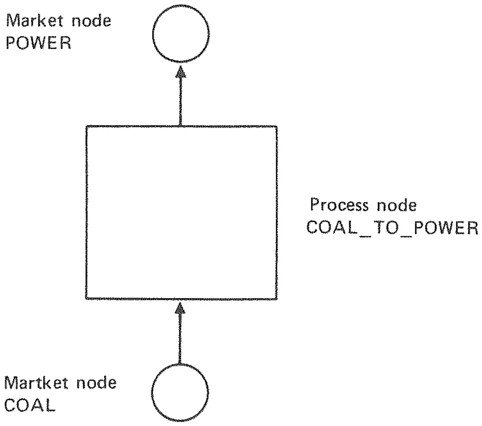
The output from PRINT provides, for each node and time period, the prices and quantities in the current market structure. The first line is prices in dollars/10^6 Btu; the second is energy measured in 10^6 Btu. The output from PLOT consists of graphs exhibiting, over the whole time horizon, either prices or quantities of single or aggregated materials. Examples are presented in the body of this paper (Figures 6-4 through 6-8).

The network file that must be provided to INPUT describes each process (square nodes) in the form:

PROCESS PROCESSNAME (FEEDSTOCK; PRODUCT)

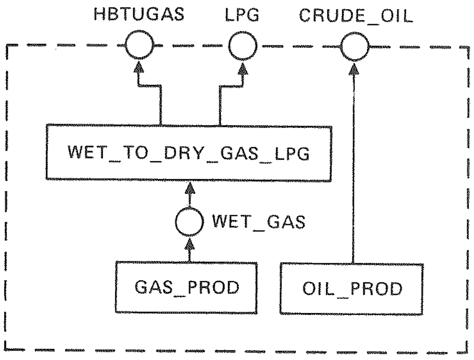
as shown in Figure D-4. Materials (circular nodes) are defined by their mention as inputs (feedstocks) or outputs (products) of processes. If no feedstock appears before the semicolon, the process is an input-free resource or raw material node such as coal-mining.

While all processes could be linked in one large model, the regionalization capabilities of EMS are best exploited through the use of sub-models which group the processes as in Figure D-5. The parameter list in the "DEFINE" line consists of material nodes capable of linkage outside the sub-model. The "MARKET RESOURCE" line lists all pertinent material (circular) nodes. Note that two of the processes are "production"as described above.



```
PROCESS COAL_TO_POWER (COAL; POWER)
```

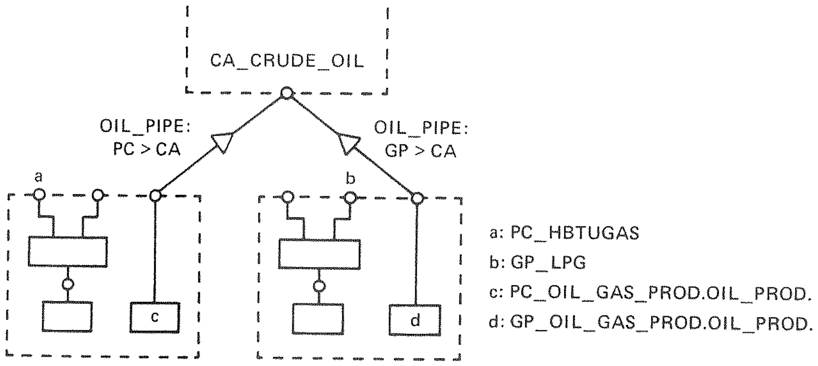
Figure D-4. One Statement Explicitly Defines a Process Node and Implicitly Defines Inputs and Outputs. The Above Statement and Diagram Represent the Generation of Electricity in a Coal-Fired Power Plant



```
DEFINE MODEL OIL_GAS_PROD (CRUDE_OIL, HBTUGAS, LPG)
  MARKET RESOURCE (WET_GAS_, CRUDE_OIL, HBTUGAS, LPG)
    PROCESS OIL_PROD (;CRUDE_OIL)
    PROCESS GAS_PROD (;WET_GAS)
    PROCESS WET_TO_DRY_GAS_LPG (WET_GAS; HBTUGAS, LPG)
END
```

Figure D-5. A Typical Submodel Describes Related Processes Occuring Together Within one or More Regions

The main model includes calls to all the sub-models and specification of each transportation link with a line that gives the type of transport, the regionalized names of the input and output materials, and abbreviations for the starting and destination points. An excerpt from a main model is given in Figure D-6.



```
CALL OIL_GAS_PROD:PC_OIL_GAS_PROD (PC_CRUDE_OIL,
      PC_HBTUGAS, PC_LPG)
CALL OIL_GAS_PROD:GP_OIL_GAS_PROD (GP_CRUDE_OIL,
      GP_HBTUGAS, GP_LPG)
TRANSPORTATION OIL_PIPE (PC_CRUDE_OIL; CA_CRUDE_OIL;
      PC > CA)
TRANSPORTATION OIL_PIPE (GP_CRUDE_OIL; CA_CRUDE_OIL;
      GP > CA)
```

Figure D-6. Oil and Gas Production in the Pacific Coast (PC) and Great Plains (GP) Resource Regions Provide Crude Oil Which is Piped to California (CA), a Refinery Region. The Main Model Contains Transportation Links and Calls to Regionalized Sub-models.

To each node in the network we must associate a calculational subroutine of a KIND recognized by EMS. In the parameter file each node defined in the network file must be classified as to KIND and the parameters required for that KIND must be supplied. Not only is a simple input format provided, but EMS allows multiple options for electing default values and simultaneously setting parameters for a class of similar nodes. These node-related sub-routines provide the means of calculating costs and efficiencies at each node and are thus the mechanism by which SOLVE calculates a price at each node when iterating upward and a quantity at each node when iterating downward.

Although designed with energy policy applications in mind, EMS has the potential for generating economic networks in a variety of contexts. Many capabilities not discussed above are in fact built into the software, including price and quantity controls, time lags, technological change and learning. The manner in which energy users and processers allocate demand among alternative suppliers and technologies is explicitly modeled.

All calculations are made dynamically, essentially simultaneously for all time periods. Thus, for example, prices in later time periods are influenced by the depletion level induced by quantities produced in previous periods, while capital investment decisions in early periods reflect an ability to project future inflation and prices and to discount to present value. Detailed documentation of the workings of EMS is available in LLL publications. [Rambo and Coles, 1978; Rousseau et al. 1978a, 1978b; Sussman and Rousseau 1978a, 1978b.]

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Appendix E

WATER-RESOM SOFTWARE

The following is a list of software developed in conjunction with the WATER-RESOM model.

- WYL.WJ.NYB.MRESON1 -- a temporary report generator;
- WYL.WJ.NYB.UTILITY -- a library containing the following files:

  --COPY -- lists the problem data (stored on tape) on hard copy;

  --COPY1 -- moves problem data from tape to disk;

  --COPY2 -- moves problem data from disk to tape;

  --COPY3 -- moves data from FILE0004 on tape to FILE0003 on the same tape, thus making available FILE0004 for the latest data update yet keeping the previous data set on FILE0003;
- WYL.WJ.NYB.MRESON -- generates the dictionary section of MAGEN input data and includes commands for report generation based on the solution file of the MPS solver;
- WYL.WJ.NYB.MRESOM -- a copy of the MAGEN file as supplied by BNL;
- WYL.WJ.NYB.MRESON2 -- another temporary report generator;
- WYL.WJ.NYB.MRUN -- control statements for making an MPS run, including a report generator;
- WYL.WJ.NYB.MAGEN -- the job control statements of the MAGEN routine;
- WYL.WJ.NYB.MPSRUN -- control statements for making an MPS run without the generation of a report.

Listings of these computer programs are available on request.