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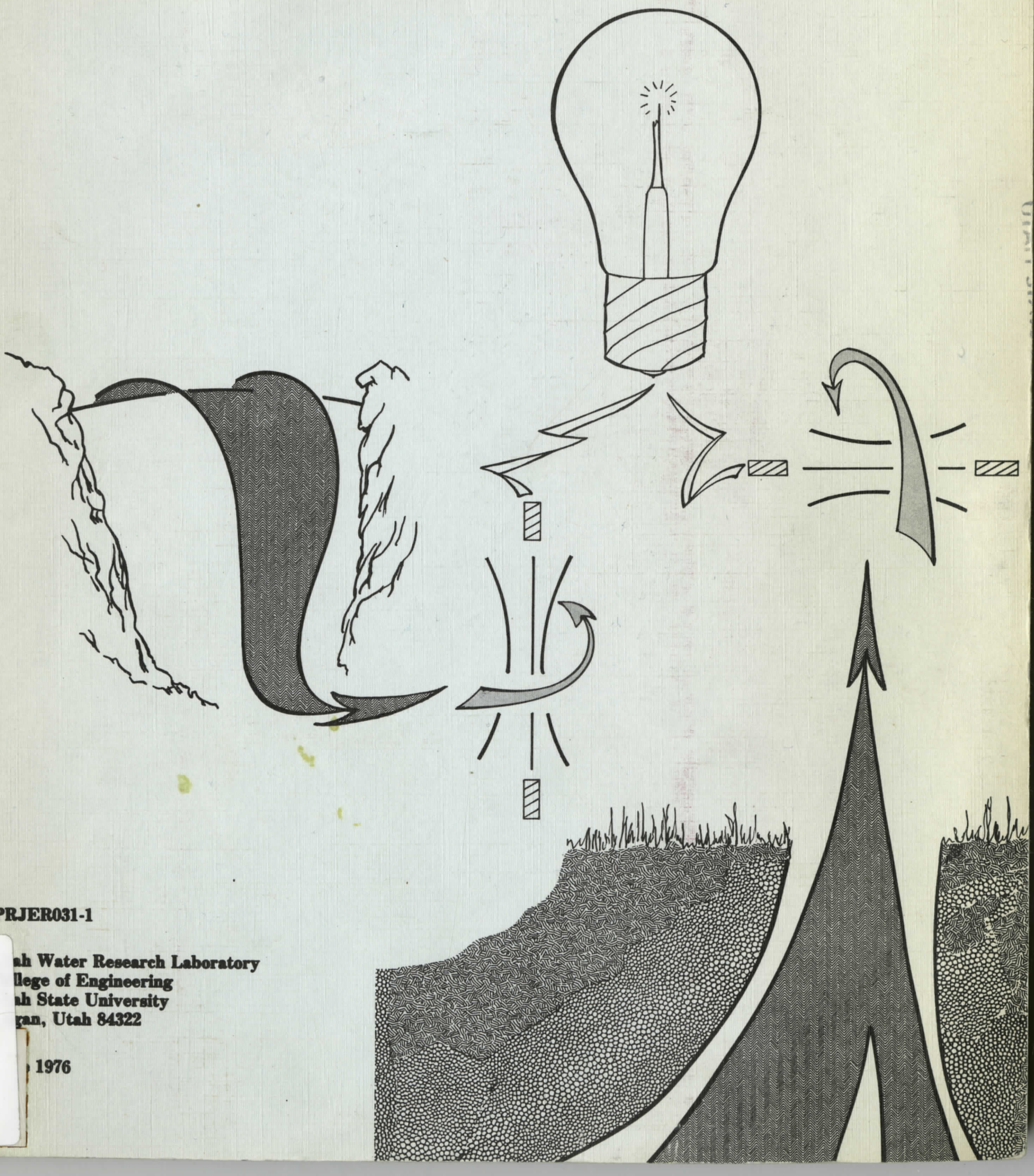

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1976

AN ENERGY ACCOUNTING EVALUATION OF SEVERAL ALTERNATIVES FOR HYDROPOWER AND GEOTHERMAL DEVELOPMENT

by

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J. Paul Riley
William J. Grenney
David A. Bell

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ABSTRACT

Alternative management strategies for hydropower and geothermal development are myriad. This study does not attempt to evaluate or even summarize the many schemes which are possible. In an era of plentiful natural resources, economic analysis procedures for selecting a particular alternative have been developed which traditionally have tended to optimize on the basis of capital and labor. The approach taken in this study is based on the notion of optimum deployment of finite resources. A legitimate question which this study has attempted to address is: Does the construction of large water management facilities, such as hydropower dams, which involve huge amounts of energy, concrete, and steel, constitute an efficient use of basic resources?

An energy accounting analysis technique is proposed, and using this procedure energy resource inputs are examined and compared for specific hydropower dams and geothermal power plants. The technique, though promising, still contains certain problems, and further development is needed in order to establish a consistent and uniform methodology.

The energy accounting technique indicates that construction of hydropower facilities is a relatively efficient use of basic energy resources. However, because of large evaporation losses from storage reservoirs, water consumption per unit of power produced tends to be high. An analysis subsequent to the energy accounting approach suggests that combining once-through cooling of thermal power plants with pumped storage hydropower facilities could produce large water savings per unit of generated power. Further study of this configuration is recommended.

The energy accounting technique also clearly identifies the high efficiency of geothermal power plants in terms of resource deployment. However, warm water geothermal resources of the type generally available in the intermountain region present formidable problems in utilization. The report proposes a heat exchanger system design which is capable of utilizing warm and highly mineralized waters, and recommends that the design be constructed and tested on a demonstration basis.

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Many people provided help, constructive comments, and suggestions throughout the course of this study. Particular appreciation is expressed for the constructive efforts of Dr. Trevor C. Hughes and of graduate students, Mr. A. John Pate and Mr. Thomas Barnard. Special thanks also are extended to the U. S. Bureau of Reclamation, the Pacific Gas and Electric Company, the Utah Geological and Mineral Survey, and other companies and agencies which provided data and other information essential to the success of the study. Gratitude also is expressed to the members of the review committee for their careful and constructive comments. These comments added significantly to the content and format of the report.

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CHAPTER I

INTRODUCTION

Water is an essential resource for most forms of energy development. This relationship has led to an increasing emphasis on water resource planning within the rapidly expanding energy resource picture.

This report deals specifically with water management problems associated with geothermal and hydroelectric power development. The important role of water in energy development is particularly clear in the cases of both geothermal and hydroelectric power development. For these installations, relatively large water flows are required per unit of energy produced when compared with the water needs of many other sources of energy.

Particularly in the West, geothermal energy development is gathering a great deal of momentum. Developers have leased large tracts of land in anticipation that the technical problems associated with exploiting the hot water resources of the area can be resolved. Because the geothermal energy resource is in the form of water, many of the crucial problems remaining to be solved involve water management. Due to the relatively low temperature of the hot water typical of geothermal resources in Utah, and the intermountain area in general, very substantial quantities of water are needed. The energy shortage, both experienced and anticipated, has renewed interest in hydroelectric power production. Development already has occurred, but particularly if the pumped storage concept is considered, a number of potential sites remain in the intermountain west.

Uncertainty now exists as to the feasibility of developing available geothermal resources and the remaining hydroelectric power potential in the country. Alternative management strategies are myriad. For this reason, water resource managers and planners have adopted specific procedures to help identify "optimum" alternatives. In an era of abundant natural resources, traditional economic analysis has tended to emphasize capital and labor in the optimization procedure. The approach taken herein is based on the notion that the optimization criteria should emphasize the judicious deployment of all finite nonrenewable resources.

The conventional approach in exploring resource development feasibility is to apply economic analysis techniques. In this report a supplemental approach is taken to economic feasibility analysis, namely the energy flow technique. Energy flow analysis is simply an attempt to trace all of the direct energy inputs from nonrenewable sources which are required for the construction and maintenance of the system in question. The technique is based on the premise that it takes energy to get energy (Figure 1). This report should in no way be interpreted as being critical of economics as a discipline, nor does the report suggest that economic analysis be replaced by energy analysis. The energy accounting methodology is simply explored as a possible supplement to economic analysis.

As part of this study, a flexible energy accounting system is proposed that can in principle be applied to any installation. This accounting system is discussed in detail in Chapter II, but briefly it involves a knowledge of the unit energy value associated with each flow or input channel. These data were developed for all major inputs in the power producing systems evaluated by the study. The total quantity required of any input is available from the project materials list (design or construction). The energy flows and balances of the project are then analyzed by a computer program, taking into account reasonable material recycle alternatives and possible energy savings associated with the re-use of recoverable components. In that it can help to minimize the depletion of energy resources in implementing power production systems, the energy accounting system pro-

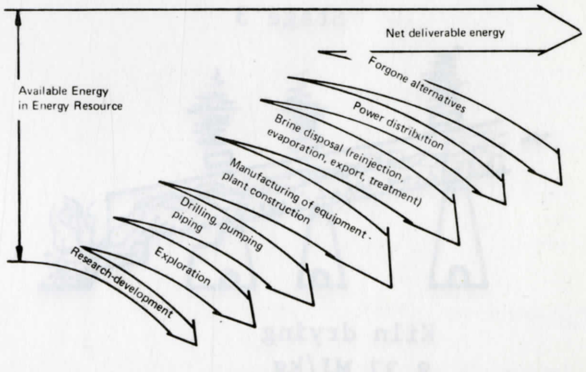


Figure 1. A representation of the concept that it takes energy to get energy. In fact, the net deliverable energy to society may be negative.

posed by this report can be an important aid to planners. Each of the inputs shown represents an energy investment per unit measure. For example, consider the production of cement. Figure 2 depicts the four main stages of cement production and the approximate energy investments in each stage The summation of the four stages yields a total energy input value per unit weight expressed in mega joules per kilogram (M J/kg) of cement. A similar procedure may be followed for estimating the energy inputs associated with metals, glass, plastics, aggregate, and all other major inputs required for any given project or operation. The total energy added through any particular input is estimated by multiplying its unit energy value by the total of the input used on the project. The total of all major energy flows to the project is estimated by summing the energy inputs across all major flows used by the installation (Figure 3).

The concept of energy flow is illustrated by Figure 2 which suggests that for each geothermal or hydroelectric power facility a variety of inputs are required in order to produce the desired energy output.

Comparisons of the relative efficiency of various energy producing systems are facilitated by computation of what is termed the break-even point (BEP). This point is computed as the summation of the energy associated with each material or operation input, called the material energy investment (MEI), divided by the average power ouput (AVE) of the project, or

$$\text{BEP(hrs)} = \frac{\Sigma \text{ MEI (kJ)}}{\text{AVE } \left(\frac{\text{kJ}}{\text{hr}}\right)}$$

A break even point (expressed in units of time) which approaches or exceeds the expected operating life of the system might cause some concern. If, on the other hand, the break even point is reached early in the expected system operating life, system implementation likely would be regarded with favor This study made no attempt to explore all of the water resource management alternatives for hydropower and geothermal development. The main scope of the project was to demonstrate the utility of the energy accounting technique for analyzing energy development proposals. For example, Chapter IV of this report contains an innovative alternative for water management associated with pumped storage hydropower, and presents preliminary energy flow analysis for various aspects of the concept.

The relatively low temperatures of the geothermal resource waters typical of the intermountain region do not lend themselves to efficient electrical production. The low temperature differences available tend to re-

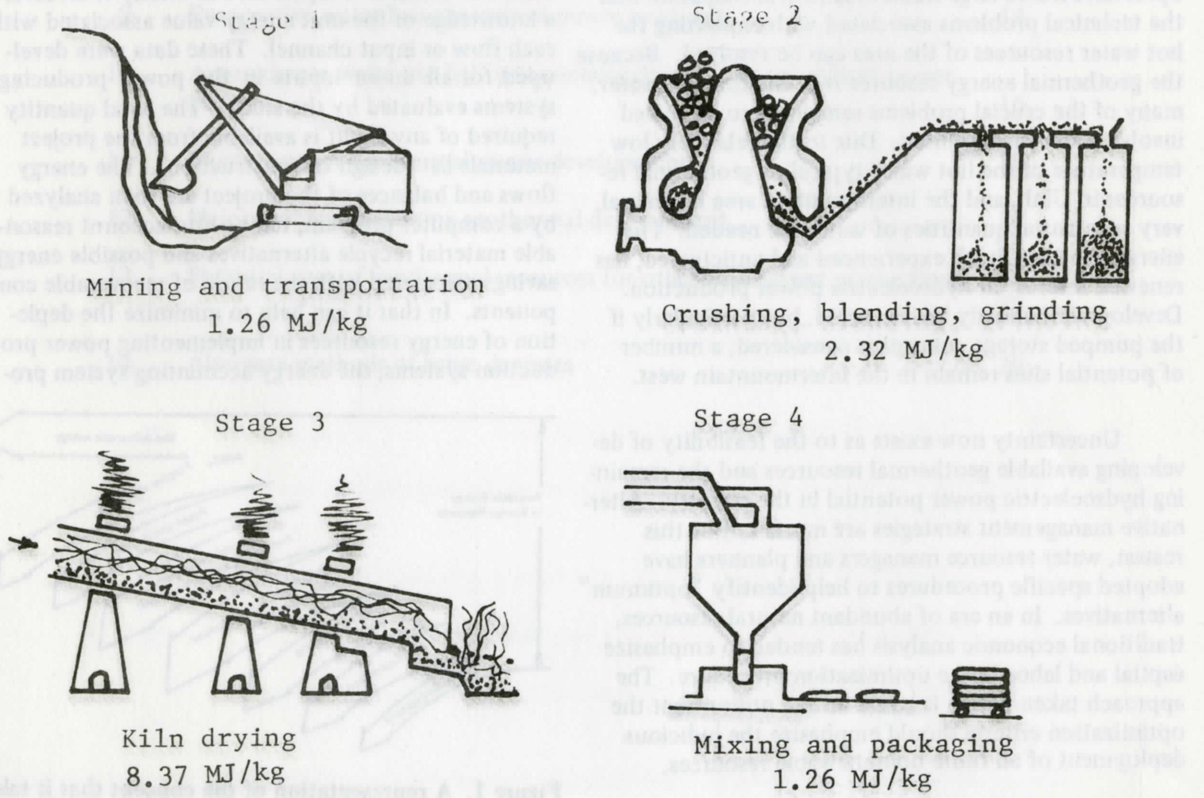


Figure 2. Energy inputs to the production of cement (Office of Science and Technology, 1972).

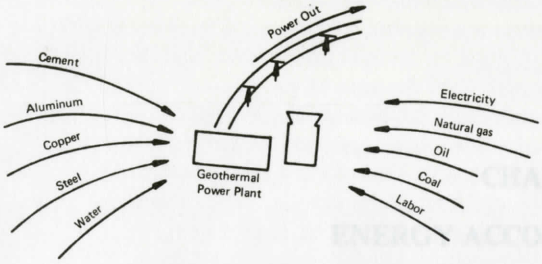


Figure 3. Conceptualization depicting energy and material flows associated with power production.

quire such large heat transfer surfaces that conventional heat exchangers are not economically feasible. In addition, the geothermal waters rapidly corrode conventional heat exchangers. For these reasons, it is suggested that alternative uses of geothermal waters in the intermountain region should be carefully examined. Thus, Chapter V presents a concept for efficiently using warm geothermal waters in green houses as an alternative or possible complementary system to electrical power generation.

The international system of units is used throughout this report. Symbols and notations used are defined in the following list.

Symbol	Name	Meaning
g	Gram	Mass
kg	Kilogram	10^3 g
mg	Milligram	10^{-3}g
m	Meter	Length
km	Kilometer	10^3 m
cm	Centimeter	10^{-2} m
m^2	Square meter	Area
hm^2	Hectare	$10^4 m^2$
cm^2	Square centimeter	$10^{-4} m^2$
m^3	Cubic meter	Volume
l	Liter	$10^{-3} m^3$
J	Joule	Energy
kJ	Kilojoule	10^3J
MJ	Megajoule	10^6J
W	Watt	Power
kW	Kilowatt	10^3 watt
MW	Megawatt	10^6 watt
GW	Gigawatt	10^9 watt
TW	Terawatt	10^{12} watt

CHAPTER II

ENERGY ACCOUNTING SYSTEMS

Introduction

Engineers have long been concerned with tracking the energy flows associated with energy conversion devices resulting in various concepts of conversion efficiency. For example, the efficiency of a hydroturbine which converts the potential energy of water to the mechanical energy of a spinning shaft is computed as the ratio of the mechanical output energy to the initial potential energy of the water. The efficiency thus computed is always less than one.

Energy accounting broadens the concept of efficiency to account for the energy inputs required to construct the system as depicted in Figure 4. A new efficiency might, therefore, be defined as the ratio of the energy produced during the life of the device to the societal energy inputs required in that same time period. Societal energy inputs are defined as energy in the form of coal, oil, natural gas, electricity, etc., which society invests in the project. This ratio may, and indeed should, exceed unity. Ratios less than unity are considered cause for concern.

During the 1950s, Dr. Howard T. Odum, a systems ecologist, in an analysis of the work being done by a group of scientists producing algae as an energy crop, discovered that the energy required to build and maintain the experimental algae farm was far greater than the energy returned (the fuel value of the algae produced). He also observed that the project was actually kept in a production mode by the use of fossil fuel purchased with research dollars (Clark, 1974).

Odum subsequently developed a symbolic energy language utilizing electrical engineering flow chart sumbols to describe energy flows in the technological fields and in the environment (Odum, 1971, p. 38). He also introduced the term "net energy," which is defined as the amount of energy remaining for or available to the consumer after the energy costs of finding, developing, refining, producing, delivering, and so on have been paid. He recommended that ("since energy drives the economy") economists might profit by incorporating energy values into their science (Odum, 1971). The idea of energy driving the economy is not new. According to Clark (1974), several 19th century economists thought of energy as the provider of wealth. He reports that even early in this century, Sir Fredrick Soddy, a British Nobel Laureate, taught that energy was the giver of wealth.

Within the last few years, as public awareness of the energy crisis spread, significant interest has been manifest in energy accounting as a supplement to traditional economic analysis. Due to political intervention in the market, unanticipated inflation, or other factors, some economic analyses have been less than adequate. For example, it is reasoned that when the price of oil reaches $3.73/bbl (Dinnen, 1972) or $6.80/bbl (Adel-

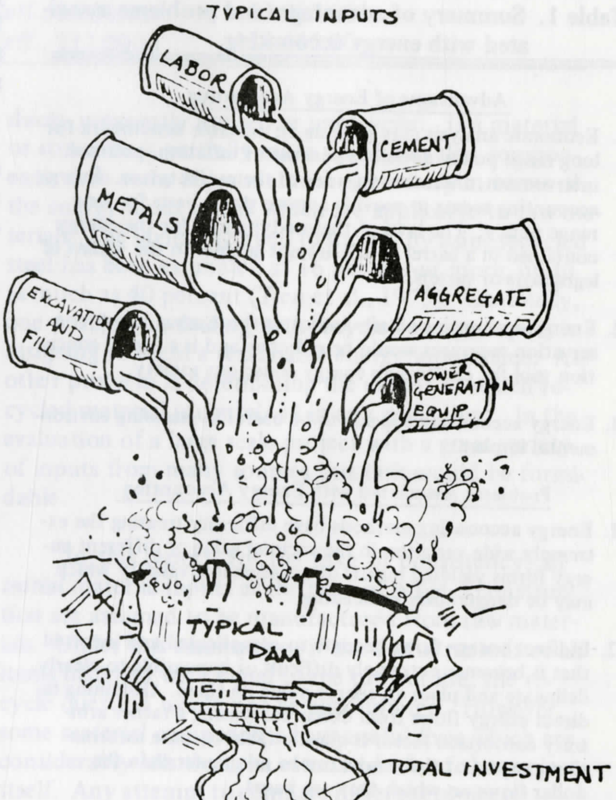


Figure 4. Typical energy resource inputs to a water management project.

man, 1974), or $15.00/bbl (Rothfield, 1975), or $21.00/bbl (MacCormick, 1976), or $25.00/bbl (Wiser, 1976), that oil shale development will become a reality. The rapidity with which these values change indicates something missing in the predictive mechanism. Perhaps the rising value of the energy required to produce the oil shale processing systems has not been adequately reflected in break-even predictions.

Various methodologies of energy accounting have been suggested. Table 1 is a summary of an extensive review of literature relating to energy flow analysis. The table suggests that an energy accounting methodology must be developed that circumvents the problems associated with current models. One possible solution is the modification of a present system labeled thermodynamic energy accounting.

Thermodynamic Energy Accounting

Thermodynamic energy accounting initiated by Berry (1972) begins with the raw material stage and analyzes each production process individually using a control volume approach. A control volume is drawn around the process as shown in Figure 5. The energy inputs, such as steel, fuel, and cement, that cross the control surface directly and are directly associated with the process are called direct energy inputs. Energy inputs implied by an operation which involves net energy investments on the part of the manufacturer in providing production facilities or the energy resource consumption of automobiles used to transport the human element or material element to a job site are defined as second generation energy inputs. Other inputs such as human labor, maintenance, engineering, research and development are labeled as indirect energy inputs.

Table 1. Summary of advantages and problems associated with energy accounting.

Advantages of Energy Accounting

1. Economic analysis may provide an unstable benchmark for long range policy decisions because of inflation, political, intervention, and other vagaries of the marketplace. Energy accounting seems to provide a more stable basis for long range policy. The laws of thermodynamics (or the energy contained in a barrel of oil) are not subject to the whims of legislators or cartels.
2. Energy accounting clearly indicates those areas where conservation measures would be effective and is a useful education tool for creating an energy conscious society.
3. Energy accounting appears to be useful in assessing environmental impact.

Problems Associated with Energy Accounting

1. Energy accounting methods have difficulty treating the extremely wide variation in the societal value of different energy forms yielding results of questionable validity which may be dangerously misleading.
2. Indirect energy flows become so complicated and involved that it becomes extremely difficult or impossible to clearly delineate and place an energy value on them. Obtaining indirect energy flows from dollar costs using a rather arbitrary conversion factor is questionable because information content of the results can be no greater than the dollar flows on which they are based.
3. The stability of the energy flow benchmark for long range policy decisions is questionable also. Technological advancement may dramatically change the energy inputs required to implement a given energy production system.

Second generation and indirect inputs are neglected in the initial analysis because of the difficulty associated with ascertaining their magnitude and because they are typically several orders of magnitude less than the direct inputs. Whatever the justification, the evaluation of such inputs often depends upon a value judgment of the energy accountant or others so that their inclusion tends to considerably complicate the analysis. The neglect of these inputs is compensated for by allowing the accountant to add an energy overhead investment that may be indicative of the more energy intensive processes or projects. Table 2 is an example of the variance that exists among inputs and gives some idea of complexities referred to.

Beginning at the raw material stage, the total analysis may involve several control volumes (Figure 5) as the energy accounting procedure moves through the several possible steps in the production process of most material.

Determination of the value of the direct energy inputs associated with a system is an important procedure. Fortunately, due to the increase in interest in energy accounting the literature abounds with input values for most common metals and other items, such as cement and glass. For items such as pumps, turbines, and motors, and activities such as excavation and fill, a lengthy process is required. Table 3 is a summary of the input values associated with the thermodynamic accounting system developed for this study.

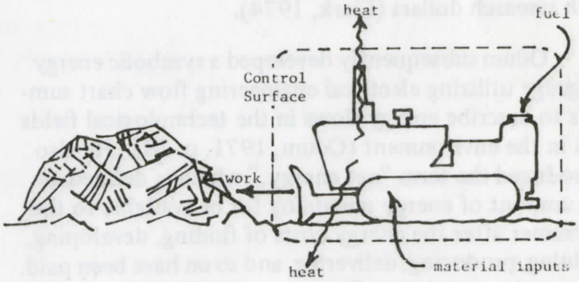


Figure 5. Control volume analysis of excavation and fill.

Table 2. An indication of the relative value of various forms of energy. This is intended to demonstrate the futility of indiscriminately adding various forms of energy in energy accounting methods.

FORM OF ENERGY	ASSUMPTIONS	VALUE OF 10^6 kJ (rounded to nearest dollar)
Fossil Fuels		
Natural Gas	36.4 J/m^3, \$35.3/Mm^3	\$ 1.00
Coal	30.3 kJ/kg, \$38/mg	1.00
Diesel	40.8 MJ/l, \$.10/l	2.00
Gasoline	34.7 MJ/l, \$.15/l	4.00
Electricity		
Industrial	1.5¢/kWH	4.00
Residential	3.9¢/kWH	8.00
Animal Feeds		
Alfalfa Hay	9.7 MJ/kg, 7.6 l/hr 20% eff.	7.00
Grain Corn	14.6 MJ/kg, 8¢/mg	11.00
Mechanical Energy		
Farm Tractor	\$11 000/6 000 hrs, 7.6 l/hr 20% eff.	30.00
Automobile	.08¢/km, 6.4 km/l, 15% eff.	100.00
Foods		
Wheat	13.8 MJ/kg, \$.16/kg	12.00
Rice	15.2 MJ/kg, \$.38/kg	25.00
Bread	11.3 MJ/kg, \$.88/kg	78.00
Potatoes	2.5 MJ/kg, \$.22/kg	86.00
Turkey	10.5 MJ/kg, \$1.32/kg	126.00
Beef	10.7 MJ/kg, \$2.64/kg	246.00
Human Labor		
Manual Labor	29.3 kJ/min, 20% eff., \$3.50/hr	9 954.00
Skilled Labor	12.6 kJ/min, 20% eff., \$8.00/hr	53 087.00
Professional	8.4 kJ/min, 20% eff., \$12.00/hr	119 446.00

Table 3. Energy input values from raw materials (Bell, 1977).

Material	Reference Input Value
steel cast	33.5 MJ/kg
steel rebar	41.9 MJ/kg
carbon steel	58.6 MJ/kg
stainless steel	67.0 MJ/kg
aluminum	276.3 MJ/kg
copper	142.3 MJ/kg
cement	12.6 MJ/kg
excavation and fill	29.3 kJ/kg
aggregates	46.1 kJ/kg
diesel fuel	40.9 MJ/l
gasoline	34.2 MJ/l
PVC	108.8 MJ/kg
polyethylene	125.6 MJ/kg
glass plate	46.1 MJ/kg
electric motors	561.1 MJ/kW - 83.7 MJ/kg
generators	83.7 MJ/kg
hydro turbines	87.9 MJ/kg
steam turbines	104.7 MJ/kg
pumps	83.7 MJ/kg
engines	83.7 MJ/kg - 14 232.4 MJ/ engine

The recycle question

In most studies, raw materials are used as the base from which the accounting process begins. However, it is unreasonable to assume that all of the materials used in power plan construction are raw material products, previously unused or unrecycled. If a material or structure is partially made up of recycled components, then some adjustments are necessary in terms of the energy input values which are applicable to raw materials. The savings accrued to society by using recycled steel has been estimated at 16 percent or more, up to as much as 40 percent (Tien et al., 1975). Obviously, one problem in dealing with recycled energy inputs is assigning to them a reasonable energy input value. Another problem is determining the extent to which recycled material is contained in any given item. In the evaluation of a large scale project with a great variety of inputs from many sources this task would be formidable.

In this report, for the sake of consistency, all *initial* material inputs at the time of project construction are assumed to be manufactured from raw materials. Under this assumption, if the useful periods of all items installed were equal to the project life, the recycle question would not be encountered. However, some material components have useful lives which are considerably less than the estimated life of the project itself. Any attempt to compare different projects would be difficult unless some common denominator of time were established so as not to inadvertantly penalize the project with the lower frequency of replacement. For the projects examined by this report the projected useful life of the generators (for hydropower projects this life is estimated at 50 years, U. S. Department of Interior, 1969) was chosen as the evalution period. The generators represent one of the largest single inputs of energy among the replaceable components of hydropower plants.

An example of the effects on energy accounting of recycling materials is shown by Table 4 in which one kilogram of aluminum is considered as being the recycled material. As the aluminum is installed and replaced during some evaluation period, the total cost to society in energy units is derived as shown by the Table 4.

In this example, when the kilogram of aluminum is initially installed, the debt owed to society is taken as being 276.3 MJ. After a certain time interval, the material is replaced; the used aluminum is scrapped and recycled with a savings to society of 60 percent of the raw material cost. In other words, in the recycle process society must provide only 40 percent of the energy associated with the initial raw material operations of mining, crushing, smelting, etc. As indicated by Table 4, this calculation is based on an estimated recycle energy input requirement of 108.9 MJ/kg cal/kg. The original kilogram of aluminum is replaced with a new kilogram which is represented by a second raw material input value of 276.3 MJ, but the used item is recycled, thus representing a return to society of 167.4 MJ/kg so that the net balance owed society is 385.2 MJ instead of 552.6 MJ. This procedure is repeated throughout the project evaluation period at a frequency equal to the life of the replaceable item.

The recycle process and its effects on energy accounting are further examined in terms of the control volume concepts (Figure 5). The total balance owed society at the end of the evaluation period may be represented in terms of raw material energy inputs, recycled material energy inputs, and the number of times the units is replaced by the following equation:

$$\left(\frac{ERC}{ERM} \text{ x } TR + 1.0\right) = RF,$$

$$\text{and } RF \text{ x } ERM = \text{energy investment}$$

in which

ERC = energy input to recycled material

ERM = energy input to raw material

TR = number of times replaced

RF = evaluation factor

Applying the investment equation to the above example yields:

$$\left(\frac{108.9}{276.3} \text{ x } 2.0 + 1.0\right) \text{ x } 276.3 = 494.0 \text{ MJ}$$

which is consistent with the initial calculation.

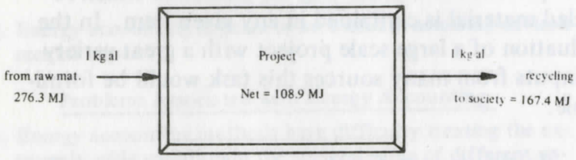


Figure 6. Control volume applied to the recycle process.

The implementation of this equation into the energy accounting process requires that the recycled energy inputs for the materials in the input section be identified. These values are listed in Table 5. The recycle values for motors, turbines, engines, and other equipment were arrived at by analyzing each basic unit and considering the energy inputs associated with activities such as disassembly, transportation, smelting, remanufacture, and distribution. In addition, the analysis considered the availability of re-usable components.

Adaption to the computer

With the energy inputs (including recycle) of the common construction materials defined, the actual evaluation of a large scale project, such as a hydro-power dam, is still a formidable task. Individual material inputs must be identified from a materials list and converted to weights. The task is made more difficult by the fact that material lists do not always adequately specify dimensions or conversion factors and it is necessary to refer to other information sources. For example, if 1 000 m of a certain pipe is specified, the energy accountant must refer to a pipe table to identify a wall

Table 4. Example of recylce effect on energy accounting using one kilogram of aluminum.

Action Taken	Debt (owed society)	Credit (owed by society)	Balance (owed society)
Initial installment	276.3 MJ		276.3 MJ
Take out, scrap		167.4 MJ	108.9 MJ
Replace with new part	276.3 MJ		385.2 MJ
Take out, scrap		167.4 MJ	217.8 MJ
Replace with new part	276.3 MJ		494.0 MJ

Table 5. Energy input values from recycled material (Bell, 1977).

Material	Recycle Value
steel cast	16.7 MJ6kg
steel reber	20.9 MJ/kg
carbon steel	29.3 MJ/kg
stainless steel	33.5 MJ/kg
aluminum	108.8 MJ/kg
copper	83.7 MJ/kg
cement	not applicable
excavation and fill	not applicable
aggregates	not applicable
diesel fuel	not applicable
gasoline	not applicable
PVC	not applicable
polyethylene	not applicable
glass plate	not applicable
electric motors	62.8 MJ/kg
generators	62.8 MJ/kg
hydro-turbines	41.9 MJ/kg
steam turbines	62.8 MJ/kg
pumps	421.0 MJ/kW
engines	41.9 MJ/kg

thickness or weight per length with which to determine a total weight for this entry. Similar problems are encountered with wires and cables. To mitigate this laborious accounting process a computer program was developed which is capable of accepting commonly used specifications for a wide range of construction items, such as pipes, cables, conduit, and concrete. Using stored information, the computer makes the necessary conversions and thus calculates the total energy input associated with each item required by the project. Chapter III discusses the results of applying this program to specific power generating projects.

Some Unresolved Questions

The accurate identification of the major material inputs and corresponding energy input values is of primary importance in applying the energy accounting procedure to an evaluation of water resource projects. However, for many materials the form (or source) of the input energy (for example, coal, natural gas, or electricity) is not specified. The only information usually reported is the total number of units of energy consumed in the manufacture of the item or material. In project evaluation energy outputs often are given in electrical power units. An incorrect assumption that all reported energy consumption related to inputs is in the form of electrical power could lead to seriously misleading results from the energy accounting analysis. The nature of this study did not lend itself to the investigation of such questions, but they are certainly worthy of further in-depth examination if a viable system of energy accounting analysis is to be established.

CHAPTER III

ENERGY FLOW ANALYSIS OF CONVENTIONAL HYDROPOWER DAMS AND GEOTHERMAL POWER PLANTS

In this chapter, the energy accounting technique is demonstrated by applying it to existing hydro and geothermal power projects.

Energy Inputs to Hydropower Dams

Energy flow analysis was performed on three of the major power dams of the Western United States. The identification of major material inputs was made by utilizing bid schedules provided by the U. S. Bureau of Reclamation. The results are summarized in Table 6. The mean replacement schedule indicates the probable number of times given components are replaced over the evaluation period.

It may be noted from Table 6 that there is considerable variations in the break-even points among the three hydropower dams analyzed. The computed operating time required to reach a break-even point at Morrow Point, for example, is less than half that at Glen Canyon or Flaming Gorge. Thus, it appears that from an energy standpoint, Morrow Point is a relatively efficient installation. Other factors which should be considered include the energy required to construct transmission lines to convey the power from the generating site to the load centers. Indirect energy inputs such as the energy required to transport the workers to and from the job sites also were neglected. An argument justifying this approach is presented in Chapter II.

Energy Inputs to Geothermal Power Plants

The only operational electrical generating system utilizing geothermal energy in the United States is at the Geysers steam field near San Francisco, California. The Geysers field, operated by Pacific Gas and Electric, currently generates 522 MW of electrical power. The operation cycle for units 5 and 6 is shown schematically by Figure 7. Dry steam is collected from the field at 882.5 kPa, 179.4°C and introduced into the turbines at 411 635 kg/hr. The steam which emerges from the turbine is condensed and pumped to the cooling towers. Approximately 71 486 kg/hr water is then reinjected in the steam field (Finney et al., 1972).

Material inputs are based on data provided by Pacific Gas and Electric Company and by Union Oil Company, specifically, for units 5 and 6, and its adjacent steam field. The inputs included fuel and equipment required to drill the wells prorated over the expected life of the drilling equipment, piping, values, concrete, excavation and power generation equipment. Transmission lines and switch year items were not included. Repair shops and associated equipment were also neglected in hydro and geothermal evaluations. The results of applying the programmed energy input calculations to units 5 and 6 of the Geysers field are shown in Table 7.

As the tables indicate, the hydropower and geothermal projects analyzed in this study require approximately the same amount of time at full production to return to society the energy invested in them. However, from a water management standpoint the exact number of hours is not important. What is important, is the fact that energy accounting shows that a given project will adequately create an energy profit early in its operational life. Needed, however, is a basis for comparison with other power production systems. For this

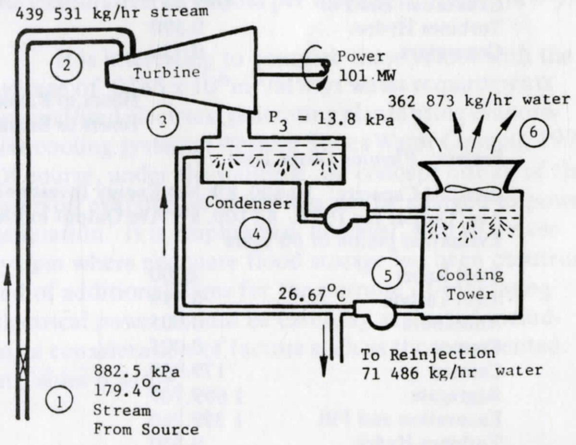


Figure 7. Schematic diagram of Geysers Units 5 and 6 Geothermal Project.

reason, an energy flow analysis was conducted on windmills which also utilize a renewable energy source.

Energy Inputs to Windmills

Windmill configurations are almost infinite in variety. For purposes of this analysis, both the conventional horizontal axis and the vertical axis windmills were considered.

The following assumptions were made regarding system parameters.

1. Windmill is of steel construction with a mass of 75 kg/m^2 of swept area.
2. The structure diameter is 9.14 m.
3. It is mounted on concrete pad .3 m thick by 9.14 m x 9.14 m.
4. The generator is rated at 15 kW.
5. It has an expected operating life of 25 years or replacement once in a 50 year period.

Shown in Table 8 are results of an energy accounting analysis for mean effective wind speeds of 16.09 km/hr and 24.14 km/hr (Simmons, 1975). Also pre-

Table 6. Results of energy flow analysis applied to hydropower projects.

	Installed Mass or Quantity (Million kg.)	Mean Replacement Schedule	Net Mat. Energy Investment TJ
Project: Glen Canyon Dam			
Installed Capacity: 900 000. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1973: 525 000. kW Ave Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	12.998	0.0	544.084
Steel Carbon	46.392	0.0	2 718.761
Aluminum	0.950	1.1	376.133
Copper	0.250	1.3	62.777
Cement	969.834	0.0	12 179.175
Aggregate	9 298.408	0.0	428.152
Excavation and Fill	11 997.946	0.0	351.565
Turbines Hydro.	4.426	1.2	611.441
Generators	5.625	1.3	930.083
		Total Energy Investment	18 202.172
		Hours to Break Even Point at Average Output	9 631.
		Hours to Break Even Point at Total Capacity	5 618.
Project: Morrow Point Dam			
Installed Capacity: 12 000C.kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1973: 10 000C.kW Ave Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	1.400	0.0	58.596
Steel Carbon	3.499	0.0	205.081
Copper	0.003	1.3	753
Cement	71.988	0.0	904.021
Aggregate	959.836	0.0	44.196
Excavation and Fill	949.837	0.0	27.838
Turbines Hydro.	0.590	1.2	81.489
Generators	0.730	1.3	120.602
		Total Energy Investment	1 442.646
		Hours to Break Even Point at Average Output	4 007.
		Hours to Break Even Point at Total Capacity	3 339.
Project: Flaming Gorge Dam			
Installed Capacity: 10 800. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1973: 82 100. kW Ave Output in Electricity kW			
Evaluation period of 50 years			
Steel Rebar	2.300	0.0	96.261
Steel Carbon	6.699	0.0	392.580
Aluminum	0.005	1.1	1.980
Copper	0.005	0.0	.712
Cement	179.969	0.0	2 260.390
Aggregate	1 699.709	0.0	78.266
Excavation and Fill	1 399.760	0.0	41.014
Turbines Hydro.	0.550	1.2	75.963
Generators	0.680	1.3	112.415
		Total Energy Investment	3 059.246
		Hours to Break Even Point at Average Output	10 351.
		Hours to Break Even Point at Total Capacity	7 869.

Table 7. **Results of energy flow analysis applied to a geothermal project.**

	Installed Mass or Quantity (Million kg.)	Mean Replacement Schedule	Net Mat. Energy Investment TJ
Project: Geysers Steam Field Units 526			
Installed Capacity: 110 000. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1975: 101 000. kW Ave. Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	0.200	0.0	8.372
Steel Carbon	22.596	0.5	1 655.278
Steel Stainless	0.151	0.2	11.160
Aluminum	0.005	0.1	1.436
Copper	0.030	0.1	4.521
Cement	1.150	0.0	14.438
Aggregate	10.998	0.0	.507
Excavation and Fill	179.989	0.0	5.274
Turbines Steam	0.434	0.0	53.593
Generators	0.256	1.1	39.156
Motor-Engines (Units)	15.		1.574
Pumps (Units)	8.		9.657
		Total Energy Investment	1 804.966
		Hours to Break Even Point at Average Output	4 964.
		Hours to Break Even Point at Total Capacity	4 558.

sented in Table 8 are the results of an analysis performed on a vertical axis Savonius rotor type windmill assuming the same system parameters as the previous example except that the assumed mass was 9.84 kg/m^2 of swept area (South and Regi, 1973). The power output was taken from a nomograph developed by the National Research Council of Canada. These results are particularly revealing when compared with similar calculations for hydropower or geothermal power shown in Tables 6 and 7.

Power schemes such as windmill systems are being heralded as environmentally benign. Energy accounting shows that such is not the case, The energy break-even time for a horizontal windmill system is approximately 10 times that of a hydropower project. In addition, a wind system operating with an average 16.1 km/hr wind and at power output equivalent to that of Glen Canyon would require more than 350,000 windmills of 9.14 m diameter. The system would involve 15 times the steel and 4 times the concrete contained in the hydro project. Further, the maintenance problems associated with such a system (which are not addressed by this study) would be relatively severe.

The above comparisons indicate that compared to windpower, hydropower and geothermal power are relatively efficient from a resource utilization standpoint. Like conclusions probably would result from a similar comparison with solar power generation. There are other important aspects to consider regarding hydropower and geothermal power which are discussed in the following section and in Chapter IV of this report.

Additional Perspectives on Hydropower

It has been shown that energy accounting can provide some valuable insights into project evaluation which are unavailable through economic analyses. However, on the basis of the information usually available to planners and designers both procedures suggest that hydropower development at desirable sites normally is a sound investment. There are, however, other considerations. For example, shown in Table 9 are summarized of average annual evaporation losses associated with three of the largest impoundments in the west (Hughes et al., 1974). Also shown are the average power outputs and the evaporative water loss per mega-watt - year (MW-yr).

It is interesting to compare these values with the average of .0185 x 10^{6}m^3/MW yr water requirements for coalfired electrical generating plants using evaporative cooling systems (Western States Water Council, 1974). Of course, under the multiple use concept not all of the reservoir evaporative water loss can be charged to power generation. It is emphasized, however, that in a river system where adequate flood storage has been constructed of additional dams for the purpose of generating electrical power should be carefully evaluated including a consideration of factors such as those presented in Tables 6 and 9.

Table 8. Results of energy flow analysis to two types of windmills.

	Installed Mass or Quantity (Million kg.)	Mean Replacement Schedule	Net Mat. Energy Investment TJ
Project: Horizontal Axis Windmill			
Installed Capacity: 2. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1976: 2. kW Ave. Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	2.041	0.0	85.428
Steel Carbon	4.923	1.0	432.778
Cement	9.480	0.0	119.054
Aggregate	47.402	0.0	2.181
Generators	0.113	0.0	9.494
		Total Energy Investment	648.935
		Hours to Break Even Point at Average Output	90 131.
		Hours to Break Even Point at Total Capacity	90 131.
Project Horizontal Axis Windmill			
Installed Capacity: 5. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1976: 5. kW Ave. Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	2.041	0.0	85.428
Steel Carbon	4.923	1.0	432.778
Cement	9.480	0.0	119.054
Aggregate	47.402	0.0	2.181
Generators	0.113	0.0	9.494
		Total Energy Investment	648.935
		Hours to Break Even Point at Average Output	36 052.
		Hours to Break Even Point at Total Capacity	36 052.
Project: Vertical Axis Windmill			
Installed Capacity: 1. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1976: 1. kW Ave. Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	2.041	0.0	85.428
Steel Carbon	0.641	1.0	56.373
Cement	9.480	0.0	119.054
Aggregate	47.402	0.0	2.181
Generators	0.113	0.0	9.494
		Total Energy Investment	272.530
		Hours to Break Even Point at Average Output	75 703.
		Hours to Break Even Point at Total Capacity	75 703.
Project: Vertical Axis Windmill			
Installed Capacity: 5. kW Net Energy Investment is Fossil Fuel Equiv.			
Ave. Output for 1976: 5. kW Ave. Output in Electricity kW			
Evaluation Period of 50 years			
Steel Rebar	2.041	0.0	85.428
Steel Carbon	0.641	1.0	56.373
Cement	9.480	0.0	119.054
Aggregate	47.402	0.0	2.181
Generators	0.113	0.0	9.494

Table 9. Evaporative water loss per unit of power produced.

Reservoir	Ave. Evap. Loss $10^6 m^3$/yr	Average Power Out MW	Water Requ. $10^6 m^3$/MW yr
Lake Powell	796.83	525	1.53
Flaming Gorge	122.26	82.1	1.49
Lake Mead	1 208.81	393	3.07

CHAPTER IV

AN ALTERNATIVE CONCEPT FOR HYDROPOWER

Pumped Storage

One of the major concerns facing electric power companies today is peak demand. To meet these demands, generating facilities must have a significantly greater installed capacity than the average rate at which power is generated. This increases the capital investment and, thus lowers both the economic and resource allocation efficiencies of the plant. Pumped storage offers a possible solution to this problem. The concept simply involves pumping water to a high elevation reservoir during periods of low electrical demand and allowing it to flow back through electrical generating hydroturbines during periods of high demand. Although the concept of storing energy as raised water has been known for years it has only recently been applied in this country on a large scale (Committee on Hydro Power Project Planning and Design of the Power Division, 1971). The major breakthrough came with the design of a hydraulic power unit that could be used for both generation and pumping. This unit consists of a turbine connected to a generator. When a flow is in the opposite direction, the unit becomes a pump and a motor. These are called pump-turbines or reversible turbines. Some older facilities used separate pumps and generators, but most pump storage stations today are equipped with reverse turbines.

Pumped storage facilities throughout the world range in size from 4MW to 1 825 MW at the recently completed Ludington project. Available heads range from 26 m at Niagara Falls to 1 000 m at Lunersee, Austria. An elevation difference of between 300 m and 500 m between reservoirs is regarded as optimum (Thorn, 1970).

In general, the trend is for more, larger volume and higher head plants throughout the world. Many excellent sites in the Western United States are available. The U. S. Bureau of Reclamation estimates that a total of 15 000 MW could be generated by the construction of such facilities (Armstrong, 1971).

There are several reasons why pumped-storage facilities are considered better than other methods of meeting peak demands (Thorn, 1970).

1. *Cost effectiveness.* Large scale facilities are usually less expensive than fossil fuel or conventional hydroelectric plants that operate at less than full capacity several hours each day.

2. *Reliability.* Forced and scheduled outages for pumped-storage facilities are usually much shorter and less frequent than for fossil fuel plants.

3. *Water conservation.* Pumped-storage facilities use and reuse water. The only losses are to evaporation and groundwater recharge. These losses, in most cases, are relatively minor.

4. *Emergency reserve.* Pumped-storage facilities are usually designed to have an energy reserve greater than their normal daily output. This reserve can be used anytime a conventional power plant fails.

5. *Flexibility.* Pumped-storage facilities do not have to be operated on a regular schedule. They can go from a cold start to full capacity in as little as 3 minutes (Anonymous, 1970). They can be shut down on weekends and holidays. Because start-up and shut-down times are very short, they can generate or store power on short notice.

Economic justification for pumped-storage facilities is quite complicated. It involves the study of many technical and economic aspects, some of which cannot easily be reduced to monetary units. Because it is used to supplement base load capacity in meeting peak demands, pure pumped-storage capacity usually is not in direct competition with base load capacity (thermal or otherwise) (Barrows, 1966). Generally, the cost of the facility is weighed against the cost of additional generating plants, be it thermal, nuclear, or conventional hydro-electric that would be needed to meet peak demand. The economic justification for the construction of pumped-storage facilities usually is defined by the relative value of power generated at peak demand compared with the value of power generated at times of low demand. Of course, another important consideration is the efficiency with which the systems convert the energy from one form to another. Only about 66 to 72 percent of the electrical energy required to pump the water is recovered during the generating stage (Science and Public Policy Program, 1975).

Once-Through Cooling

The present method of converting coal into electricity generally involves circulating large quantities of water to the power plant condensor cooling towers where the waste heat is rejected to the atmosphere through evaporation of a part of the cooling water. As shown by Table 10, cooling tower make-up water approximates 18.5 10^6 m^3/yr for a 1 000 MW plant.

Table 10. Approximate water use for various methods of cooling coal fired power plants.

Method*	Consumptive Use 10^6 m^3/yr/1000 mega watts
Evaporative cooling towers	18.50
Pond cooling	12.33
Dry radiation towers	2.47
Once-through	0

* From Bishop, et al. (1975).

An alternative to evaporative cooling is once-through cooling in which cool water from some source simply flows through the condensor once and is rejected back to the environment at a higher temperature. Evaporative cooling has been adopted at most power plants for a number of reasons. The two most important of these reasons are cited as follows:

1. Many power plants are not located near sufficiently large sources of water to obtain the huge flow rates required for once-through cooling.

2. Even those power plants planned for construction near ample water sources are designed for evaporative cooling. Power company management seems to be uncertain regarding the interpretation and enforcement of antipollution laws, particularly, PL92-500. This uncertainty leads to the adopting of the total containment approach to power plant cooling system designs.

The evaporative cooling approach is shown schematically by a part of Figure 8. Water is pumped from

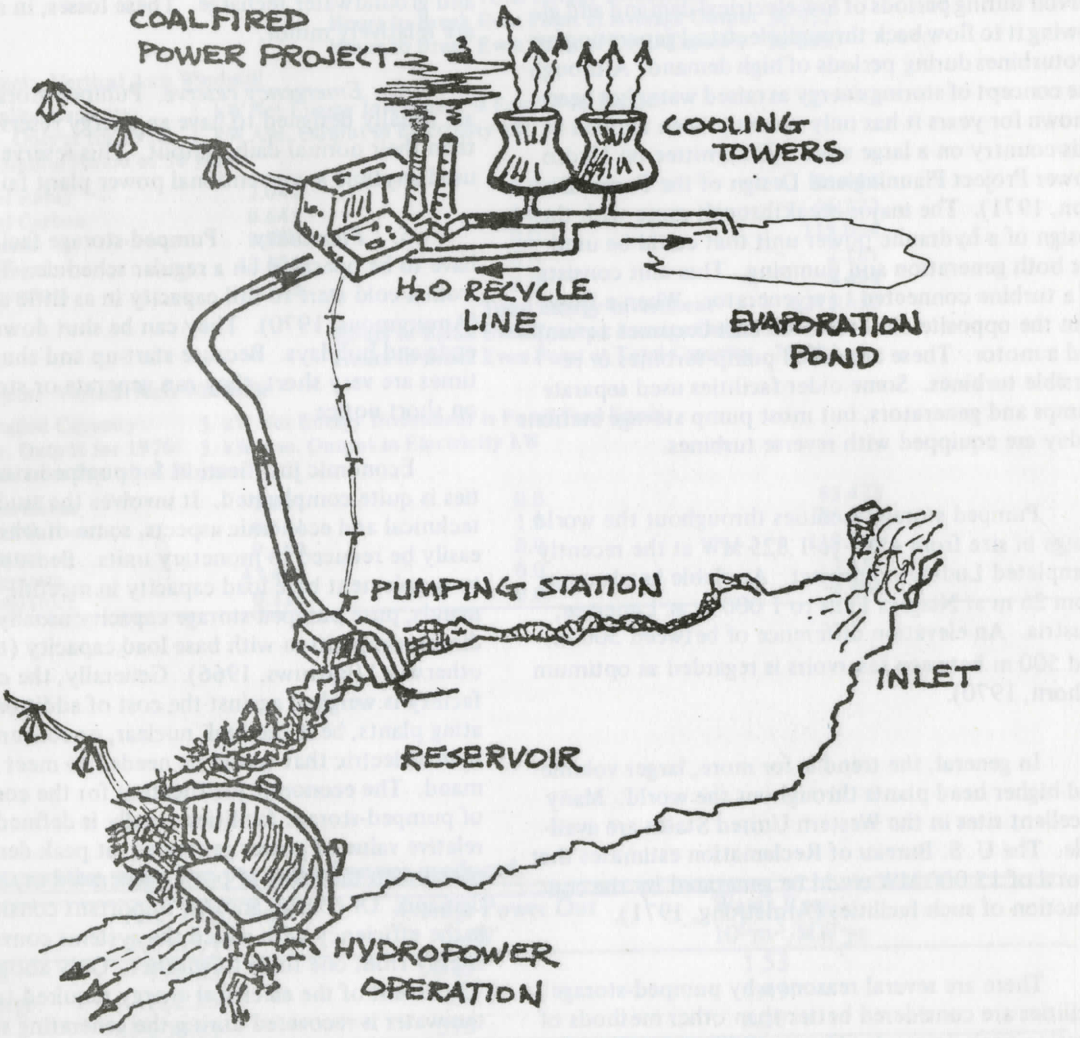


Figure 8. Schematic of evaporative cooling approach.

the source to a small reservoir at the plant site. Make-up water then is injected into the system to compensate for cooling tower losses. To avoid mineral build-up in the cooling water loop, an additional quantity of water containing a quantity of minerals equal to that in the make-up water is removed and sent to an evaporation pond. Evaporative cooling is inherently wasteful of precious water resources, and this is strong justification for re-examining the basic concept, particularly under conditions encountered in Utah and the Intermountain region, water supplies for energy development are limited. The substantial supplies of low sulfur coal in the region suggests that a method of cooling is needed which conserves available water supplies.

Once-through Cooling and Pumped Storage Combined

A combination of once-through cooling of thermal power plants and pumped storage hydropower plants (depicted in Figure 9) is a system which pumps water from the source to an onsite reservoir during periods of low electrical demand. Water from this reservoir flows through the condenser of the thermal plant in a once through mode to a second onsite reservoir. During periods of high electrical demand, water is returned to the source through hydroturbines, thus generating electricity. In the following example a hypothetical power plant (or plants) producing 1 000 MW of electicity is located on a plateau several hundred feet above Lake Powell in the vicinity of Glen Canyon Dam. In examining such a concept the points raised in the following discussion are considered.

Direct water savings

Cooling tower makeup water to the 1 000 MW (coal fired) plant would amount to about 14.8 to 18.5 10^6 m^3/yr. With once-through cooling most of this water is returned to the river system, thus making it avail-

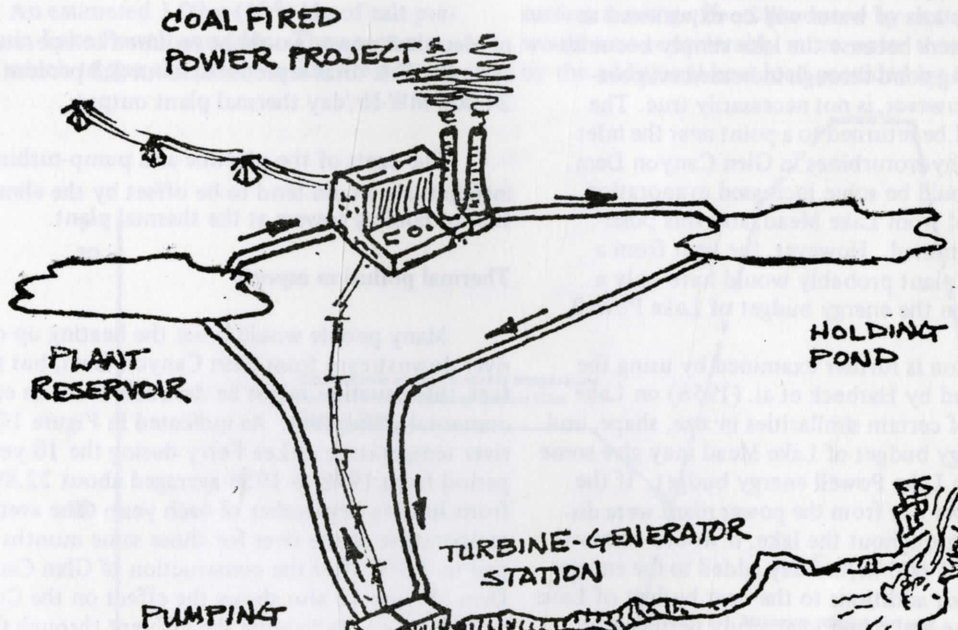


Figure 9. Schematic of once through cooling concept combining pumped storage and possibly lake mixing to reduce evaporation.

able for other purposes. This quantity of water could annually irrigate typically about 1 618.80 hm^2. In todays world of potential food shortages this production potential cannot be ignored. However, not all of the water withdrawn from the lake is returned. There is, of course, some evaporation loss in the high elevation storage reservoirs. For estimation purposes, it is assumed that the cool water reservoir (first reservoir) holds a three-day cooling water supply of 5.14 x 10^6 m^3, and has a surface area of 48.16 hm^2 with an average depth of 10.7 m. The warm-water reservoir (second reservoir) holds a one-day supply of 1.71 x 10^6 m^3, and has a surface area of 16.19 hm^2. Assuming evaporation rates of 1.65 m/yr and 2.29 m/yr on the cool and warm water reservoir, respectively, the total annual evaporation loss is 1.17 x 10^6 m^3. This quantity amounts to about 8 percent of the evaporation losses through conventional cooling towers.

An obvious objection to once-through cooling is the proposition that if the warm water is returned to the lake, the same loss of water will be experienced as in the cooling towers because the lake simply becomes an effective cooling pond through increased evaporation. The state, however, is not necessarily true. The warm water could be returned to a point near the inlet penstocks of the hydroturbines in Glen Canyon Dam. There perhaps would be some increased evaporation from the river and from Lake Mead, and this possibility should be studied. However, the heat from a 1 000 MW power plant probably would have only a minimal impact on the energy budget of Lake Powell.

This situation is further examined by using the budget determined by Harbeck et al. (1958) on Lake Mead. Because of certain similarities in size, shape, and climate, the energy budget of Lake Mead may give some indications of the Lake Powell energy budget. If the 146. TJ of heat per day from the power plant were distributed evenly throughout the lake, it would amount to approximately 1 600 kJ/m^2-day added to the energy budget. The major additions to the heat budget of Lake Mead during a one and a half year study period were 21 000 kJ/m^2-day of solar radiation and 28 900 kJ/m^2-day of incoming longwave radiation (Harbeck et al., 1959). The heat from a 1 000 MW power plant would therefore, amount to about 1.4 percent of the average energy added by solar radiation and 1 percent of the average longwave radiation.

Cooling water flow rates

Truly large amounts of water must be diverted through the condensors for once-through cooling. Assuming a 20°C temperature rise (21.1°C to 41.1°C) of the cooling water could be tolerated, a condensor flow rate of about 19.54 m^3/s would be required when the plant is operating at full capacity. If pumping occurs from the reservoir (Lake Powell) during only 16 hours of low electrical demand and water is then returned to the lake during 8 hours of high demand, the pumping and the generating flow rates would be about 29.3 m^3/s and 58.6 m^3/s, respectively.

Power requirements

It is estimated that 150 MW or approximately 15 percent of the 1 000 MW plant output during the 16 hour pumping period would be required to lift 29.31 m^3/s through an elevation difference of 426.7 m. Of course, by installing turbines in the return line much of this energy is recovered. About 200 MW of power are generated by the hydroturbines during 8 hours of return flow. Thus overall plant capacity is increased by 20 percent to meet peak demands during this period. These estimates are based on an assumption of 84 percent efficiency for both pumping and generating. Allowance also is made for friction losses in the line. It thus appears that about

$$(150 \text{ x } 16) - (200 \text{ x } 8) = 800 \frac{\text{MW-Hr}}{\text{day}}$$

of electrical power would be required to operate the system. This total represents about 3.3 percent of the 24 000 MW-Hr/day thermal plant output.

The costs of the pipeline and pump-turbine installations would tend to be offset by the elimination of cooling towers at the thermal plant.

Thermal pollution aspects

Many people would resist the heating up of the river downstream from Glen Canyon Dam, but in fact, this situation might be desirable from an environmental standpoint. As indicated in Figure 10, river temperature at Lee Ferry during the 10 year period from 1948 to 1958 averaged about 22.8°C from June to September of each year. The average temperature of the river for those same months dropped to 7.8°C after the construction of Glen Canyon Dam. Figure 10 also shows the effect on the Colorado River of discharging the effluent through Glen Canyon Dam (without mixing with impounded water). The bottom line is the present monthly average temperature. The middle line shows the effect of adding 146.TJ per day to the flow. Actually, this line is somewhat unrealistic. Under conditions of pumped-storage water is discharged only during the generation part of the cycle, which occurs from approximately 8-10 hours each day. Pumping occurs during the rest of the day. The upper line shows the effect of adding one days output of heat directly to the Colorado River during the eight hour power generation period. The bottom line then represents the river temperature during the rest of the day. These calculations assume that the discharge of heat is completely mixed with the river waters and that the discharge past the dam is constant throughout the day. Thus, once-through cooling of a 1 000 MW plant would increase the temperature of the river by only about 1.7°C even during periods of minimum flow. Thus, once-through cooling could even be considered beneficial with respect to the pristine conditions of the river.

Impact on salt loading of river systems

With once-through cooling the water together with its dissolved solids are removed temporarily and then both are returned to the system. Because the average salinity at Lee Ferry is 580 mg/l and at Imperial Dam is 847 mg/l (Bishop et al., 1975), the saving of 14.8×10^6 m^3 of the higher quality water would certainly be beneficial. It has been calculated, for example, that the loss of water through the cooling towers of the proposed and now apparently defunct 3 000 MW Kaiparowits power plant would have resulted in the addition of 1.2 mg/l at Imperial Dam (Bessler, 1975). There are, of course, other considerations. An estimated $1.09 \times (10^4)$ Mg of salt precipitation in Lake Powell annually. The exact mechanisms which trigger the precipitation are not yet established. However, it is probable that the mixing effect due to withdrawing and returning large volumes of water and the associated temperature changes would decrease the salt precipitation rate in the reservoir.

Lake mixing

Another intriguing notion is that the mixing due to the removal from and replacement of large quantities of water could probably reduce lake evaporation. In a recent study Hughes et al. (1975) formulated a computer model which involves a very detailed energy budget for Lake Powell. The model predicts that approximately 20 percent of the annual lake evaporation could be saved by thermal mixing of the lake water. This figure represents more than 123.35×10^6 m^3 annually if the entire lake were thermally mixed. The predicted savings result from a cooling of the water surface as shown in Figure 11. The long term savings would, of course, be less than this if heated water were used to accomplish the mixing. However, it appears that the surface cooling effects produced by destratification would save considerably more water than losses induced by the additional heat load provided by the cooling

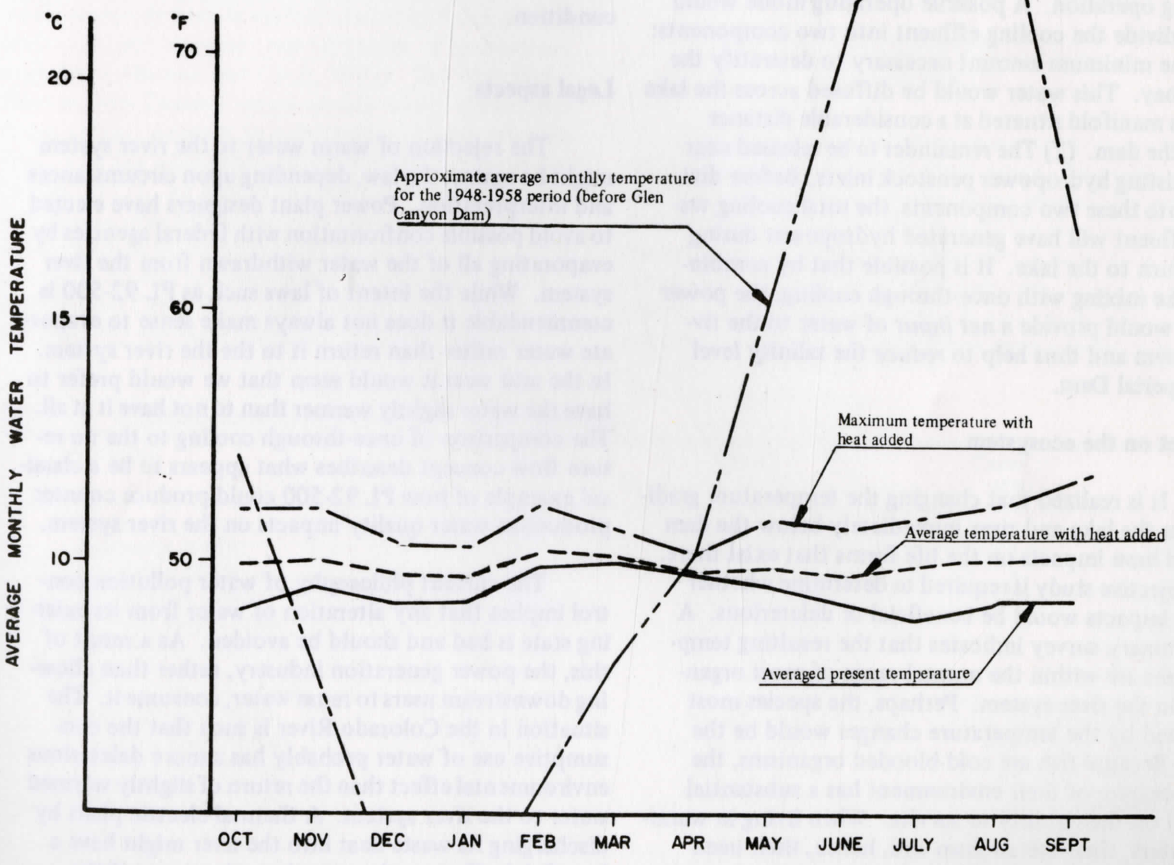


Figure 10. Temperature of the Colorado River at Lee Ferry with and without heat additions.

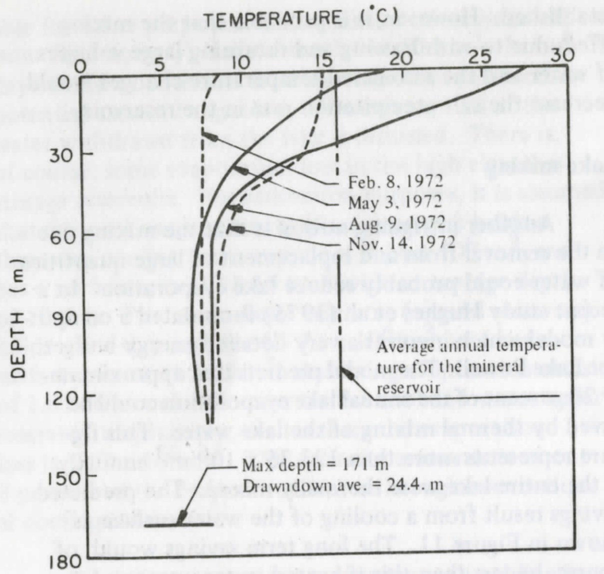


Figure 11. Lake Powell water temperature profiles (after Hughes et al., 1975).

water. It is probable that the amount of water required to destratify the main bay near the dam is less than the total quantity of water available from the once-through cooling operation. A possible operating mode would be to divide the cooling effluent into two components: (1) The minimum amount necessary to destratify the main bay. This water would be diffused across the lake from a manifold situated at a considerable distance from the dam. (2) The remainder to be released near the existing hydropower penstock inlets. Before division into these two components, the total cooling water effluent will have generated hydropower during its return to the lake. It is possible that by combining lake mixing with once-through cooling, the power plant would provide a *net input* of water to the river system and thus help to *reduce* the salinity level at Imperial Dam.

Impact on the ecosystem

It is realized that changing the temperature gradients in the lake and river immediately below the dam would have impacts on the life forms that exist there. An objective study is required to determine whether these impacts would be beneficial or deleterious. A preliminary survey indicates that the resulting temperatures are within the normal range of most organisms in the river system. Perhaps, the species most affected by the temperature changes would be the fish. Because fish are cold-blooded organisms, the temperature of their environment has a substantial effect on their ability to survive. When living in warmer waters, their metabolism and, hence, their need for food is increased. For example, rainbow trout are "cold water" fish, so that the addition of heat and destratification of the reservoir would reduce their habitat. The anticipated temperature changes would have beneficial effects on warm-water fish that are found in large western lakes. These fish include largemouth bass, crappie, bluegills, and sunfish. The new water temperatures actually would be closer to the ideal temperatures of these fish than the existing temperatures. Seasonal water temperature cycles also would be somewhat altered, but this effect likely would have little influence on the spawning habits of the fish.

There is some concern that the mixing currents in Lake Powell would be so great that they would cause habitat problems for the threadfin shad. If the shad cannot find algae in sufficient concentrations, its growth might be limited. Its presence is considered critical to the ecosystem of the reservoir. The same temperature effect would be noted downstream of the Glen Canyon Dam.

If the alternative proposal of discharging the heated water directly at the dam outlet were implemented, there would be little adverse effects. The addition of heat would partially offset the decrease in stream temperatures that was caused by construction of the dam. Even with the added heat, between May and October, the river still would be colder than it was in its pristine condition.

Legal aspects

The rejection of warm water to the river system might be against the law, depending upon circumstances and interpretation. Power plant designers have elected to avoid possible confrontation with federal agencies by evaporating all of the water withdrawn from the river system. While the intent of laws such as PL 92-500 is commendable it does not always make sense to evaporate water rather than return it to the the river system. In the arid west it would seem that we would prefer to have the water slightly warmer than to not have it at all. The comparison of once-through cooling to the no return flow concept describes what appears to be a classical example of how PL 92-500 could produce counter productive water quality impacts on the river system.

The current philosophy of water pollution control implies that any alteration of water from its existing state is bad and should be avoided. As a result of this, the power generation industry, rather than allowing downstream users to reuse water, consume it. The situation in the Colorado River is such that the consumptive use of water probably has a more deleterious environmental effect than the return of slightly warmed water to the river system. A thermal electric plant by discharging its waste heat into the river might have a beneficial effect on the aquatic environment if the proper controls were used.

The Colorado River is one of the most altered river systems in our country, both in terms of flow and chemical composition. When evaluating the environmental effects of a project, the current condition of the river might not serve as a good point of reference. Concepts such as combining pumped storage with once-through cooling could possible tend to reverse impacts of prior alterations to the natural system. Any proposed further alteration to the system should be judged by its projected benefits, and the existing condition of the river should not be considered as the "natural condition."

Other factors

Obviously, the scope of the present study has not permitted an in-depth analysis of the combined pumped storage once-through cooling concept. There are many aspects of the problem which this study has not addressed. For example, the use of 10°C water from the bottom of the lake as cooling water for the thermal plant rather than 26.7°C water from conventional cooling towers likely would improve the thermal efficiency of the plant, and thus would influence its design. In addition, it is suggested that the cost of transmission of additional power from a remote site such as the Lake Powell area to the load centers should be considered. Also, the cost of the hydraulic structure necessary to deliver large quantities of warmed water to the penstock inlets while simultaneously diffusing water through a manifold extending across the main bay would be large. Certainly this proposal would prompt environmental objections. However, it is considered that an in-depth benefit-cost analysis of the entire concept is warranted and should be conducted.

CHAPTER V

ADDITIONAL PERSPECTIVES ON GEOTHERMAL WATER USE

Types of Geothermal Sources

There are three basic types of geothermal sources. The first type, the vapor dominated source, is exemplified by the Geysers, northeast of San Francisco, California, where Pacific Gas and Electric has installed numerous power-plants, the largest rated at over 100 megawatts. At the Geysers, steam is used directly as it comes from the well, super heated and with relatively small fractions of undesirable gases and corrosives. Its rarity is due to the high temperature and pressure as well as the low impurity levels at this particular site.

The second type, the water dominated source, is most commonly seen in surface manifestations, though surface activity may not representative of geothermal availability (Bowen and Groh, 1971). The Wairakei plant in New Zealand uses a system which flashes wet steam at high pressure to a drier steam at a lower pressure. The dry steam then is run through a turbine (Axtmann, 1975). As Axtmann states, however, the chemical and thermal effluents from this plant may be as undesirable as those from fossil or nuclear plants. High salinity is typical of many water dominated sources (Kruger and Otte, 1973, and Milligan et al., 1966), and accounts for the major problem of brine disposal.

The third type, high temperature underground dry rock bed, is utilized by pumping water into the permeable rock bed at the bottom and by drawing hot liquid out at the top of the reservoir. The reservoir may consist of natural or man-fractured rock beneath an impermeable rock cap. The Imperial Valley in California is estimated to have nearly 5 percent underlayment of hot dry rock (Kruger and Otte, 1973) which, it is hoped, can be utilized in this way to yield 8 000 000 megawatt-centuries of energy by flashing hot water.

Table 11 lists the existing major geothermal power plants with their types of energy sources, as well as type of cycle.

Converting Geothermal Energy into Electricity

The cycles used in energy recovery from geothermal sources are generally of three types. The open system of Figure 12a operates by taking geothermal steam directly into the turbine as the working fluid at source temperature and pressure, exhausting it into the atmosphere after use, at atmospheric pressure. Such low cost systems are generally used only in the initial testing of a geothermal field or where power demands are low.

Table 11. Existing major geothermal power developments.

Location	Type	Cycle	Capacity (MW)
Larderello, Italy	Dry Steam	Open System	380
Paratunka, USSR	Hot Water	Closed System	0.75
Pauzhetka, USSR	Wet Steam	Open System	5
The Geysers, Calif.	Dry Steam	Open System	900[a]
Imperial Valley, Calif.	Hot Water	Closed System	3[b]
Matsukawa, Japan	Dry Steam	Open System	20
Otako, Japan	Wet Steam	Open System	11
Los Alamos, New Mexico	Hot Rock	Closed System	Under development
Tatio Geysers, Chile	Wet Steam	Open System	Under development
Wairakei, New Zealand	Wet Steam	Open System	198
Kawerau, New Zealand	Wet Steam	Open System	10
Pathe, Mexico	Wet Steam	Open System	3.5
Mexicalli, Mexico	Wet Steam	Open System	75
Akureyi, Iceland	Wet Steam	Open System	2.5

[a] Estimated capacity as of 1976.

[b] Estimated ultimate capacity is 20 000 to 30 000 MW.

With the addition of a pump and condenser the cycle of Figure 12a becomes the cycle of Figure 12b with an increase of efficiency by exhausting at a pressure maintained below atmosphere.

In the so-called binary cycle, shown in Figure 12c, the energy in the hot geothermal fluid is transferred, through a heat exchanger, into another working fluid which drives the turbine. The binary cycle, generally, utilizes a fluid such as isobutane (Kruger and Otte, 1973) which has a lower vaporization temperature than water. The lower boiling temperatures allow the utilization of energy in water not hot enough to be used efficiently by flashing. The binary cycle also has the advantage of preventing turbine corrosion by the often corrosive geothermal source water.

The three main types of cycles should not preclude the possibility of other cycles, perhaps unique to geothermal applications. For example, the vapor pressure of a geothermal fluid could be utilized to lift the vaporized water from the warm liquid surface to a cooling shield at some distance above. As shown in Figure 13 the condensed vapor could be accumulated much like a solar still, and dropped as liquid to ground level through a hydroturbine yielding both a distilled water supply and electric power. The temperature of the condensing surface could be maintained by air cooling. Such a cycle would have the advantage of eliminating many corrosion problems as well as being able to utilize relatively low temperature water.

As we examine each of these cycles from a water management point of view it becomes apparent that there are major differences in the waterflows required to produce power at a given level. We have arbitrarily selected a 10 MW plant as being representative of a typical geothermal installation. To put this number in perspective such a plant would provide the electrical power requirements for a typical community of about 10 000 people. Ninety such plants would be required to produce the power delivered by Glen Canyon Dam.

Shown in Figure 14 are estimates of the water flows associated with a typical open cycle plant which produces its own cooling water by means of a cooling tower. As mentioned previously, such systems are used where relatively hot water is available.

Figure 15 shows approximate water flows required in a binary or closed cycle system and it may be noted that under the conditions shown the primary wat-

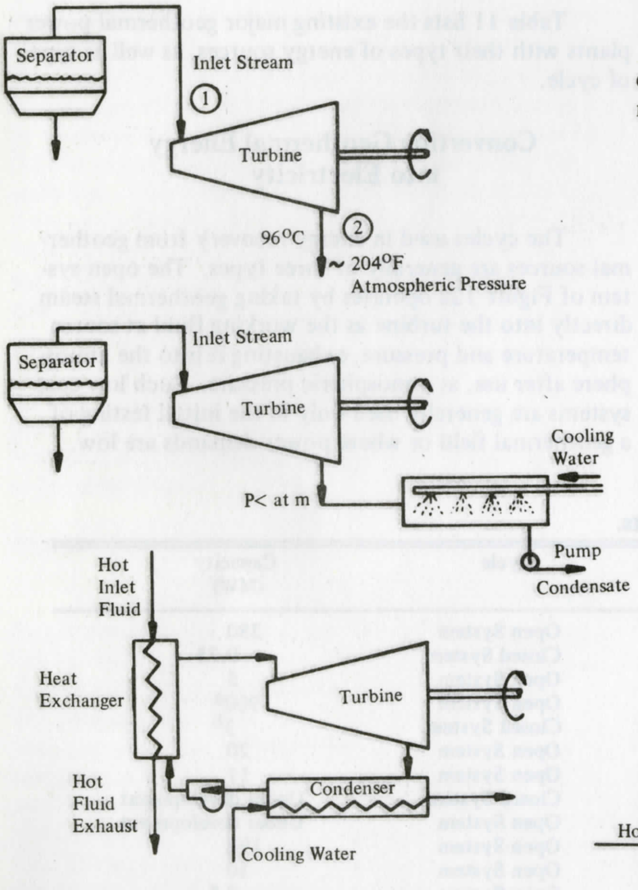


Figure 12. a. Open cycle with exhaust to atmospheric pressure. b. Open cycle with exhaust to pressure less than atmosphere. c. Binary cycle.

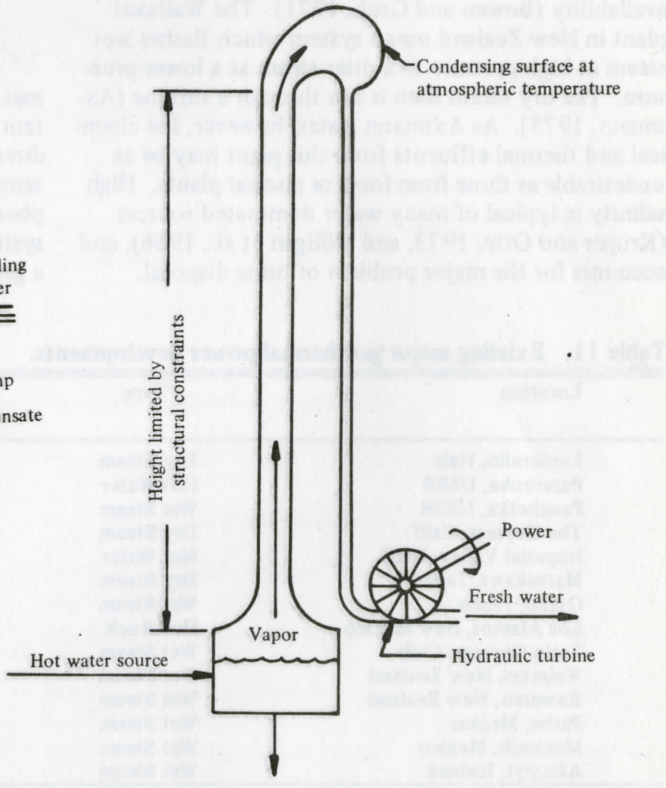


Figure 13. The geothermal hydropower tower.

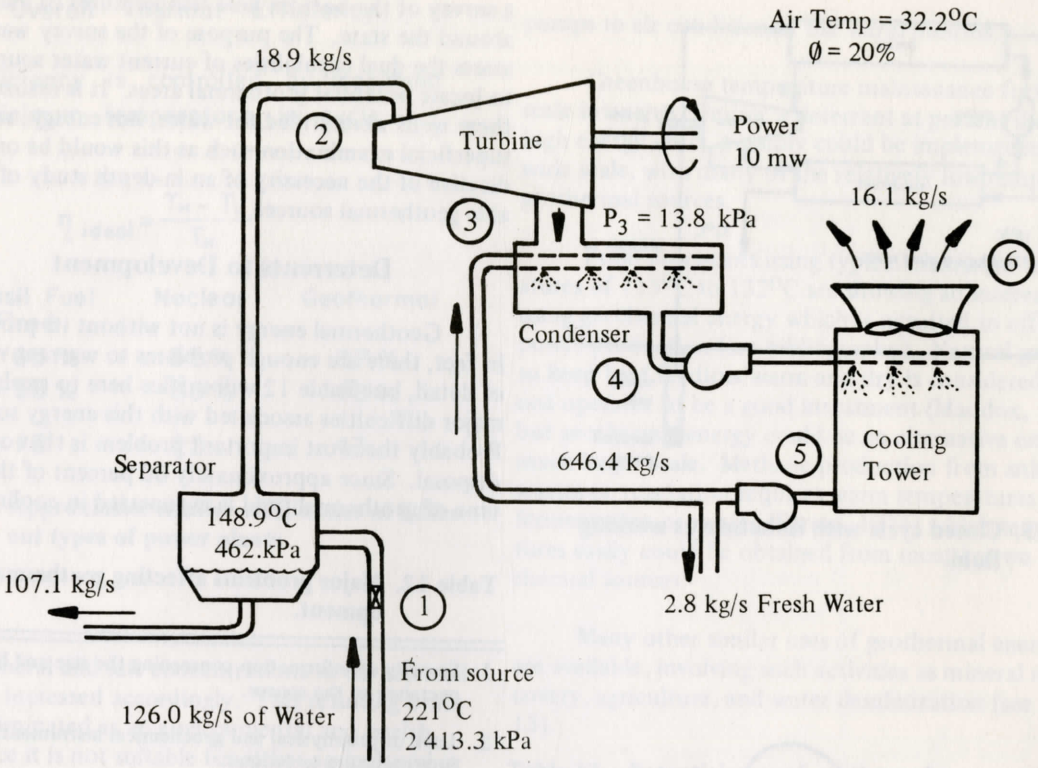


Figure 14. Open cycle power plant producing cooling water from geothermal source.

er flow rates are four times as great as those required in the open cycle in Figure 14.

The value of a water flow analysis becomes obvious as we examine such schemes as the hydropower tower described in Figure 13. As indicated in Figure 16, the flow rate of primary 148.9°C geothermal water required for a tower 152.4 m high producing 10 MW of power would be on the order 73.6 m^3/s, or more than 600 times than required for the traditional open cycle of Figure 14.

Thermal Efficiency

To put geothermal energy development in the proper perspective, a look at thermal efficiency is in order. The Carnot or ideal efficiency of a power cycle is determined by the temperatures of the heat source and heat sink utilized as shown in the following formula (Figure 17):

$$\eta = \frac{T_H - T_L}{T_H}$$

where η is the ideal efficiency; T_H is the absolute temperature of the heat source, in this case the geothermal water or steam, and T_L is the absolute temperature of the heat sink, usually the atmosphere. Thus it is clearly evident that geothermal power plants with their relatively low maximum temperatures would be expected to have relatively low thermal efficiencies. The thermal efficiency of an actual power plant is usually defined as the ratio of the desired energy produced to the energy input. In a coal fired electrical generating plant, for example, with maximum cycle temperatures of around 538°C, about 38 percent of the heating value of the coal is converted to electrical energy.

The thermal efficiency of a geothermal power plant is a little more difficult to define because the energy input is less clear. Also, thermal efficiency has little real value in comparing geothermal plants with fossil fuel powered plants. A much better comparison is the cost of the energy produced. The main point of this discussion, however, is that only a very small fraction of the total energy passing through low temperature hot water systems can be converted into electricity, necessitating the handling of huge water flows for a reasonable power output.

The map of Figure 18 superimposes fault zones on a map of the major thermal springs in Utah. The map was developed as part of this study and is based on

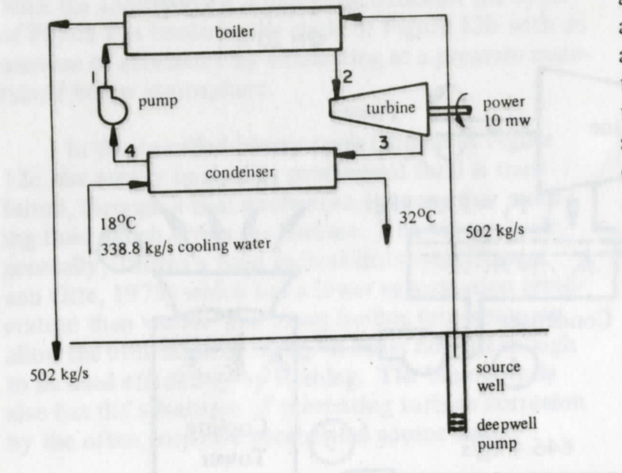


Figure 15. Closed cycle with isobutane as working fluid.

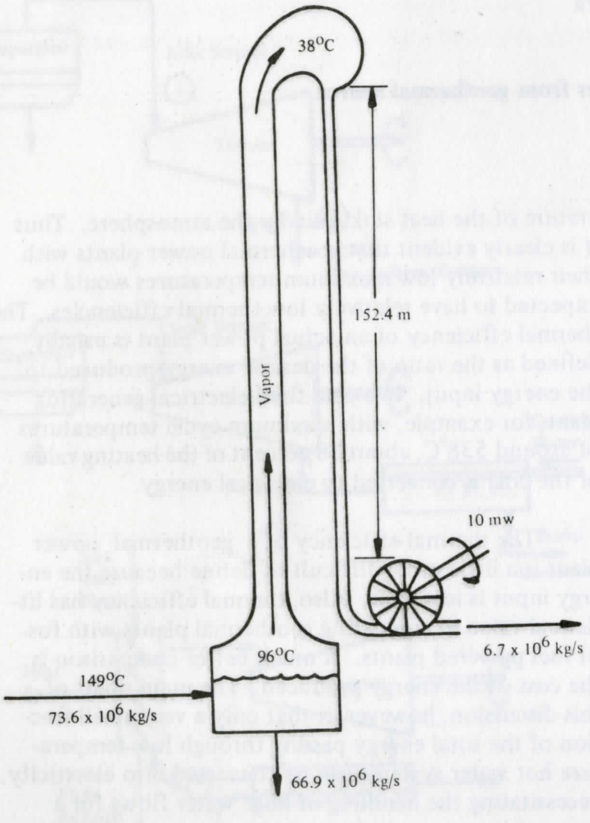


Figure 16. Water flow rates associated with geothermal hydropower for the conditions indicated.

a survey of the bottom hole temperatures of many wells around the state. The purpose of the survey was to assess the dual capabilities of current water sources and to locate potential geothermal areas. It is realized that these wells were drilled for water, not energy, and a superficial examination such as this would be only indicative of the necessity of an in-depth study of available geothermal sources.

Deterrents to Development

Geothermal energy is not without its problems. In fact, there are enough problems to warrant volumes of detail, but Table 12 will suffice here to explain the major difficulties associated with this energy source. Probably the most important problem is that of brine disposal. Since approximately 80 percent of the volume of geothermal fluid is evpaorated in cooling tow-

Table 12. Major problems affecting geothermal development.

1. Scarcity of information concerning the size and life expectancy of the source.
2. Lack of geophysical and geochemical instrumentation and interpretation technique.
3. Lack of information concerning the life expectancy and well maintenance technique.
4. Possible emissions of undesirable gases.
5. Aesthetic problems associated with vapor emissions from the cooling towers (steam plumes).
6. Disposal of liquid wastes.
7. Well drilling technology consistent with the unique characteristics of geothermal development.
8. Mufflers for noise abatement may not be sufficiently effective.
9. Land subsidence in the vicinity of the well.
10. Waste heat discharged into the environment.
11. Legal and institutional problems.
12. Economics of geothermal compared with other sources of energy.
13. Corrosion and abrasion on mechanical equipment.
14. Heat exchangers capable of utilizing low temperature differences.
15. Hot water pump technology.
16. Possible increase in earthquake hazard produced by both withdrawal and reinjection of hot water.
17. Geothermal power generating installations needs to be located at geothermal sites which might be at considerable distances from load centers, with a resulting loss of energy through the transmission process.

Overall Thermal Efficiency

Efficiency is controlled by maximum and minimum temperature in cycle —

$$\eta_{\text{ideal}} = \frac{T_H - T_L}{T_H}$$

	Fossil Fuel Fired	Nuclear	Geothermal
ideal	65 %	55%	37 %
actual	38 %	33%	18 %
cooling water	15	22	43

Figure 17. Approximate relative efficiencies of different types of power plants.

ers, the mineral and salt concentrations in the rejected solution is increased accordingly. This resulting brine must be eliminated as an environmental and health hazard since it is not suitable for either agricultural or culinary use. Each of the main methods of disposal listed below is accompanied by its own problems. Desalinization basically involves an energy consuming water distillery. Discharge into surface waters produces pollution problems with potential for significant impacts, considering the vast amounts of fluid required for power generation. Discharge to nearby evaporation ponds involves the flooding of large land areas with its accompanying environmental difficulties. The conveyance of the brines through canal or pipe to a convenient depository also is a possibility. Reinjections of the brines for the geothermal field avoids surface disposal problems. This method is used successfully at the Geysers in California. Some energy is required to reinject the solution but the water has an opportunity to be re-cycled. Some of the important advantages and disadvantages of various brine disposal methods are listed in Table 14.

Alternate Uses

Because only a small fraction of the energy in a hot water geothermal resource can be converted into electrical energy, a look at alternative uses of geothermal energy is warranted. Many energy dependent processes do not require the high temperatures required for efficient power production. The feasibile potential uses of geothermal energy are numerous. As demonstrated in about 200 residential and commercial establishments in Boise and over 400 in Klamath Falls, Oregon, (Bowen and Groh, 1971) space heating and water heating can use water at even sub-boiling temperatures. The same energy source can be utilized to run heat pumps to air condition in the warm months.

Greenhouse temperature maintenance for large scale intensive farming, a deterrant at present due to high energy costs, possibly could be implemented on a wide scale, with many of the relatively low temperature geothermal sources.

Food processors using typical maximum temperatures of 115°C to 132°C are showing an interest in using geothermal energy which is unsuited to efficient power production (see bibliography). Natural gas heat to keep beef feedlots warm and dry is considered by one operator to be a good investment (Maddox, 1975) but geothermal energy could be an alternative on a much larger scale. Methane production from animal wastes or vegetation requires warm temperatures for fermentation processes (Sarma, 1974) which temperatures easily could be obtained from most known geothermal sources.

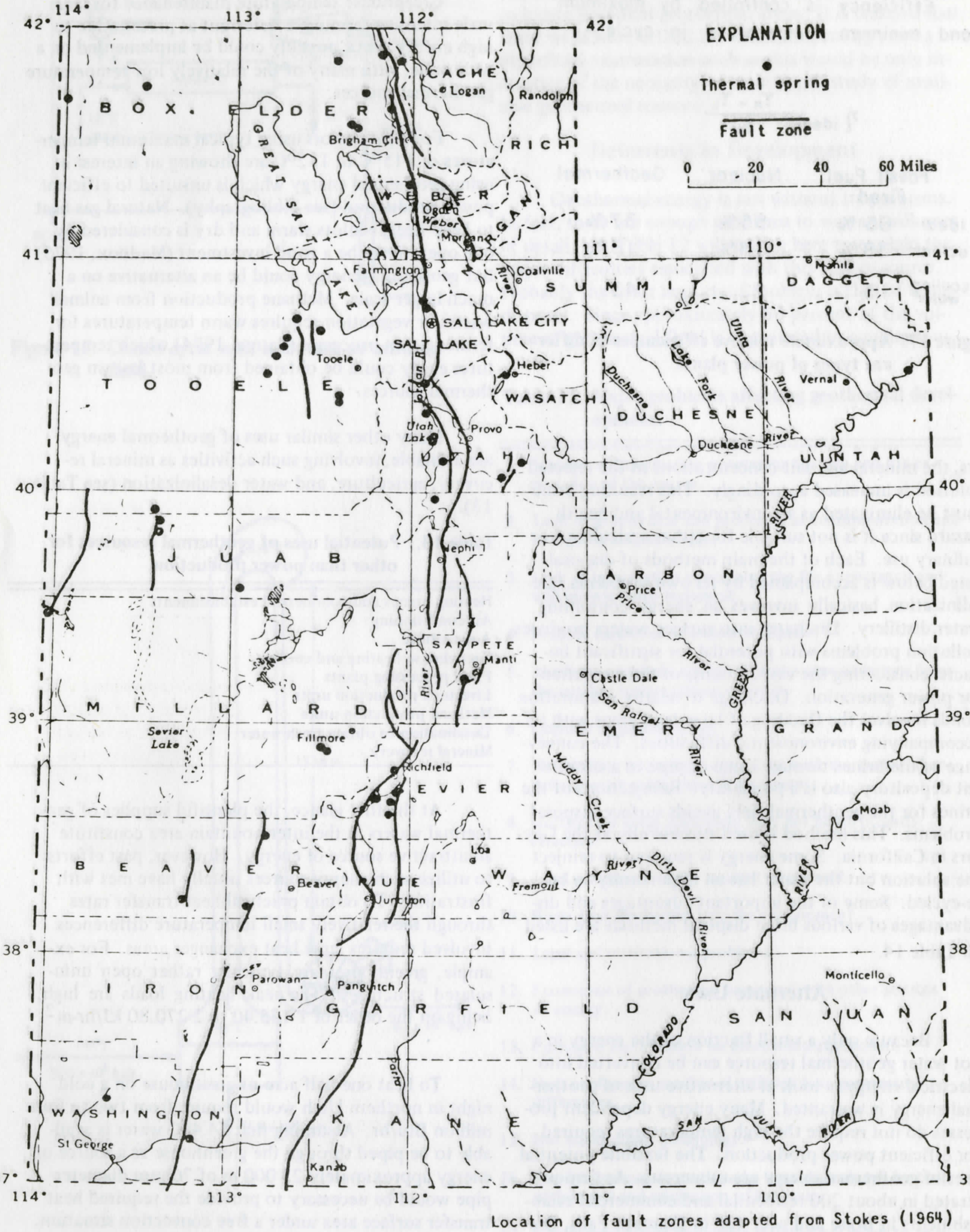
Many other similar uses of geothermal energy are available, involving such activities as mineral recovery, agriculture, and water desalinization (see Table 13).

Table 13. Potential uses of geothermal resources for other than power production.

Heating homes and commercial establishments
Air conditioning
Aquaculture
Greenhouse heating and cooling
Food processing plants
Livestock production units
Methane production units
Desalination to obtain fresh water
Mineral recovery

At the first glance, the plentiful supplies of geothermal waters in the intermountain area constitute an attractive source of energy. However, past efforts to utilize such energy sources usually have met with frustration. To obtain practical heat transfer rates through the relatively small temperature differences involved requires large heat exchanger areas. For example, greenhouses are typically rather open uninsulated structures. The peak heating loads are high, being on the order of 1 135.40 to 2 270.80 kJ/hr-m^2.

To heat one-half acre of greenhouse on a cold night in northern Utah would require from two to four million Btu/hr. Assuming that 54.4°C water is available to be piped through the greenhouse as a source of energy approximately 23 000 m of 76 mm diameter pipe would be necessary to provide the required heat transfer surface area under a free convection situation. This type of system would be prohibitively expensive and particularly so in the greenhouse industry where profit margins are usually slim. The conventional heat



Location of fault zones adapted from Stokes (1964)

Figure 18. Locations of major thermal springs and fault zones in Utah.

Table 14. Alternate methods of brine deposits.

Technique	Advantages	Disadvantages
Reinjection	reduces the likelihood of land subsidence	salt precipitation resulting from lowered brine temperature
	regenerates the water source	might tend to reduce the porosity of the reservoir material
	reduces pollution hazards to surface and groundwater supplies	pollution hazards to groundwater aquifers overlying the thermal reservoir
		capital and operating and maintenance costs associated with the reinjection well
Evaporation Ponds (complete containment)	reduces pollution hazard to surface and groundwater supplies	requires large land areas
	recovery of minerals having economic value	may require lining to prevent seepage to groundwater
		aesthetics
		ground fog
Discharge to Surface Water	low cost of disposal	salinity pollution
		thermal pollution
Export	eliminates local problem	high cost of transport
	water may be used as a vehicle for solids (such as coal)	transfers the problem to another area
Desalinate	use power to desalinate brine	lower volume more concentrated brine
	supplemental fresh water supply	cost of power used for desalination
	recovery of minerals having economic value	

exchanger with bundles of many small diameter finned tubes also would be outsized in this application. The difficulties are often further compounded by exchanger fouling when highly mineralized geothermal waters are used (Utah Geological and Mineral Survey, 1970). After a few weeks or months of operation under such conditions the exchanger tubes and pipes are choked with precipitated solids. Another problem to be considered in heating greenhouses is the tendency for wide variation between daytime and nighttime temperatures because of the low thermal inertia inherent in this type of structure.

The challenge then is to devise a high capacity heating system which can utilize relatively low temperature water as an energy source, tolerate corrosion and precipitation problems, and provide high thermal inertia. The typical greenhouse configuration with its long rows of growing tables lends itself to an innovative approach to heating. The essence of the concept is to use the entire internal structure of the greenhouse as the heat exchanger. The proposed system is shown schematically in Figures 19 and 20.

The growing tables could be constructed of light gage corrugated galvanized steel in such a fashion that large quantities of water may be enclosed directly underneath the bedding soil. The metal is provided with a plastic liner and is suitably reinforced. The warm source water is conveyed through these large tanks in flexible tubing. Significant features and advantages of the proposed system are:

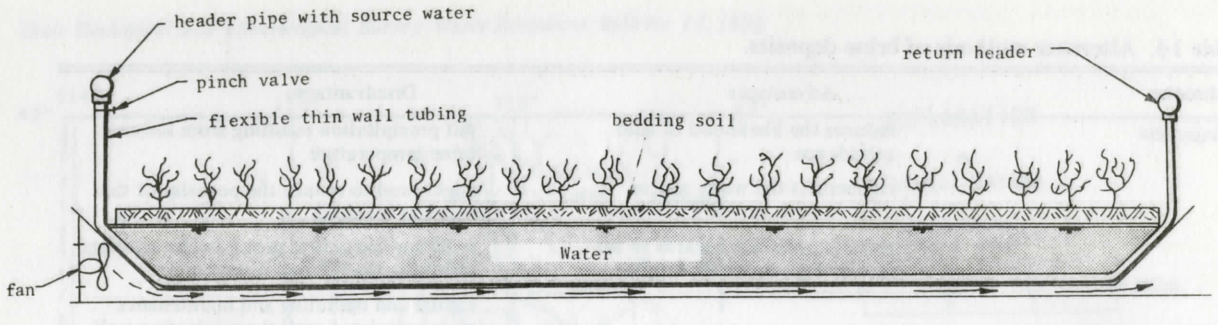
1. The surface area exposed to the warm water source area is minimized since the convective heat transfer coefficient for surface to water configuration is approximately 50 times that of the surface to air configuration encountered in conventional systems.

2. An extremely large effective heat exchanger area exposed to the air, approximately equal to twice the floor space of the greenhouse, is obtained at reasonable cost.

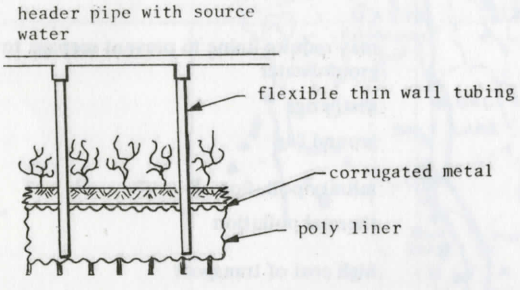
3. The greenhouse temperature gradients tend to be inverted in that the soil and the air nearest the plants are warmest rather than the air near the top of the green house as in conventional forced air heating system.

4. The ratio of the soil temperature to air temperature can be rather precisely controlled by simply adjusting the level of water in each table.

5. The system tends to stablize temperature



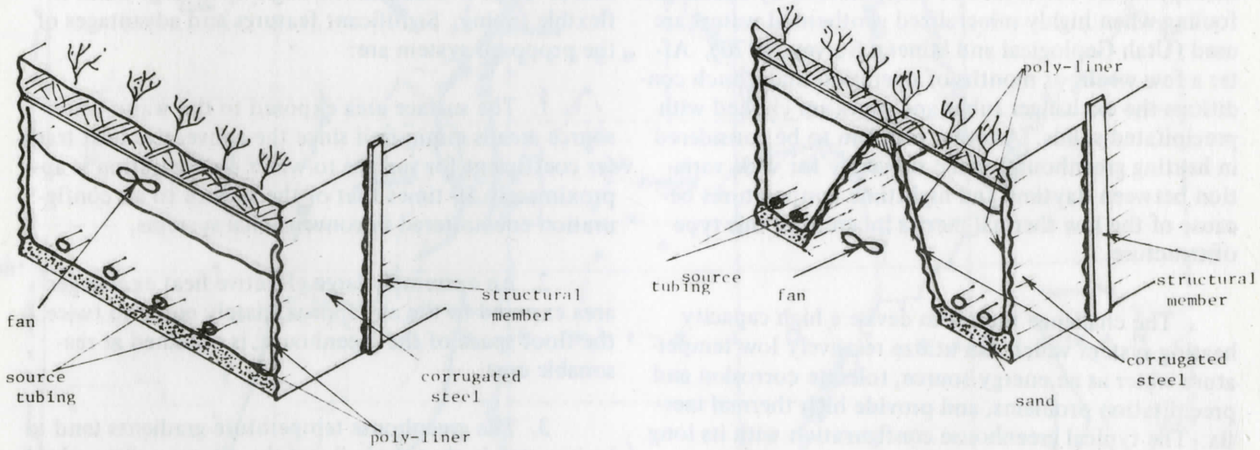
a) Longitudinal cross-section view



b) Transverse cross-section

Longitudinal and transverse cross-sections of heat exchanger tables. The tables are constructed of light gage corrugated metal lined with a polythylene film and suitably reinforced. Each table thus stores a large quantity of water. The warm resource water is conveyed through the stored water in the thin wall flexible tubing which can be easily and inexpensively replaced if fouled with mineral precipitates. The heat transfer is limited by the free convective film coefficient between table walls and air thus necessitating the use of fans to force air past the bottom surface.

Figure 19. Longitudinal and transverse cross-sections of greenhouse exchanger table design.



This approach reduces cost because of less steel required but the effective heat transfer area is also reduced slightly.

This configuration increases heat transfer area. There are of course, several possible variations of this design.

Figure 20. Schematic diagrams of two alternative designs of greenhouse heat exchanger units.

fluctuations by providing an extremely large thermal inertia. As the temperature in the greenhouse drops, the rate of heat addition increases, and as the temperature in the greenhouse increases the rate of heat addition decreases even without the use of automatic controls. If it became necessary to shut down the source water in cold weather, the energy stored in the system would keep the greenhouse temperature above freezing for more than 24 hours, which is ample time to make repairs in most conceivable circumstances.

6. The system could provide summer cooling and humidity control as well as winter heating with no additional equipment required. (The warm source water would be eliminated and the tank water used as evaporation bed.)

7. The system can easily be dismantled for repair or cleaning. Major components could easily be replaced in a few minutes time using non-skilled labor.

8. The system can be constructed almost entirely from standard "off the shelf" components, thus reducing costs and facilitating maintenance and repair.

9. The system can tolerate even highly corrosive brines as all components exposed to the source waters are constructed of inert materials. Expensive valves are almost entirely eliminated.

Preliminary heat transfer calculations indicate that the heat exchanger concept in the proposed design is technically feasible, but it must be tested.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

Alternative management strategies for hydropower and geothermal development are myriad. This study does not attempt to evaluate or even summarize the many schemes which are possible. Traditional economic analysis procedures optimize on the basis of capital and labor. The approach taken in this study is based on the notion of optimum deployment of finite resources. A legitimate question which this study has attempted to address is: Does the construction of large water management facilities, such as hydropower dams, which involve huge amounts of energy, concrete, and steel, constitute an efficient use of basic resources?

Summary

This study resulted in the following accomplishments:

1. A methodology for conducting energy accounting studies is proposed. Problems and inconsistencies of energy accounting are pointed out.

2. The direct energy resource inputs to the construction of three major hydropower dams were determined. Results indicate that developing suitable sites for hydropower is a relatively efficient use of basic energy resources. For example, Glen Canyon Dam need operate only about 10 000 hours to return to society the energy invested in its construction. This figure compares to approximately 90 000 hours required for a conventional horizontal axis windmill operating in a 16.1 km/hr wind. On the other hand, it is observed that the water lost through evaporation from hydropower reservoirs in the west is large when expressed in terms of water lost per unit of power produced. This loss is significantly larger than water requirements for power production by means of coal fired power plants, excluding evaporation from water storage reservoirs.

3. The direct energy resource inputs to the construction of geothermal power plant at Units 5 and 6 of the Geysers installation in California were determined. The results indicate that in terms of efficiency of resource deployment, the type of system in use at the Geysers is comparable to the hydropower units studied. It also was observed that the dry steam field at the Geysers is rather unique. Hot water geothermal resources present much more formidable problems in utilization.

4. Several water management problems associated with geothermal development in hot and warm water fields were defined. An alternative scheme called the geothermal hydropower tower is presented and analyzed. Perhaps the most practical contribution of the study is the concept of a heat exchanger design which can effectively utilize warm highly mineralized waters.

5. An alternative concept for hydropower development is presented in which hydro-pumped storage systems possibly could be combined with once-through cooling of thermal electrical power plants, resulting in significant water savings.

Recommendations

The following recommendations are made as a result of this study.

1. An in-depth analysis of energy accounting should be pursued in an effort to develop a consistent and uniform methodology. For example, questions require investigation relating to the form of the input energy associated with the manufacture or processing of many construction items and materials. Energy impact statements or life cycle costing for large scale publicly financed projects, such as those associated with water development, eventually might be legislatively mandated. The water research community would be well advised to anticipate such possible legislation and be prepared to respond.

2. The possibility of combining once-through cooling with pumped storage should be carefully scrutinized. The potential for water savings is too large to ignore.

3. The heat exchanger system recommended by this study and which is capable of effectively utilizing warm and highly mineralized waters, should be constructed and tested on a demonstration basis.

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