$12.00

JUN.28.1976

003350

NET ENERGY ANALYSIS:
AN ENERGY BALANCE STUDY
OF FOSSIL FUEL RESOURCES

April, 1976

by

THE COLORADO ENERGY RESEARCH INSTITUTE
P.O. Box 366
Golden, Colorado 80401

Thomas J. Vogenthaler, Director

Project Investigators

Albert G. Melcher, Colorado Energy Research Institute, Project Coordinator
Dr. Kenneth Maddox, Colorado School of Mines Research Institute
Dr. Charles Prien, Denver Research Institute
Dr. Thomas Nevens, Denver Research Institute
Dr. Victor Yesavage, Colorado School of Mines
Dr. Philip Dickson, Colorado School of Mines
Prof. Jackson Fuller, University of Colorado
Dr. William Loehr, Denver University
Dr. Robert Baldwin, Colorado School of Mines
Dr. Richard Bain, Colorado School of Mines

Advisory Members of Project Team

Mr. Richard Doran, Denver Research Institute
Dr. John Golden, Colorado School of Mines
Dr. Jerome Morse, Colorado Energy Research Institute

Editor

Mr. Bruce Polich, Consultant

This report was prepared by the COLORADO ENERGY RESEARCH INSTITUTE (CERI) to advance the development and use of net energy analysis of fossil fuels. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the Project Investigators and CERI; they do not necessarily reflect the views or policies of the Project Sponsors listed below, the State of Colorado, or the employers of the Project Investigators. The support and encouragement of the Project Sponsors and the State of Colorado may not be interpreted as either approval or disapproval of the report.

The Project Sponsors are:

U. S. Department of the Interior
(Office of Research and Development, Contract No. 14-01-0001-2156)

Sun Oil Company

Getty Oil Company

Public Service Company of Colorado

Marathon Oil Company

Standard Oil Company (Indiana)

Colorado-Ute Electric Association

Gulf Energy and Minerals Company

Cleveland-Cliffs Iron Company

Colorado Interstate Corporation

Rocky Mountain Energy Company

TABLE OF CONTENTS

ABSTRACT

"Net Energy Analysis: An Energy Balance Study of Fossil Fuel Resources"
Colorado Energy Research Institute
Albert G. Melcher, Deputy Director for Operations, Project Coordinator

Energy analysis is a broad field of study dealing with the development and use of all aspects of energy. Net energy analysis, a more limited field of study, deals with the analysis of the energy made available to society by energy production processes after the deduction of energy lost to society as a result of the processes.

This study examines industrial energy production in fossil fuels, emphasizing those of the Western United States. It accounts for the complete direct and indirect energies which must be utilized to produce energy from fossil fuels. These include the direct and indirect energies which "drive" or sub-sidize" the production. It includes those energies sequestered in materials needed to build and operate the industrial production and transportation facilities which either directly or indirectly are necessary for energy production. The study includes all steps in bringing fossil fuels from reserves in the ground to the point of end use (exploration, extraction, conversion, transportation, etc.) A given fossil fuel can be directed through a number of different paths to end users, arriving there in a variety of forms.

Excluded from the study are ecological energy, human metabolic and life style energy, research and several other flows.

Several energy accounting methods are used to deal with different social or policy issues. Data are given for about 20 different process pathways for obtaining gas, liquid, solid and electrical energy from coal, gas, petroleum and oil shale.

Data, methodology, "boundary" questions, philosophy, and possible applications of net energy analysis are covered in this report.

I. INTRODUCTION

It is increasingly important to America that decisions regarding the development and utilization of fossil fuels be based on more complete information than available heretofore. The complex relationships of reserves, production rates, economics, regulation, foreign politics, environmental quality and the demand for energy have not received proper attention until recent years. Now, however, national energy deficiencies - present and potential - are of great significance to the well-being of the nation. Better information concerning energy production and utilization must be made available to government, industry, and public organizations to insure intelligent and accurate policy decisions.

Efficient use of energy resources is becoming more and more mandatory. There is little doubt that a great quantity of energy has been wasted in the past. Some fossil fuel resources are dwindling rapidly, thus more efficient use of those resources will serve to stretch the time before effective exhaustion occurs. Dependence on foreign energy could be reduced if the output of net usable energy from a given resource quantity could be increased. Environmental impact reductions could result in some cases if this output ratio were improved.

In the last several years, there has developed a growing concern about the question of how much energy is required to produce and deliver useable energy. There is evidence, or at a least strong supposition, that the energy required to produce and deliver a given amount of useable energy is increasing. Now, oil wells must be deeper, costly off-shore drilling rigs are needed, cold-weather engineering feats such as the Alaska pipeline are required, and synthetic fuels may be needed, which may utilize large amounts of energy consumed in the chemical, mechanical and thermal stages of the production processes.[1]

These concerns have arisen from various sources, such as the resource managers, engineers, scientists and environmentalists, all of whom have become aware of the exponential rate of increase in the depletion of finite resources. Another group expressing concern involves those engaged in the science of ecology.[2,3,4] Some ecologists have focused attention on the flow of energy through ecosystems, which include human beings and industrial society.

These sources have raised the issue of increased accuracy and a possible expansion of decision-making parameters to include energy analysis. Normal economic decisions do not adequately identify hidden energy costs or resource depletion factors which are not measured in a system of monetary transactions.

As a result of these concerns, initial efforts to examine the energy requirements of energy production have occurred.[5,6] Also, several pieces of legislation have appeared which include references to the efficiency or net energy in energy production systems.[7,8,9]

Initial discussions of net energy have been controversial, or at least, misunderstood and misquoted.[10,11] Part of the problem is due to the exploratory and experimental nature of studies in this new field of "energy analysis." There are no well-defined ground rules or quidelines. Another part of the problem seems to lie in an apparent misunderstanding of net energy concepts by lay people.

Realizing the prospect of intensive development of fossil fuels in the West, and having observed the problems associated with public understanding of initial and exploratory "net energy" studies, a group of engineers and scientists were assembled under the auspices of the Colorado Energy Research Institute (CERI) to conduct this study. It was decided to initiate research on net energy, concentrating on the energy inputs and outputs in Western fossil fuel production. (The list of the research team members is given on Page .) The result is this study: "Net Energy Analysis: An Energy Balance Study of Fossil Fuel Resources."

OBJECTIVES

The proposed objectives of the project were:

A. to provide reliable, objective, credible information to government and industry on the net energy inputs and outputs of western fossil fuels energy systems;

B. to provide a workable methodology, which can be used by CERI or others in subsequent expanded net energy studies, and which is oriented towards the potential use of net energy information in decisions about resource production;

C. to provide the best possible documentation of data related to net energy;

D. to discuss and describe the usefulness and limitation of net energy studies and their potential values in decision-making; to discuss philosophy and issues pertaining to net energy studies.

The CERI study is oriented towards an examination of net energy in the frame of reference of the decision-making process. For this reason, neither the study nor the report are intended for the pure scientist, the physicist, or the technologican.

This study was originally called an "energy balance study." This indicates the intent of analyzing the balances of energy inputs and outputs in energy processes. The term "net energy analysis" has subsequently become accepted and will be discussed later.

Funding was obtained from a variety of private industries, and from a contract with the Office of Research and Development, Department of the Interior. The study was commenced in April, 1975.

References and Footnotes: - Section I

Number

1 Clark, Wilson; "It Takes Energy to Get Energy; the Law of Diminishing Returns is in Effect", Smithsonian, Vol. 5, No. 9, December 1974, page 84.

2 Kendeigh, Charles S.; "Ecology, With Special Reference to Animals and Man", Prentice-Hall, Inc., New Jersey, 1974.

3 Odum, Eugene P.; "Fundamentals of Ecology", Third Edition, 1971, W. B. Saunders Company, Philadelphia, 1971.

4 Gates, David M.; "The Flow of Energy in the Biosphere", Energy and Power, Scientific American, W. H. Freeman and Company, San Francisco, 1971.

5 Office of Energy Research and Planning, Office of the Governor, State of Oregon; "Transition", 1975. This was the first study known to the CERI investigators which constituted a complete analysis with calculations.

6 International Federation of Institutes for Advanced Study; (IFIAS) "Energy Analysis", Workshop Report #6, Stockholm, 1974. This Workshop identified the general approaches and outlined a framework for energy analysis, but did not actually accomplish any net energy analyses.

7 California; "Energy Resources Conservation and Development Act", State of California, 1974.

8 Congress of the United States; "Federal Non-Nuclear Energy Research and Development Act of 1974", Public Law 93-577. Sec. 5(a) requires that the comprehensive ERDA program in research, development and demonstration designed and executed according to several principles, one of which is: "The potential for production of net energy by the proposed technology at the stage of commercial application shall be analyzed and considered in evaluating proposals".

9 Congress of the United States; "Energy Reorganization Act of 1974", Public Law 93-438. This Act, which established ERDA, speaks of "efficient extraction, conversion, transmission and utilization" of energy, and "reducing total energy consumption" and "maximum possible improvement in the efficiency of energy use". These considerations could include energy use in producing energy.

10 Wilson, George; "Study Disputes Usefulness of Oil Shale", Washington Post, Washington,DC, October 30, 1974. This article states that a subcontractor to the Federal Energy Administration on Project Independence studies referred to an apparently erroneous "Business Week" article (see ref. 11 below) about net yields from oil shale.

11 Business Week; "The New Math for Figuring Energy Costs", June 8, 1974. This article misquoted one energy company, who subsequently refuted the article, and created an impression that oil shale recovery is "an energy standoff".

II. FINDINGS AND RESULTS

A. General Summary

Energy analysis is a broad field of study dealing with the development and use of all aspects of energy in human society and its environment. Net energy analysis, a more limited field of study, deals with the analysis of the energy made available to society by energy production processes after the deduction of energy lost to society as a result of the processes.

This project by the Colorado Energy Research Institute studies industrial energy production of fossil fuels, emphasizing those of the Western United States. This study examines fossil fuels from resources in the ground through production processes which deliver usable energy ready for consumption. It accounts for the complete direct and indirect energies which must be utilized to produce energy from fossil fuels, including the energies which "drive" or "subsidize" the production. It includes those energies used in the production of materials needed to build and operate the industrial production and transportation facilities which either directly produce energy or which indirectly provide energy or materials to the energy production processes.

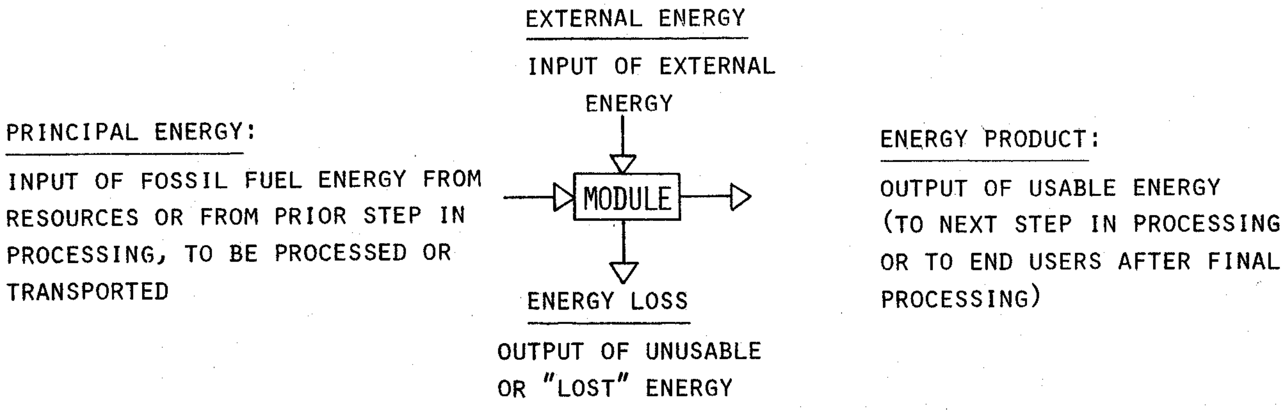
Each step in processing or transporting energy has energy inputs and outputs, as shown on Figure 1(a).

The inputs are:	PRINCIPAL ENERGY:	fossil fuel to be processed or transported.
	EXTERNAL ENERGY:	energy which is required from outside to operate the process and to make the materials needed to build and operate the processing system.
The outputs are:	ENERGY PRODUCT:	processed or transported energy delivered from the process.
	ENERGY LOSS:	energy unavailable for further use as a result of the process; this can include physical losses, unrecovered resources in extraction, internally consumed energy, and external energy.

The external energy represents direct energies and materials, as well as all the indirect energies and materials needed throughout the entire industrial system to eventually build and operate an energy production or transportation process. This is shown conceptually in Figure 1(b).

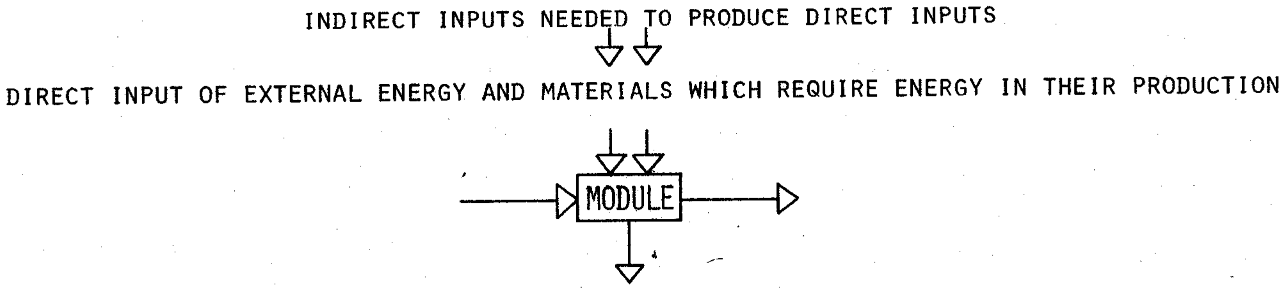
A number of steps are needed to deliver energy from the ground to the end user. Hence, a series of steps are linked so that the "energy product" output of one becomes the "principal energy" input of the next, as in Figure 1(c).

The flows of energy at a single step or "module" are shown in greater detail in Figure 2. All steps in bringing fossil fuels from resources in the ground to the point of end use including exploration, extraction, conversion, transportation, etc., are shown in



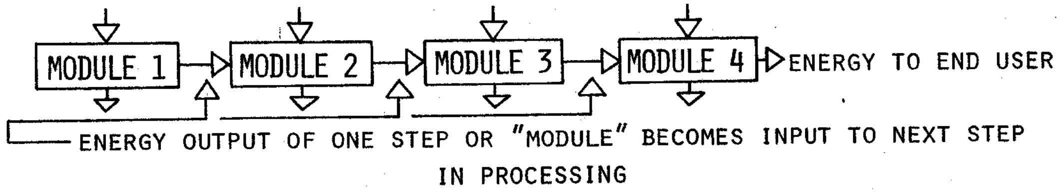
A "MODULE" IN PRODUCING FOSSIL FUEL ENERGY

FIGURE 1(A)



MODULE SHOWING CONCEPT OF DIRECT AND INDIRECT EXTERNAL ENERGY

FIGURE 1(B)



MODULE STRING OR "TRAJECTORY"

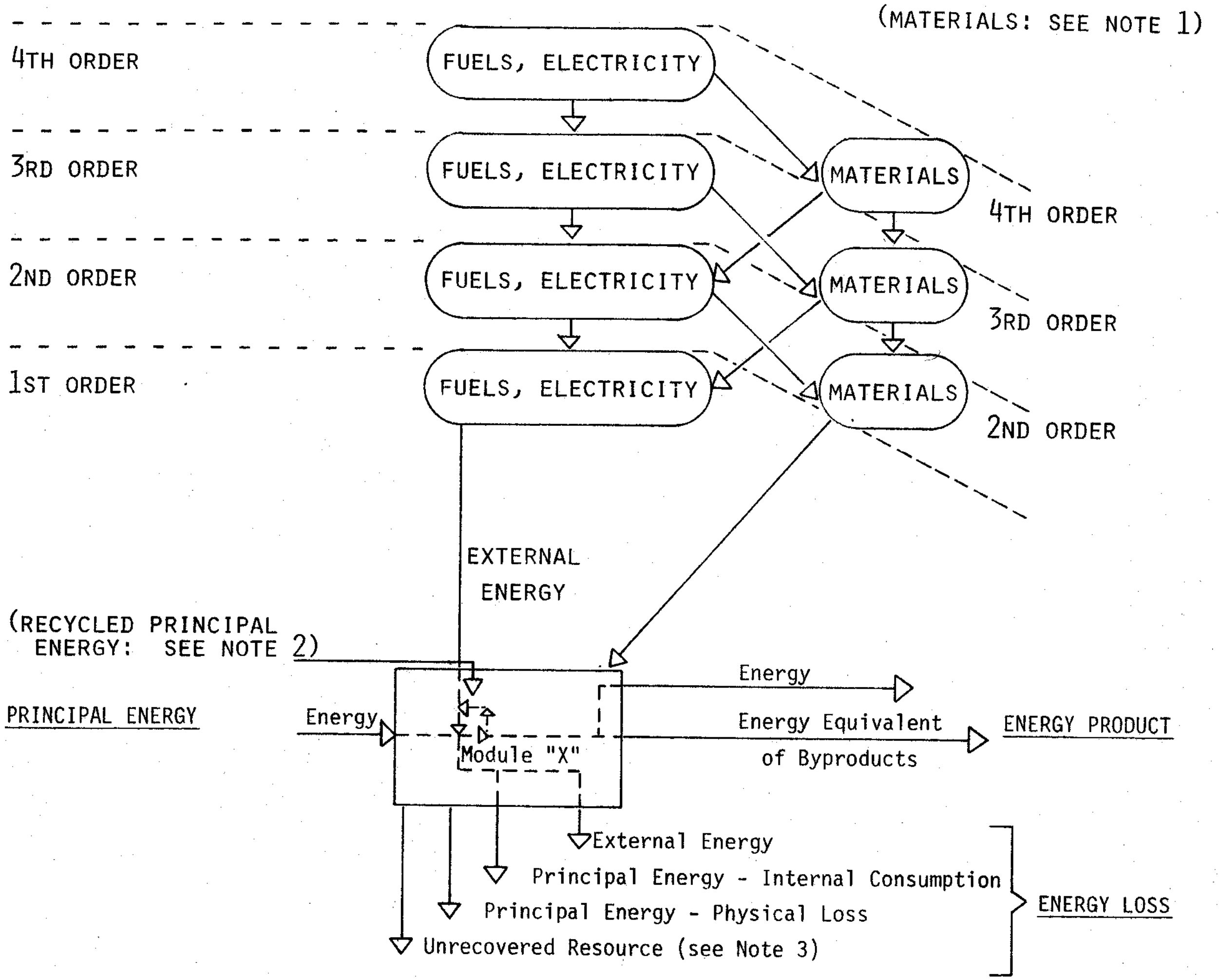
FIGURE 1(C)

ENERGY PRODUCTION "MODULES": CONCEPT

FIGURE 1

ENERGY FLOWS

GENERALIZED MODULE "X"



(1) MATERIALS INCLUDE RAW MATERIALS, CONTAINERS, MACHINERY, CONSUMABLE MANUFACTURED ITEMS (CATALYSTS, LUBRICANTS, CHEMICALS, PROCESS ADDITIVES, ETC.), TOOLS, PIPELINES, WIRING, CONSTRUCTION MATERIALS, AND ROAD MATERIALS (ASPHALT, CEMENT, TAR, STEEL, ETC.).

(2) PRINCIPAL ENERGY CAN BE USED TO OPERATE A PROCESS IN SOME CASES, THEREBY REPLACING EXTERNAL ENERGY.

(3) UNRECOVERED RESOURCES ARE IN INITIAL FOSSIL FUEL EXTRACTION ONLY, AND ARE THE RESOURCES LEFT IN THE GROUND, OR DAMAGED, LOST OR OTHERWISE DEGRADED, GIVEN CURRENT TECHNOLOGY AND ECONOMICS.

ENERGY FLOWS: GENERALIZED MODULE "X"

FIGURE 2

Figure 3. A given fossil fuel can be directed through a number of different paths to end users, arriving there in a variety of forms.

The reader must understand that no fossil fuel process produces more usable energy as an output than the amount of energy which is input to be processed. There is always some loss of usable energy in converting, processing or moving energy. In other words, it always requires more energy input than is obtained as yield. Every process degrades energy; this is the Second Law of Thermodynamics.

Energy flows through many paths in ecological and human industrial systems. Many of these paths affect each other, and it may be feasible and desirable to examine them. However, we decided to select, for this study, a smaller boundary, not including all possible energy flows. The reason is that this study is intended to be workable for potential near-term decisions; analysis of macro-systems is very cumbersome and poses many problems in theory and practice.

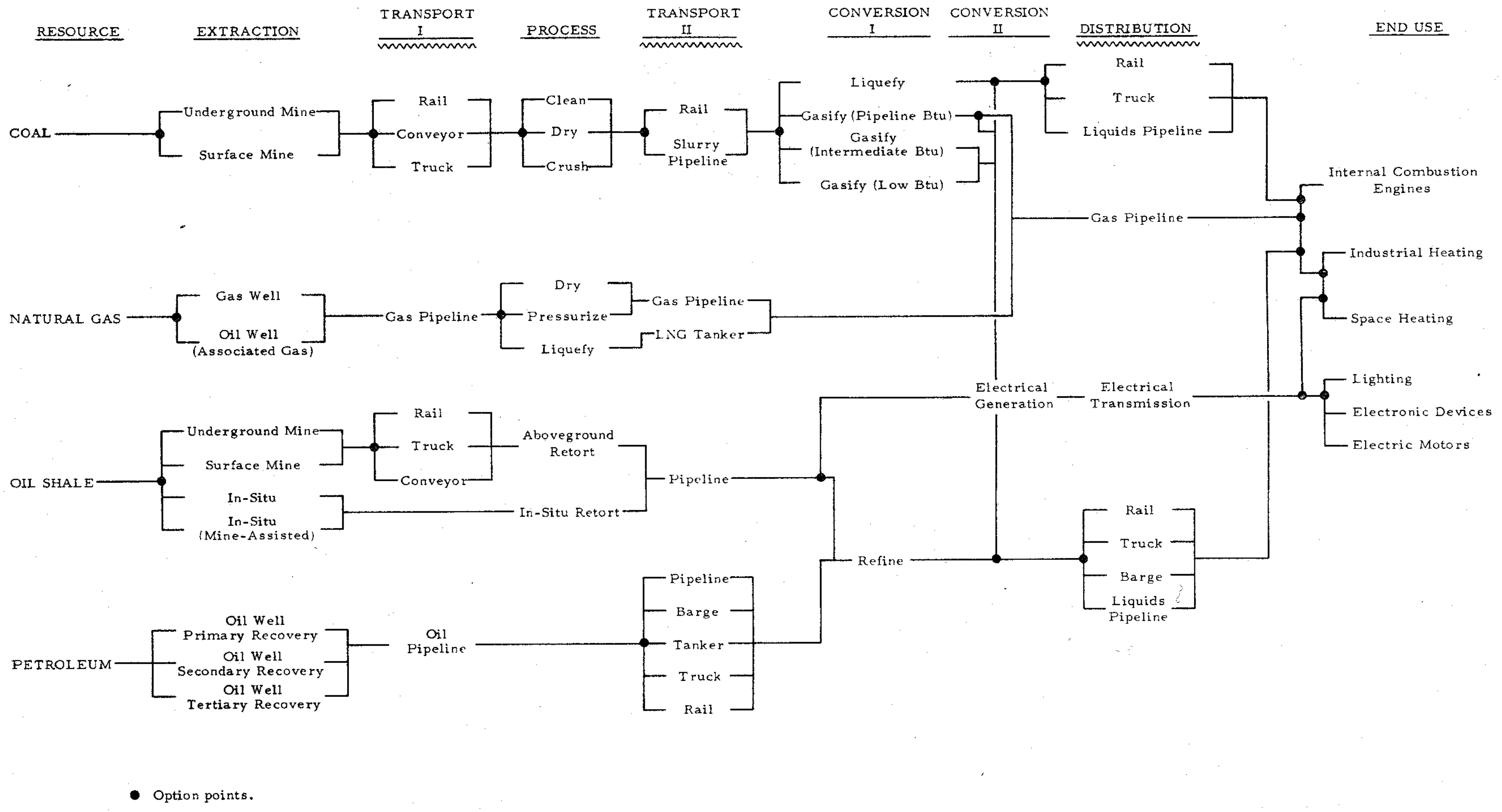
ENVIRONMENTAL ENERGY FLOWS

Environmental relationships to industrial energy production and consumption have a linkage through energy flows, among other links. Usually, energy flows in ecosystems affected by fossil fuel production systems are very small, quantitatively, compared to the fossil fuel itself (as in the disturbance of agricultural lands through surface mining prior to rehabilitation). Some people have advocated that energy should be the primary "numeraire" or unit of valuation in all transactions, because it is more common to all components of society and the biosphere than is money or some other unit of valuation. There are many arguments against this philosophy of the "energy theory of value." However, energy analysis involving ecosystems and industrial energy flows may add valuable information to that which is needed to make responsible decisions about the environment. This is true in site-specific studies or planning, and in finding how renewable energy can replace non-renewable energy.

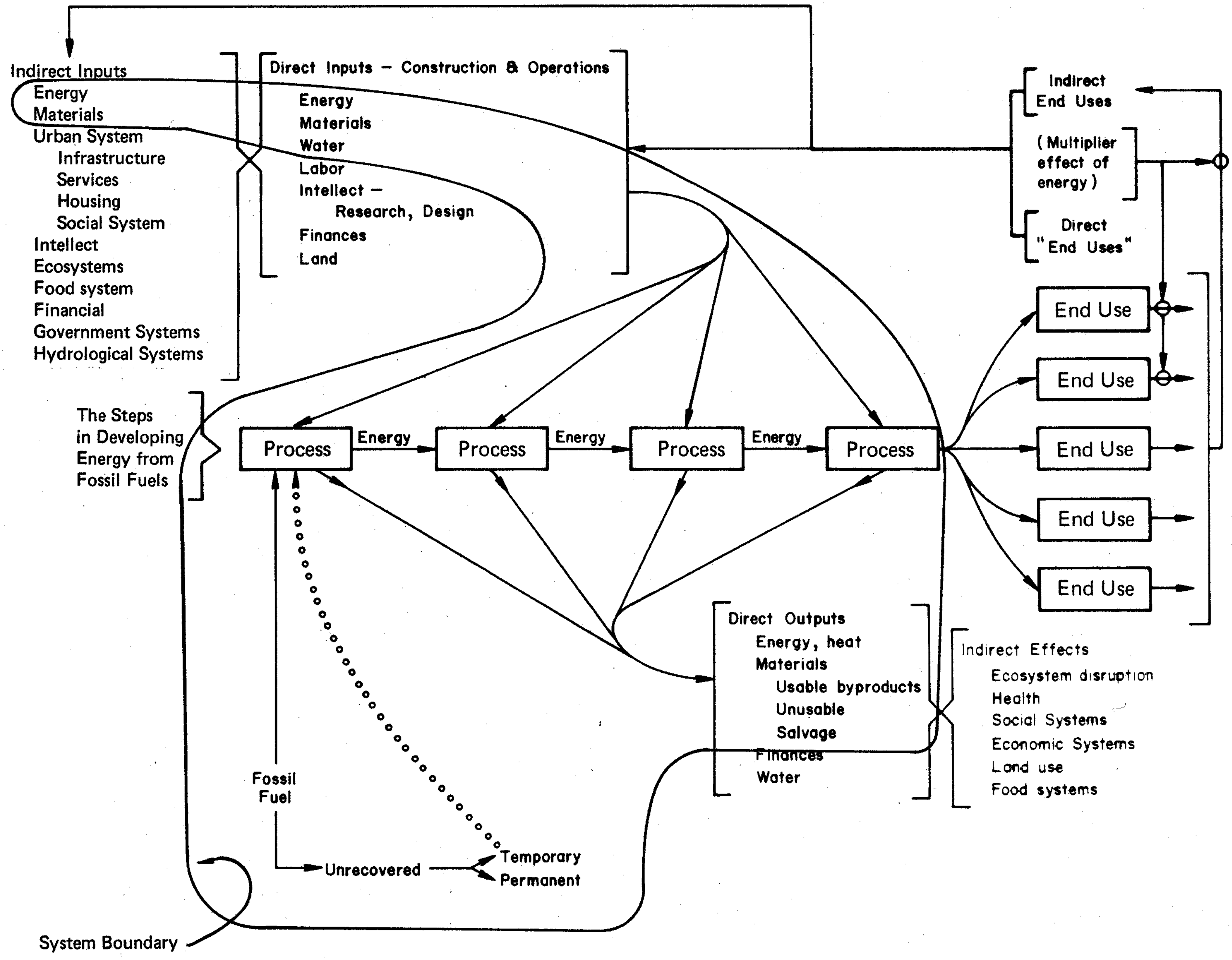
BOUNDARIES

The overall boundaries or scope of this study are outlined in Figure 4. It shows a number of processes linked into a "trajectory" of steps, as in Figure 1(c), to deliver energy to a variety of end uses. The boundary of the system of this study is shown. Ecological energy, human life-style and metabolic energy, research energy and several other types of energy are excluded. The analysis of the time periods of energy flows and of theoretical efficiencies of energy production are not included in the objectives of this particular project.

The issues of the finiteness of fossil fuel resources and the rate of depletion are of concern to society. Hence, we have included an initial step in all trajectories which relates to these issues. It describes the amount of "gross fossil fuel resources" in the ground which is affected by recovery with present technology and economics. Future generations may be forced to recover some of the presently-unrecovered resource at a high cost and energy investment. For today's society, the "capital stock" of fossil fuels is effectively degraded by the use of part of it; only a portion of the gross energy is deliverable as net energy.



TRAJECTORIES FOR FOSSIL FUEL PRODUCTION



STUDY BOUNDARY

FIGURE 4

This study assumes current technologies which might be on line in the early 1980's. The data herein are not site-specific, but are general and for typical processes. They are derived for the Rocky Mountain region, although the coal gasification data were derived for eastern coal and could apply there.

TRAJECTORY DATA

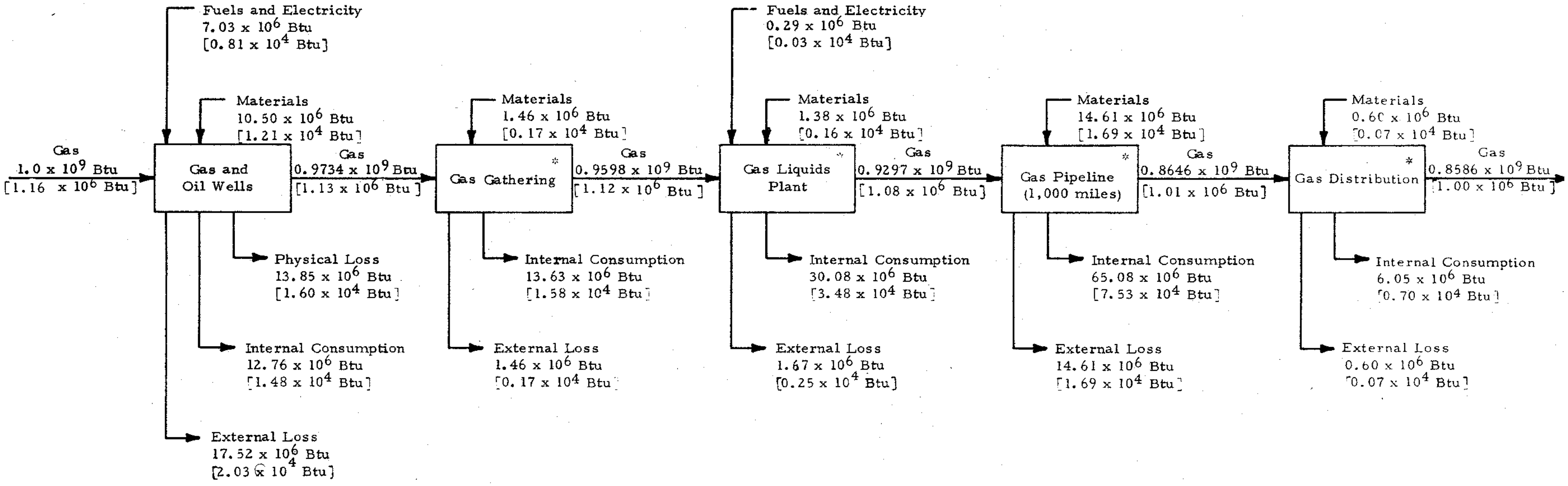
The selected trajectories represent typical fossil-fuel derived, energy-producing systems of the western United States (and particularly of the Rocky Mountain region). Trajectories in Figures 5(a-k) display the choices made for each module. On these figures, the upper numbers at each point are the data referred to 1.0×10^9 Btu as the PRINCIPAL ENERGY of the fossil fuel reserve; the final ENERGY PRODUCT is some fraction of this. The lower figures in brackets are stated relative to a final ENERGY PRODUCT output of 1.0×10^6 Btu, so that a progressively larger PRINCIPAL ENERGY is displayed in moving from right to left across the diagram. The final output is identified by energy type (gas, gasoline, coal, electricity) as a general indicator of the quality of the energy. The figure $1\text{x}10^9$ Btu's denotes one billion British thermal Units (Btu's); $1\text{x}10^6$ denotes 1 million Btu's. "Quality" is a term referring to thermodynamic properties of different forms of energy and to social value factors such as location, transportability, storability, utility, etc. Energy qualities are as important as energy quantities. The qualities create the social preferences which are a cause of variations between dollar costs and net energy yields of various types of energy with different qualities. It should be noted that the quality changes as energy is processed, and that external energy inputs are comprised of different qualities of energy. Hence, a trajectory represents quantitative measurements (British termal units, for instance), but is qualitatively a mix of different types of energies.

For some of Figures 5(a-k), two trajectories are actually shown: from the left, the top line is surface mining, and the bottom line is underground mining. Trajectories for coal as a solid fuel, surface or underground-mined, can be followed on Figure 5(b) by using only the two left-hand modules. Thus, these figures represent 20 different trajectories. Transportation distances are assumed and are as shown in the appropriate modules.

Figures 7(a) through 7(t) present the data in a different graphic form. These figures are drawn to represent a whole trajectory from beginning to end. Figure 6 is a "key" for reading them. The numbers represent the sums of the external inputs and of the losses of all of the modules of a complete trajectory. The figures also represent the policy issue of the gross energy resource of fossil fuels in the ground. Part of the fossil fuel is unrecoverable as a result of the extraction, given today's economics and technology. Hence, Figure 7(h) tells us that, to obtain $1\text{x}10^6$ Btu of gasoline for end users from surface-mined coal liquefaction, $1.57\text{x}10^6$ Btu of coal in the ground will be needed and $0.10\text{x}10^6$ Btu of external "driving" energy (both energy and energy sequestered in materials) will be needed from society. The gross energy resource requirement is $(1.57+0.10)\text{x}10^6$ Btu of energy to produce a net yield of $1\text{x}10^6$ Btu of gasoline. If one does not include the unrecovered resource of surface-mined coal, then $1.49\text{x}10^6$ Btu of coal must be recovered to start off the trajectory.

There are three basic issues for which we have developed data tables. This places the information of the figures into tabular form. Each issue has an appropriate accounting method, and each issue relates to a smaller "boundary" than the main boundary of the study.

NATURAL GAS; GAS PRODUCED FROM DRY GAS WELLS AND FROM OIL WELLS (NATIONAL AVERAGE MIX), GATHERED FROM A FIELD BY PIPELINE (REGIONAL AVERAGE), DRYED AT A GAS LIQUIDS PLANT (REGIONAL AVERAGE), PIPELINED 1000 MILES (NATIONAL AND REGIONAL AVERAGE), AND DISTRIBUTED BY PIPELINE (TYPICAL REGIONAL CASE).



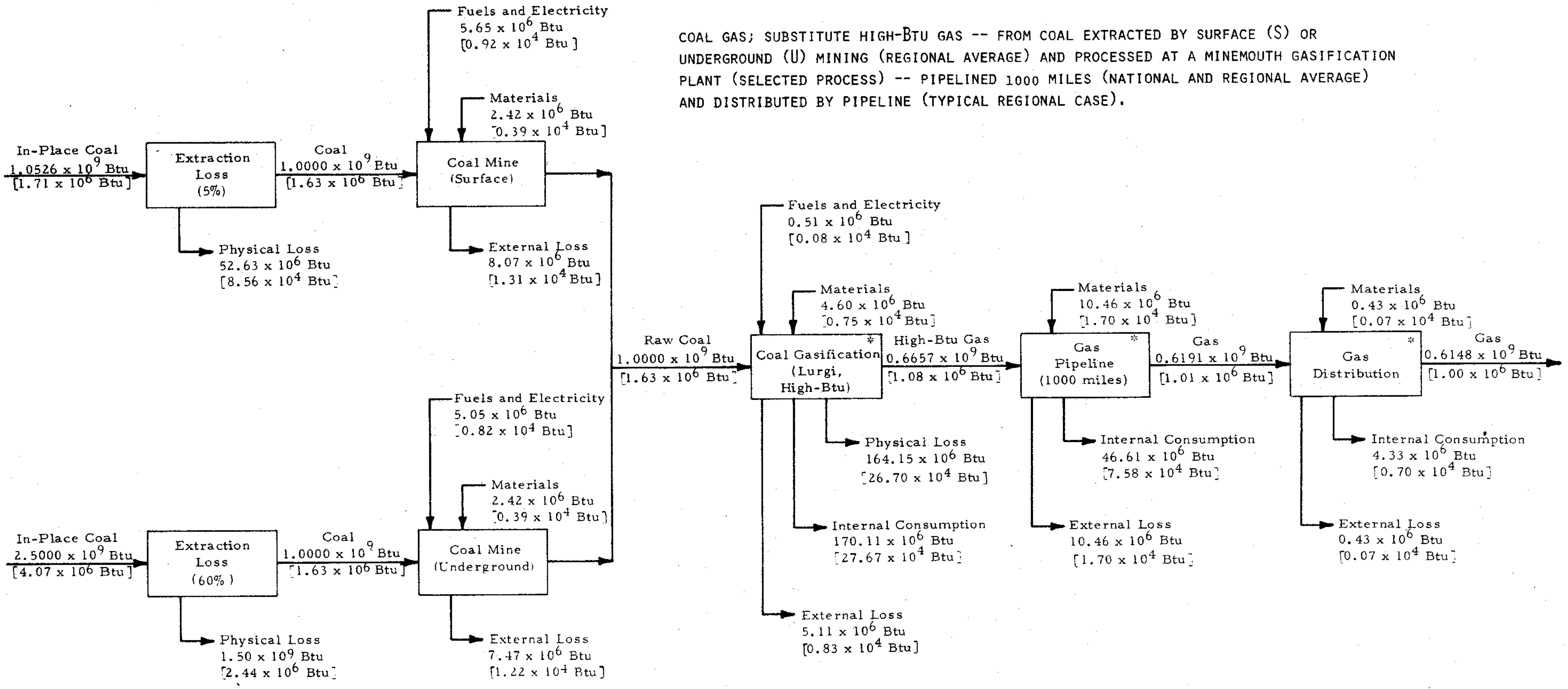
Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.

*Option 1: Use of internally converted energy in lieu of external energy.

SELECTED NATURAL GAS TRAJECTORY

FIGURE 5(A)

COAL GAS; SUBSTITUTE HIGH-BTU GAS -- FROM COAL EXTRACTED BY SURFACE (S) OR UNDERGROUND (U) MINING (REGIONAL AVERAGE) AND PROCESSED AT A MINEMOUTH GASIFICATION PLANT (SELECTED PROCESS) -- PIPELINED 1000 MILES (NATIONAL AND REGIONAL AVERAGE) AND DISTRIBUTED BY PIPELINE (TYPICAL REGIONAL CASE).



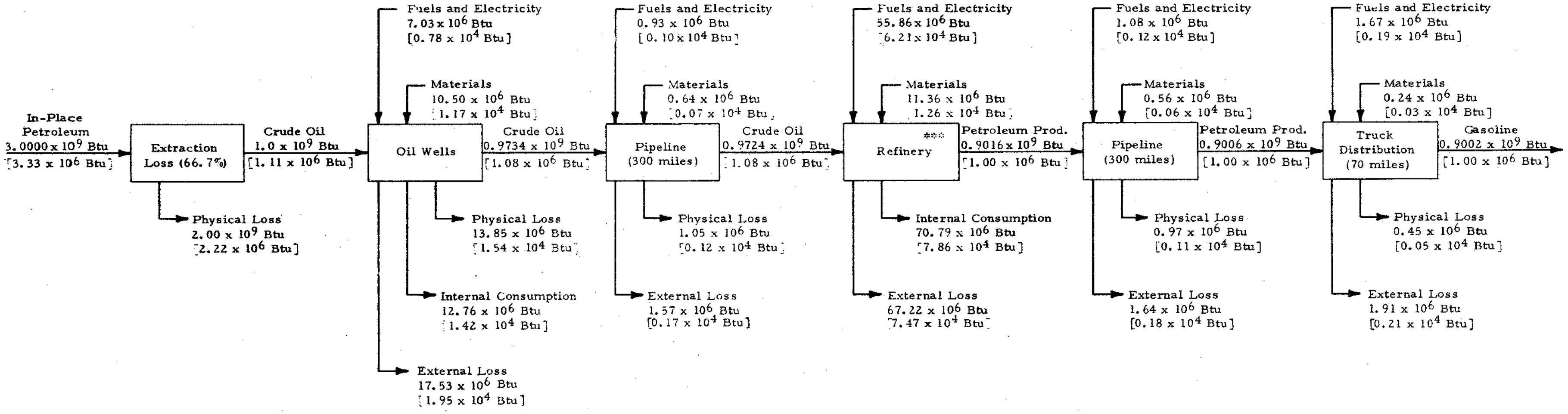
Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.

*Option 1: Use of internally converted energy in lieu of external energy.

SELECTED COAL GASIFICATION TRAJECTORY

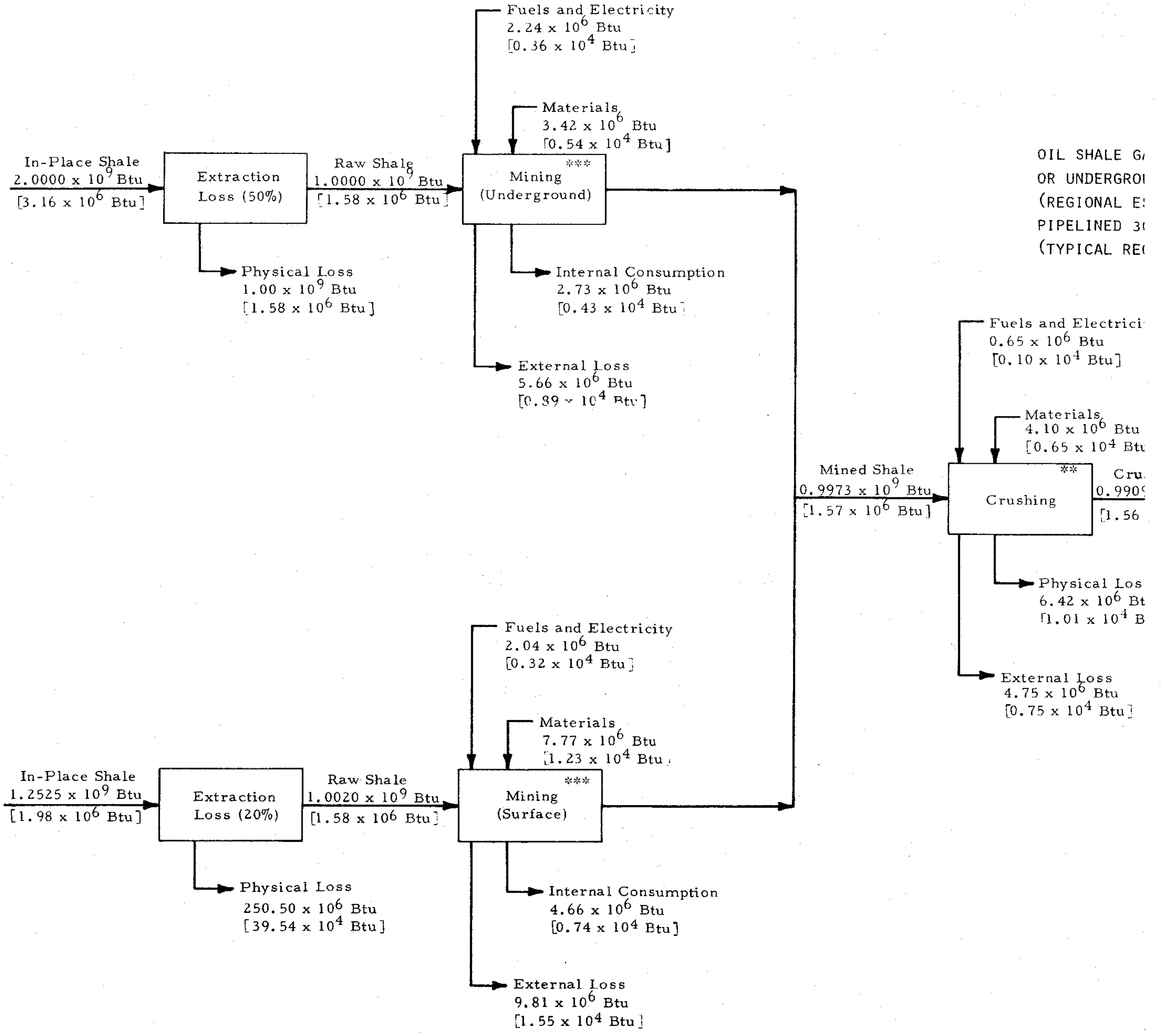
FIGURE 5(B)

PETROLEUM GASOLINE; AUTOMOTIVE GASOLINE -- FROM CRUDE OIL PRODUCED FROM OIL WELLS (NATIONAL AVERAGE), PIPELINED 300 MILES (NATIONAL AND REGIONAL AVERAGE), AND REFINED (UPDATED NATIONAL AVERAGE) -- PIPELINED 300 MILES (NATIONAL AVERAGE), AND DISTRIBUTED BY TRUCK 70 MILES (TYPICAL REGIONAL CASE).



Note: [ ] denote numbers normalized tp 1.00×10^6 Btu final output.
*** Option 3: Economically optimal (current) combination of internally generated energy and external energy.

SELECTED PETROLEUM-TO-GASOLINE TRAJECTORY
FIGURE 5(c)

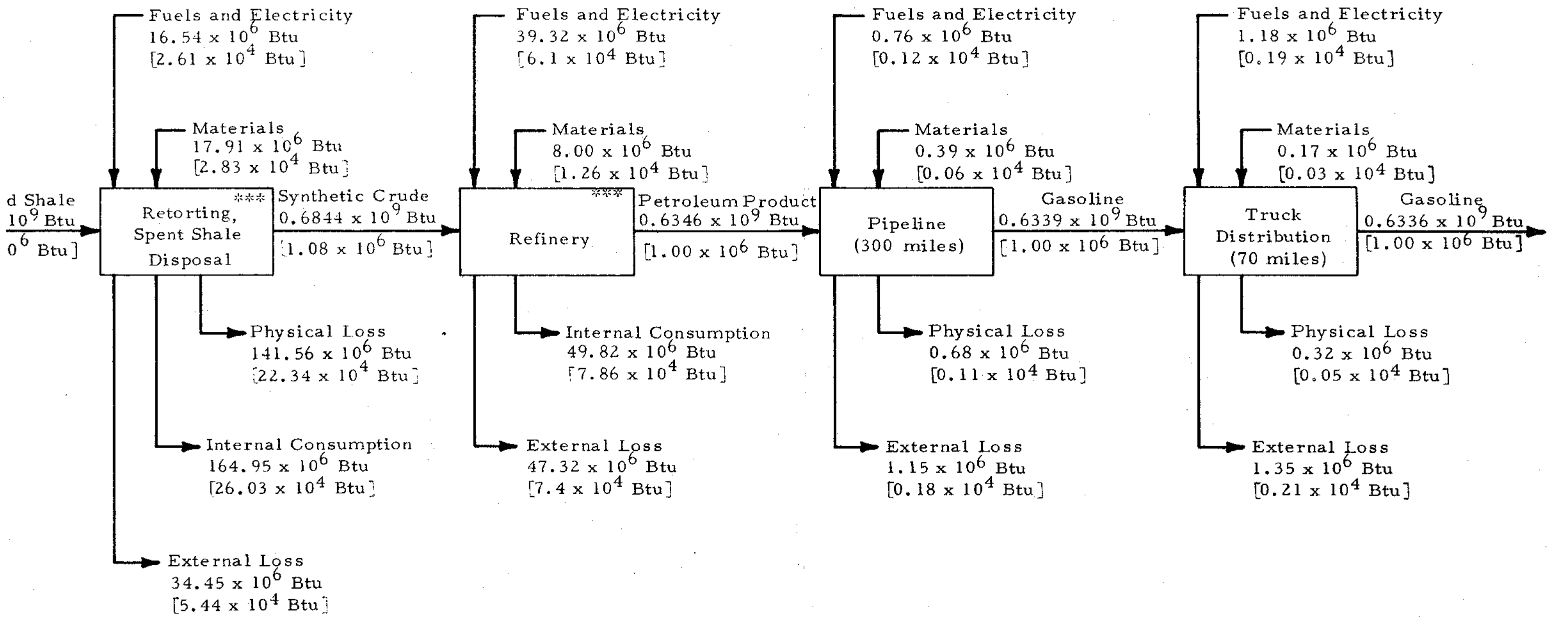


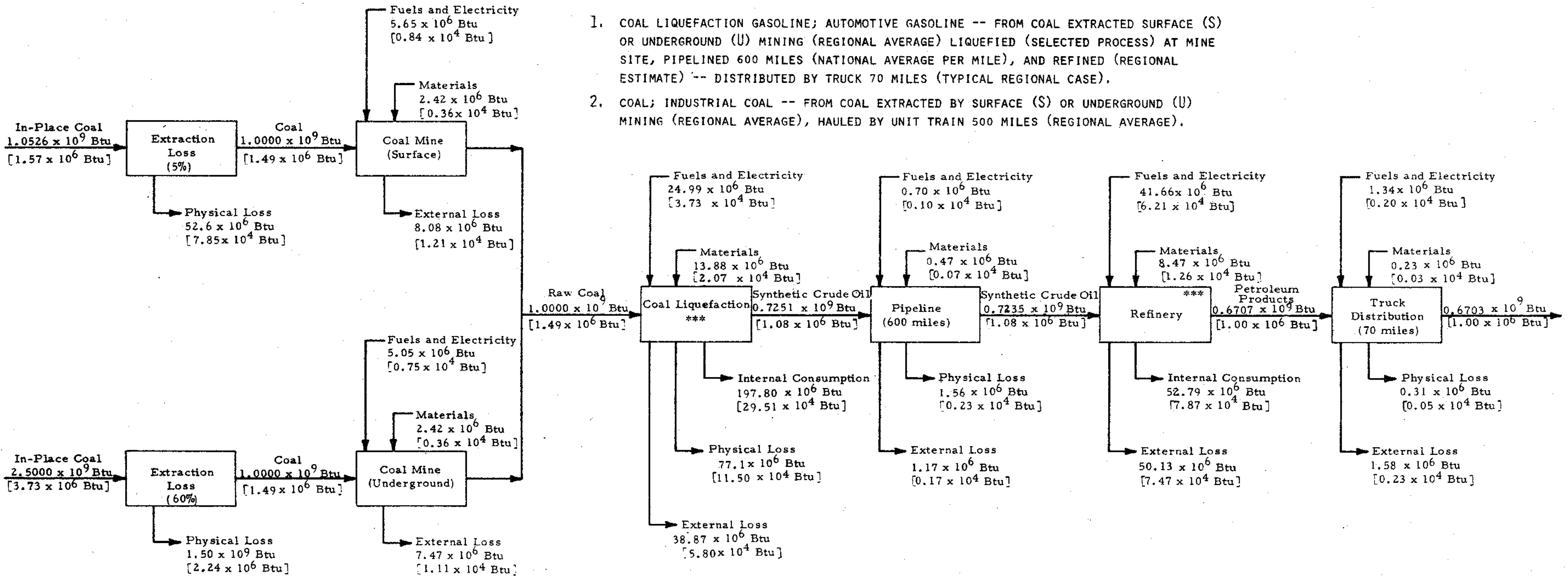
Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.
** Option 2: Use of external energy in lieu of internally generated energy.
*** Option 3: Economically optimal (current) combination of internally generated energy and external energy.

SELECTED OIL-SHALE-TO-GASOLINE TRAJECTORY

FIGURE 5(D)

LINE; AUTOMOTIVE GASOLINE -- FROM OIL SHALE EXTRACTED BY SURFACE (S)
(U) MINING (REGIONAL ESTIMATE) AND CRUSHED RETORTED ABOVEGROUND
MATE), REFINED (REGIONAL ESTIMATE) AT OR NEAR THE PLANT SITE --
MILES (NATIONAL AVERAGE), AND DISTRIBUTED BY TRUCK 70 MILES
NAL CASE).





1. COAL LIQUEFACTION GASOLINE; AUTOMOTIVE GASOLINE -- FROM COAL EXTRACTED SURFACE (S) OR UNDERGROUND (U) MINING (REGIONAL AVERAGE) LIQUEFIED (SELECTED PROCESS) AT MINE SITE, PIPELINED 600 MILES (NATIONAL AVERAGE PER MILE), AND REFINED (REGIONAL ESTIMATE) -- DISTRIBUTED BY TRUCK 70 MILES (TYPICAL REGIONAL CASE).
2. COAL; INDUSTRIAL COAL -- FROM COAL EXTRACTED BY SURFACE (S) OR UNDERGROUND (U) MINING (REGIONAL AVERAGE), HAULED BY UNIT TRAIN 500 MILES (REGIONAL AVERAGE).

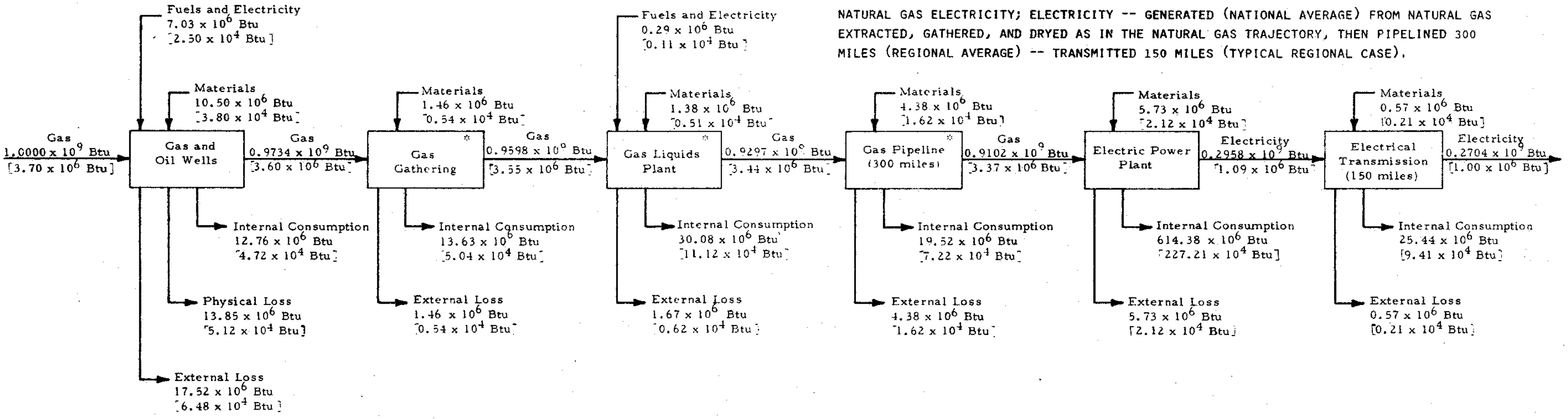
Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.

* Option 1: Use of internally converted energy in lieu of external energy.
*** Option 3: Economically optimal (current) combination of internally generated energy and external energy.

1. SELECTED COAL-LIQUEFACTION-GASOLINE TRAJECTORY
2. SELECTED COAL TRAJECTORY (LEFT PORTION OF FIGURE ONLY)

FIGURE 5(E)

NATURAL GAS ELECTRICITY; ELECTRICITY -- GENERATED (NATIONAL AVERAGE) FROM NATURAL GAS EXTRACTED, GATHERED, AND DRYED AS IN THE NATURAL GAS TRAJECTORY, THEN PIPELINED 300 MILES (REGIONAL AVERAGE) -- TRANSMITTED 150 MILES (TYPICAL REGIONAL CASE).

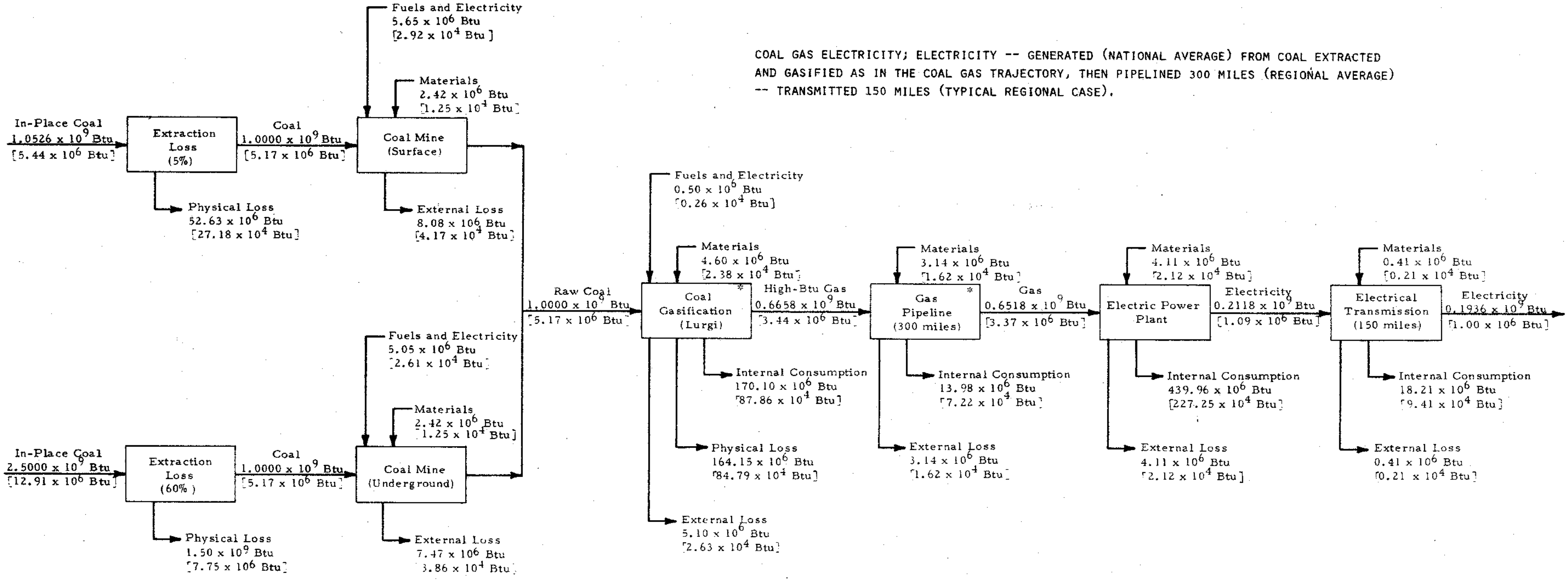


Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.
*Option 1: Use of internally converted energy in lieu of external energy.

SELECTED NATURAL GAS-ELECTRIC TRAJECTORY

FIGURE 5(F)

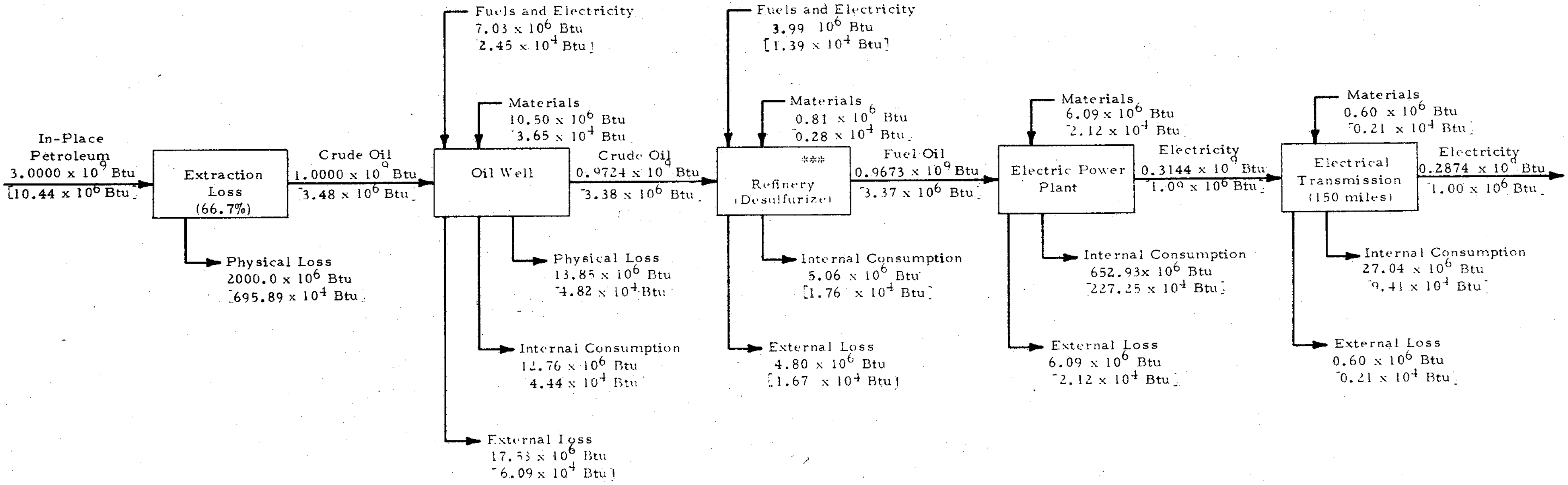
COAL GAS ELECTRICITY; ELECTRICITY -- GENERATED (NATIONAL AVERAGE) FROM COAL EXTRACTED AND GASIFIED AS IN THE COAL GAS TRAJECTORY, THEN PIPELINED 300 MILES (REGIONAL AVERAGE) -- TRANSMITTED 150 MILES (TYPICAL REGIONAL CASE).



Note: [ ] denote numbers normalized to 1.00×10^{6} Btu final output.
*Option 1: Use of internally converted energy in lieu of external energy.

SELECTED COAL-GAS-ELECTRIC TRAJECTORY
FIGURE 5(G)

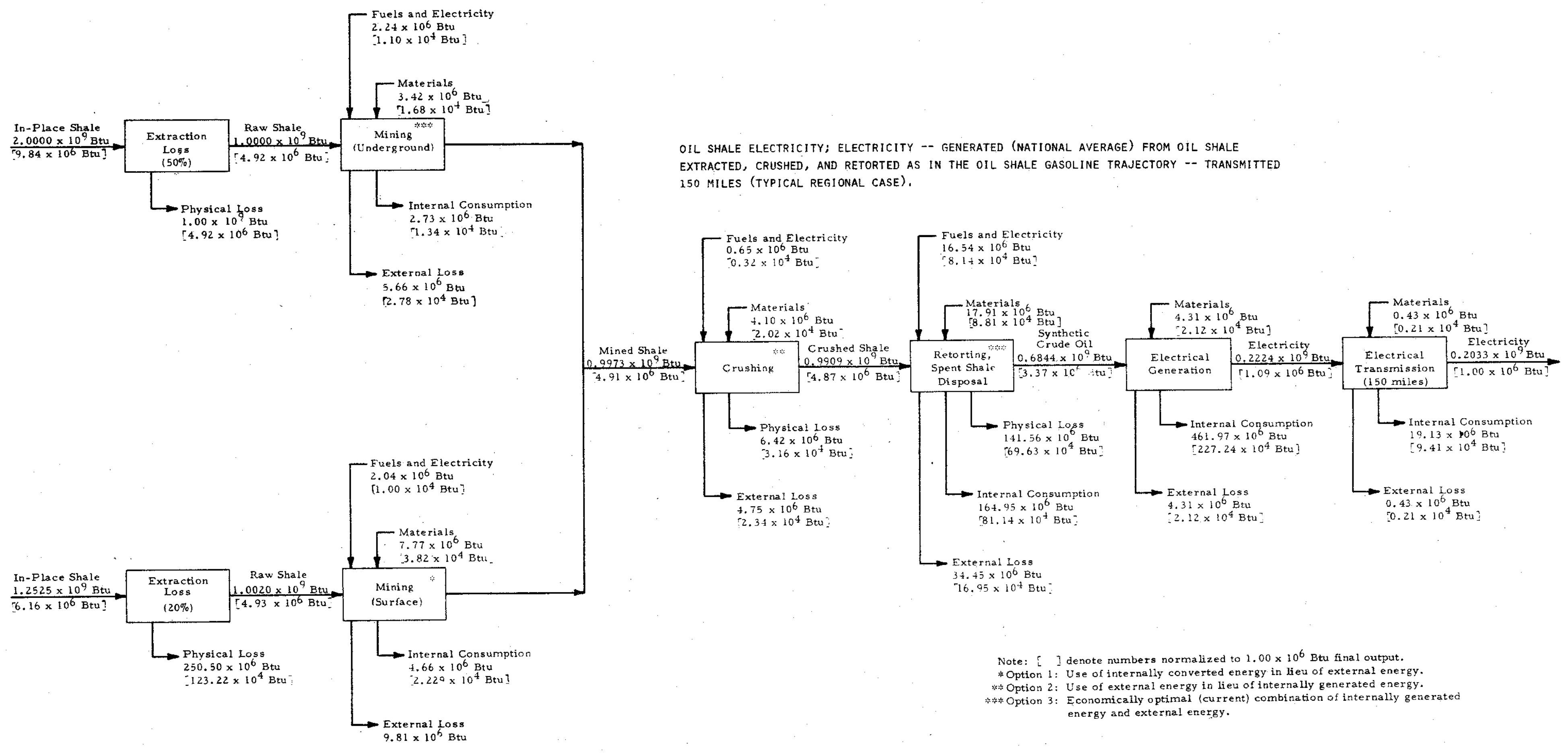
PETROLEUM ELECTRICITY; ELECTRICITY -- GENERATED (NATIONAL AVERAGE) FROM PETROLEUM EXTRACTED FROM AN OIL WELL (NATIONAL AVERAGE) AT OR NEAR A REFINERY (UPDATED NATIONAL AVERAGE) -- TRANSMITTED 150 MILES (TYPICAL REGIONAL CASE).



Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.
*** Option 3: Economically optimal (current) combination of internally generated energy and external energy.

SELECTED PETROLEUM-ELECTRIC TRAJECTORY
FIGURE 5(H)

OIL SHALE ELECTRICITY; ELECTRICITY -- GENERATED (NATIONAL AVERAGE) FROM OIL SHALE EXTRACTED, CRUSHED, AND RETORTED AS IN THE OIL SHALE GASOLINE TRAJECTORY -- TRANSMITTED 150 MILES (TYPICAL REGIONAL CASE).

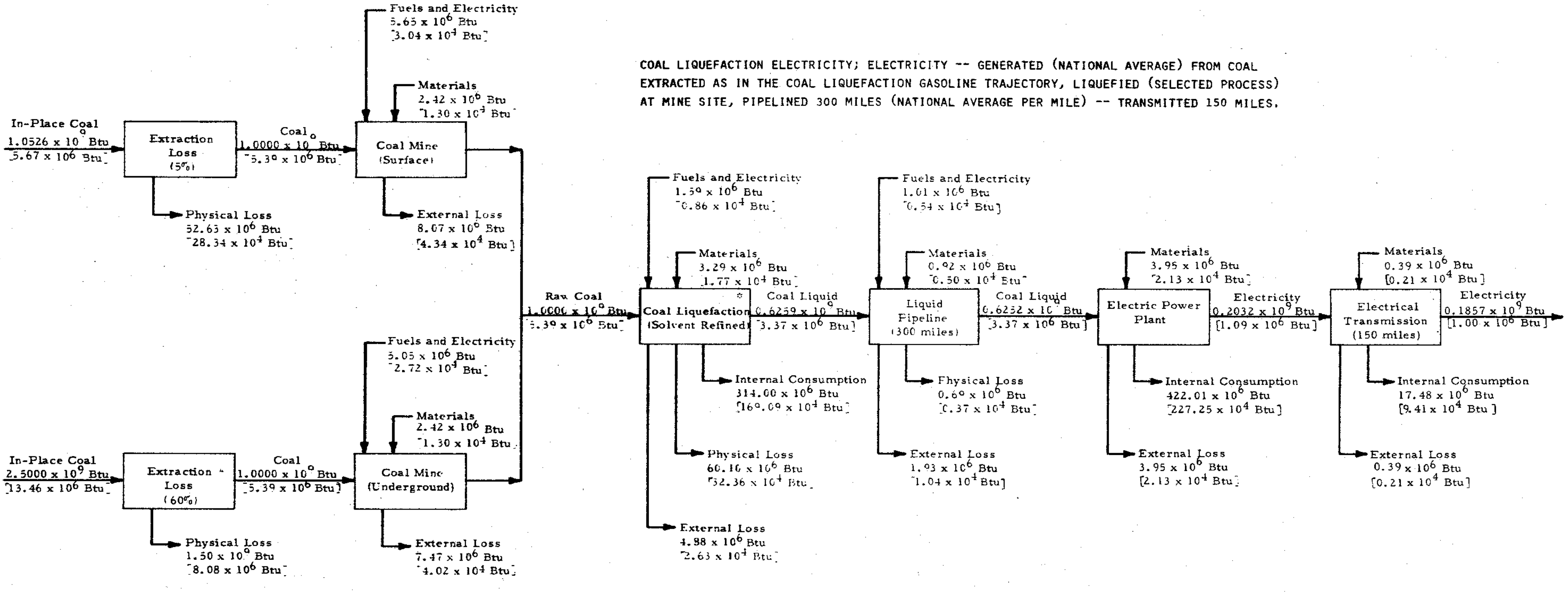


Note: [ ] denote numbers normalized to 1.00×10^6 Btu final output.
*Option 1: Use of internally converted energy in lieu of external energy.
**Option 2: Use of external energy in lieu of internally generated energy.
***Option 3: Economically optimal (current) combination of internally generated energy and external energy.

SELECTED OIL-SHALE-ELECTRIC TRAJECTORY

FIGURE 5(I)

COAL LIQUEFACTION ELECTRICITY; ELECTRICITY -- GENERATED (NATIONAL AVERAGE) FROM COAL EXTRACTED AS IN THE COAL LIQUEFACTION GASOLINE TRAJECTORY, LIQUEFIED (SELECTED PROCESS) AT MINE SITE, PIPELINED 300 MILES (NATIONAL AVERAGE PER MILE) -- TRANSMITTED 150 MILES.

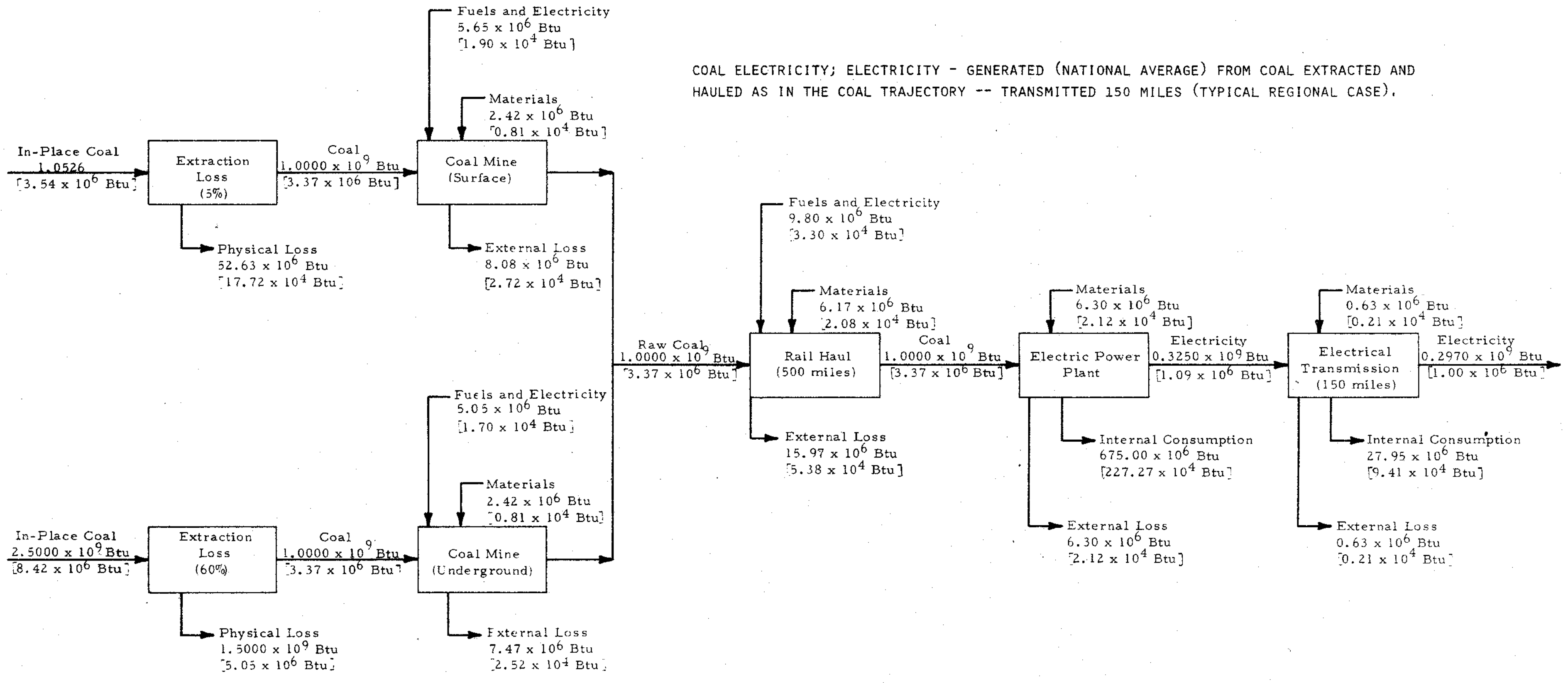


Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.
*Option 1: Use of internally converted energy in lieu of external energy.

SELECTED COAL-LIQUEFACTION-ELECTRIC TRAJECTORY

FIGURE 5(J)

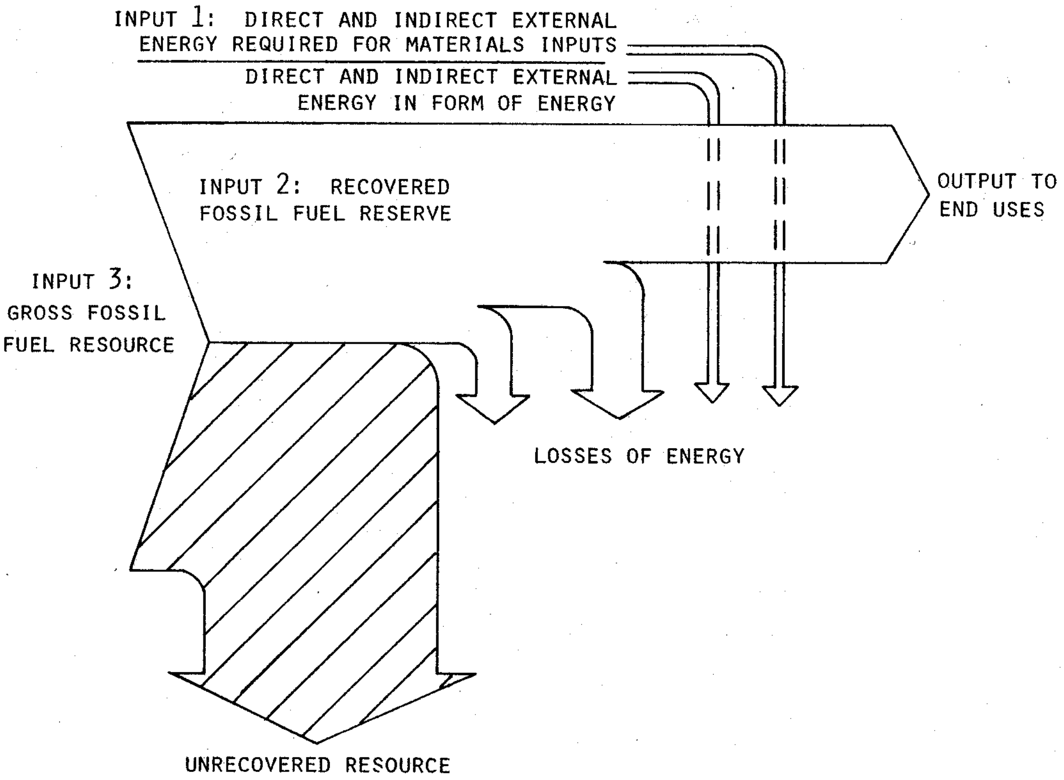
COAL ELECTRICITY; ELECTRICITY - GENERATED (NATIONAL AVERAGE) FROM COAL EXTRACTED AND HAULED AS IN THE COAL TRAJECTORY -- TRANSMITTED 150 MILES (TYPICAL REGIONAL CASE).



Note: [ ] denote numbers normalized to 1.00 x 10^6 Btu final output.

SELECTED COAL-ELECTRIC TRAJECTORY

FIGURE 5(K)



KEY DIAGRAM: ENERGY BALANCE OF TRAJECTORY

FIGURE 6

For each issue, the appropriate accounting method includes both a total of input and outputs, and a ratio of outputs to inputs. Ratios have advantages for comparing trajectories, and are a standard mathematical approach which tells what one quantity (output) is relative to another (input). However, they must be used cautiously; for example, a small change in the denominator makes a large change in a ratio. Also, the use of internally recycled process energy for plant operation, instead of the use of external energy, can affect Ratio R-1.

These issues and accounting methods are as follows, (referring to Figure 2 for terminology).

1. Issue: How much energy is required from the industrial component of society to "drive", or establish and operate an energy production process, relative to the energy yeild of the process.

Accounting Methods:

(a) Net Yield

By subtracting the external energy from the final output, the yield is shown. This is not a true balance for a module. For comparative purposes between trajectories, external energy can be compared if trajectory outputs are equal.

(b) Ratio

Ratio R_1: "External Net Energy Ratio"

$$\text{Ratio:} = \frac{\text{Total ENERGY PRODUCT out}}{\text{Total EXTERNAL ENERGY in}}$$

2. Issue: In extracting, processing and moving fossil fuels to provide energy to end users, what final yields do we get relative to losses of the total energy of the recovered fossil fuel resource and of the industrial energy which is needed to establish and operate the fossil energy production systems?

Accounting Methods:

(a) Net Yield

The total of "external and process losses" shows how much energy is made unavailable for a given output of energy product. To look at this in another way, for a given output, one can see what principal energy and external energy inputs are needed.

(b) Ratio

Ratio R_2: "Process Net Yield Ratio"

$$\text{Ratio:} = \frac{\text{Total ENERGY PRODUCT out}}{\text{Total ENERGY LOSS of External and process energy}}$$

Comment: This accounts for all inputs and outputs except for the unrecovered, lost or damaged fossil fuel resource. It includes the energy reserves and the energy inputs and losses in the extraction of the reserves.

3. Issue: For a given output of fossil fuel energy for end use, what total amounts of the gross fossil fuel resources in the ground and industrial energies are necessary to establish and operate the system?

Accounting Methods:

(a) Net Yield

The total of "external and process losses and unrecovered resource" shows how much energy, including fossil fuels in the ground, is made unavailable for a given output of energy product, given today's technology and economics. Looking at this in another way, for a given output, one can see what resource in the ground and external energy inputs are required.

(b) Ratio

Ratio R_3 = "Resource Net Yield Ratio"

$$\text{Ratio:} = \frac{\text{Total ENERGY PRODUCT out}}{\text{Total ENERGY LOSS including "Unrecovered Resource"}}$$

Comment: This accounts for fossil fuels which are lost, damaged, or unrecoverable, given today's economics and technologies, as a result of the extraction and processing of the fossil fuels. It views the gross energy as the energy resource, and the net as that which is made available to end users.

Table 1 presents data on input and output totals for 20 different trajectories, yielding energy of four different qualities: gas, gasoline, coal and electricity. The table shows data for each trajectory, based on a Final Output of 100 units:

- Initial Resource Required (fossil fuel in the ground)
- Unrecovered Resource (made unavailable, given today's technology and economics, as a result of bringing part of it into use by extraction processes)
- Initial Process Input (the "energy product" of the extractable reserves which becomes "principal energy" into processing - transporting part of trajectory)
- Total External Losses ("external energy" input and loss into total of modules in trajectory)
- Total External and Process Losses: ("external energy" input and lost, and "principal energies" made unavailable as a result of processing it)
- Total External and Process Losses, and Unrecovered Resource (total losses from resource in ground to end of trajectory).

Table 1 presents totals of trajectory energy quantities. The data can be used in a comparative way between trajectories, but one should not compare different columns for different trajectories, (i.e., "total external losses" of "petroleum-gasoline" compared with "total process and external losses" of "oil shale-gasoline").

Table 2 presents Ratios R-1, R-2 and R-3 for the same trajectories. Table 3 gives the complete analytical information for all trajectories.

The full methodology which has been utilized in this analysis is described in detail in Section IV of this Report. Issues and boundary considerations in net energy analysis and in this study are described in detail in Sections III and IV. The data are discussed and presented in detail in Section VI.

There are a number of potential applications of net energy analysis. There could involve a broad range of decisions at Federal and State government levels and in industry. However, there are also a number of problems associated with applying net energy analysis, including the cost and personnel requirements for significant implementation of net energy analysis. The weight to be given to net energy factors in decisions must be thought out. We recommend that the potential applications of net energy analysis be carefully examined and demonstrated before any massive use, especially in legislation and regulation. The entire concept of net energy analysis may prove to be less useful than its most ardent proponents would lead us to believe. The policy-maker should understand the problems and short-comings of net energy analysis as well as the potential for revealing new information. Net energy analysis may be useful to supplement economic and other information.

Table 1

Net Energy Analysis Fossil Fuels Summary of Selected Trajectories

Selected Trajectory	Primary Final Product	Initial Resource Required	Unrecovered Resource	Initial Process Input	Total External Losses	Total External and Process Losses	Total External and Process Losses, and Unrecovered Resource	Final Outpu
Natural Gas	High-Btu Gas	116	------	116	4.13	20.23	20.64	100
Coal (S) Gas	High-Btu Gas	171	8.56	163	4.04	68.28	78.23	100
Coal (U) Gas	High-Btu Gas	407	244.00	163	3.93	68.01	313.26	100
Petroleum Gasoline	Gasoline	333	222.00	111	10.41	24.35	248.77	100
Oil Shale (S) Gasoline	Gasoline	198	39.54	158	16.48	84.92	128.38	100
Oil Shale (U) Gasoline	Gasoline	316	158.00	158	15.83	83.96	245.88	100
Coal (S) Liquefaction Gasoline	Gasoline	157	7.85	149	15.59	73.51	88.71	100
Coal (U) Liquefaction Gasoline	Gasoline	373	224.00	149	15.50	73.82	304.93	100
Coal (S)	Coal	105	5.26	100	2.59	3.54	12.22	100
Coal (U)	Coal	250	150.00	100	2.53	3.87	157.06	100
Natural Gas Electricity	Electricity	370	------	370	11.77	283.18	284.51	100
Coal (S) Gas Electricity	Electricity	544	27.18	516	11.16	432.75	464.36	100
Coal (U) Gas Electricity	Electricity	1291	775.00	516	10.85	434.31	1212.22	100
Petroleum Electricity	Electricity	1044	696.00	348	10.34	263.34	965.74	100
Oil Shale (S) Electricity	Electricity	616	123.00	493	27.77	445.75	574.77	100
Oil Shale (U) Electricity	Electricity	984	492.00	493	25.73	443.71	941.73	100
Coal (S) Liquefaction Electricity	Electricity	567	28.34	538	10.79	454.90	487.95	100
Coal (U) Liquefaction Electricity	Electricity	1346	808.00	538	10.47	456.56	1267.67	100
Coal (S) Electricity	Electricity	354	17.72	337	11.03	250.89	279.36	100
Coal (U) Electricity	Electricity	842	505.00	337	10.83	251.99	766.95	100

Table 2

Net Energy Analysis
Fossil Fuels
Net Energy Ratios of Selected Trajectories

Selected Trajectory	Primary Final Product	R_1 External Ratio	R_2 Process Ratio	R_3 Resource Yield Ratio
Natural Gas	High-Btu Gas	24.21	4.94	4.84
Coal (S) Gas	High-Btu Gas	24.75	1.46	1.28
Coal (U) Gas	High-Btu Gas	25.45	1.47	0.32
Petroleum Gasoline	Gasoline	9.61	4.11	0.40
Oil Shale (S) Gasoline	Gasoline	6.07	1.18	0.78
Oil Shale (U) Gasoline	Gasoline	6.32	1.19	0.41
Coal (S) Liquefaction Gasoline	Gasoline	6.41	1.36	1.13
Coal (U) Liquefaction Gasoline	Gasoline	6.45	1.35	0.33
Coal (S)	Coal	38.61	28.25	8.18
Coal (U)	Coal	39.53	25.84	0.64
Natural Gas Electricity	Electricity	8.50	0.35	0.35
Coal (S) Gas Electricity	Electricity	8.96	0.23	0.22
Coal (U) Gas Electricity	Electricity	9.22	0.23	0.08
Petroleum Electricity	Electricity	9.67	0.38	0.10
Oil Shale (S) Electricity	Electricity	3.60	0.22	0.17
Oil Shale (U) Electricity	Electricity	3.89	0.23	0.11
Coal (S) Liquefaction Electricity	Electricity	9.26	0.22	0.20
Coal (U) Liquefaction Electricity	Electricity	9.55	0.22	0.08
Coal (S) Electricity	Electricity	9.07	0.40	0.36
Coal (U) Electricity	Electricity	9.23	0.40	0.13

I

									Energy Requir	
									External	
Selected Trajectory	1 Primary Final Product	2 Percent of Trajectory Products (Btu/Btu)	3 Initial Resource Required	4 Unrecovered Resource	5 Initial Process Input (3-4)	6 Physical Losses	7 Internal Consumption	8 Process Losses (6+7)	9 Fuels and Electricity	10 Materi
Natural Gas	High-Btu Gas	83	116	------	116	1.60	14.01	15.61	0.84	3.2
Coal (S) Gas	High-Btu Gas	79	171	8.56	163	26.70	35.95	62.65	1.00	2.9
Coal (U) Gas	High-Btu Gas	79	407	244.00	163	26.70	35.95	62.65	0.90	2.9
Petroleum Gasoline	Gasoline	46	333	222.00	111	1.82	9.28	11.10	7.40	2.5
Oil Shale (S) Gasoline	Gasoline	45	198	39.54	158	23.51	34.63	58.14	9.44	6.0
Oil Shale (U) Gasoline	Gasoline	45	316	158.00	158	23.51	34.32	57.83	9.48	5.3
Coal (S) Liquefaction Gasoline	Gasoline	37	157	7.85	149	11.78	37.38	49.16	11.08	3.7
Coal (U) Liquefaction Gasoline	Gasoline	37	373	224.00	149	11.78	37.38	49.16	10.99	3.7
Coal (S)	Coal	100	105	5.26	100	-----	------	------	1.54	0.8
Coal (U)	Coal	100	250	150.00	100	-----	------	------	1.48	0.8
Natural Gas Electricity	Electricity	59	370	------	370	5.12	264.72	269.84	2.71	8.8
Coal (S) Gas Electricity	Electricity	53	544	27.18	516	84.79	331.74	416.53	3.18	7.5
Coal (U) Gas Electricity	Electricity	53	1291	775.00	516	84.79	331.74	416.53	2.87	7.5
Petroleum Electricity	Electricity	100	1044	696.00	348	4.82	242.86	247.68	3.84	6.26
Oil Shale (S) Electricity	Electricity	96	616	123.00	493	72.79	319.13	391.92	9.46	16.98
Oil Shale (U) Electricity	Electricity	96	984	492.00	493	72.79	319.13	391.92	9.56	14.84
Coal (S) Liquefaction Electricity	Electricity	55	567	28.34	538	32.73	405.75	438.48	4.44	5.91
Coal (U) Liquefaction Electricity	Electricity	55	1346	808.00	538	32.73	405.75	438.48	4.12	5.91
Coal (S) Electricity	Electricity	100	354	17.72	337	-----	236.68	236.68	5.20	5.22
Coal (U) Electricity	Electricity	100	842	505.00	337	-----	236.68	236.68	5.00	5.22

(1) Direct Losses include all direct and indirect energy for Materials.

(2) Indirect Losses are calculated for Fuels and Electricity (column 9).

Table 3

Energy Analysis
ossil Fuels
nts for Selected Trajectories

Direct Losses (1)			Indirect Losses (2)			Total Losses						
11 Total (9+10)	12 External and Process Losses (8+11)	13 External and Process Losses, and Unrecovered Resource (4+12)	14 External	15 External and Process Losses	16 External and Process Losses, and Unrecovered Resource	17 External (11+14)	18 External and Process Losses (12+15)	19 External and Process Losses, and Unrecovered Resource (13+16)	20 Final Output	21 R_1 External Ratio (20 ÷ 17)	22 R_2 Process Ratio (20 ÷ 18)	23 R_3 Resource Yield Ratio (20 ÷ 19)
4.07	19.68	19.68	.06	0.55	0.96	4.13	20.23	20.64	100	24.21	4.94	4.84
3.91	66.56	75.12	0.13	1.72	3.11	4.04	68.28	78.23	100	24.75	1.46	1.28
3.81	66.46	310.46	0.12	1.55	2.80	3.93	68.01	313.26	100	25.45	1.47	0.32
9.99	21.09	243.09	0.42	3.26	5.68	10.41	24.35	248.77	100	9.61	4.11	0.40
15.50	73.64	113.18	0.98	11.28	15.20	16.48	84.92	128.38	100	6.07	1.18	0.78
14.85	72.68	230.68	0.98	11.28	15.20	15.83	83.96	245.88	100	6.32	1.19	0.41
14.87	64.03	71.88	0.72	9.48	16.83	15.59	73.51	88.71	100	6.41	1.36	1.13
14.78	63.94	287.94	0.72	9.88	16.99	15.50	73.82	304.93	100	6.45	1.35	0.33
2.40	2.40	7.66	0.19	1.14	4.56	2.59	3.54	12.22	100	38.61	28.25	8.18
2.34	2.34	152.34	0.19	1.53	4.72	2.53	3.87	157.06	100	39.53	25.84	0.64
11.59	281.43	281.43	0.18	1.75	3.08	11.77	283.18	284.51	100	8.50	0.35	0.35
10.76	427.29	454.47	0.40	5.46	9.89	11.16	432.75	464.36	100	8.96	0.23	0.22
10.45	426.98	1201.98	0.40	7.33	10.24	10.85	434.31	1212.22	100	9.22	0.23	0.08
10.10	257.78	953.78	0.24	5.56	11.96	10.34	263.34	965.74	100	9.67	0.38	0.10
26.44	418.36	541.36	1.33	27.39	33.41	27.77	445.75	574.77	100	3.60	0.22	0.17
24.40	416.32	908.32	1.33	27.39	33.41	25.73	443.71	941.73	100	3.89	0.23	0.11
12.22	450.70	479.04	0.44	6.07	10.78	10.79	454.90	487.95	100	9.26	0.22	0.20
11.90	450.38	1258.38	0.44	8.15	11.16	10.47	456.56	1267.67	100	9.55	0.22	0.08
10.42	247.10	264.82	0.61	3.79	14.54	11.03	250.89	279.36	100	9.07	0.40	0.36
10.22	246.90	751.90	0.61	5.09	15.05	10.83	251.99	766.95	100	9.23	0.40	0.13

The confidence level of this study is not definable by statistical means. A "standard deviation" or similar mathematical device is not relevant because the confidence level, or degree of accuracy, is dependent upon the assumption. For example, in the refinery data, a "typical" refinery is presented, but there is no such thing as a "typical" or "average" refinery. As another example, a 40% recovery is assumed for underground coal mining. Hence, the professional judgement of the investigators is important. For each process, assuming a correctness of the professional judgement of the investigator, the data accuracy range maybe 3 or 4 percent. The summary of a trajectory is probably in the same accuracy range. The data are carried to two decimal places for calculation purposes and consistency, but that does not imply precision to the second decimal. If a number of actual site-specific processes were examined, there would be variation between them. However, these variations would not be large enough to invalidate the data herein. As discussed in Section VI, the trajectories are not process-sensitive (i.e., one type of shale plant versus another) to a significant extent for the purposes of our "selected trajectory" data.

B. Analysis of Findings

Tables 1 and 2 present the numerical information for selected processing sequences or "trajectories" in developing typical fossil fuel resources. For purposes of comparing the trajectories, attention is focused on the overall energy input and output totals and on the ratios R_1, R_2 and R_3.

It is recognized that, in some of the cases shown, the sequence from fossil fuel to end product may be (a) of limited practical significance or (b) economically unattractive for other than energy balance reasons. The energy ratios are still a useful tool, however, even in such cases, as one component of an overall technical and economic analysis of the conversion of the fossil fuel to a useful energy form. The "modular" approach of the CERI study makes it possible for the reader to select other trajectories of his own choosing.

NET YIELDS

Initially we will examine the input-output totals. The issue of external inputs only is one which this team feels is least important. However, it reveals some interesting information. The external inputs required for an output of 100 energy units are lowest for the solid fuel coal. The next lowest are for gas, with natural gas and syngas for surface and underground coal all about equal. Gasoline and electrical systems are in the same range of external requirements, with the exception of oil shale to electricity, which is highest. Indeed, it may be significantly high when an external investment of about 26 units is needed to obtain 100 units of energy.

Oil Shale - gasoline requires about 50 percent more external energy than conventional oil to gasoline (with primary and secondary recovery.) Coal gas-electricity, coal liquefaction-electricity, natural gas-electricity and coal-electricity all require about the same external energy.

The "total external and process losses" are more indicative of the effectiveness of the use of extracted fossil fuel resources. Here, coal is very low: 3 to 4 units are lost for every 100 delivered to end uses. Surface and underground mining are comparable, interestingly enough. Natural gas (20) and petroleum-gasoline rank next. Synfuels of gas from coal and gasoline from coal or shale are in the same general range of 68 to 85. Any electrical generation results in the highest losses. These range from 250 for surface-coal-electricity to 45 percent for the coal liquefaction-electricity trajectory.

In examining the in situ gross resource which is degraded by our present consumption of fossil fuels, we find an enormous range. This results from the great difference between surface-minable fuels and underground mining in coal and shale, and from the relative low recovery of petroleum by primary and secondary recovery. The next-to-last column of Table 1 shows this range. Surface coal is very low, as is natural gas. However, in terms of this issue, surface coal to gasoline and to syngas, and surface shale to gasoline give better yields than petroleum to gasoline. All electrical trajectories are higher except those of natural gas or surface coal.

RATIOS

The following observations are pertinent to the energy ratios R_1, R_2 and R_3. For each selected trajectory, the numerical values of the energy ratios decline substantially from R_1 to R_2 to R_3, as expected from the definitions of each ratio type. Several examples are perhaps of interest. In the case of natural gas production and distribution, the energy of the product gas is 24.21 (R_1) times as great as the external energy required to extract, gather, process and distribute it. But if physical losses, including those in the total recovery of the in-place resource are included, the energy ratio (R_3) is reduced to 4.84. For coal extraction by surface mining, the two ratios are R_1=38.61 and R_3=8.18.

In the case of petroleum to gasoline end-product R_1 is 9.61, while R_3, due primarily to resource left in the ground, is only 0.40; i.e., the product gasoline has less energy than the total system losses, including the unrecovered original petroleum in place. For gasoline from oil shale R_1 is 6.07, while R_3 is only 0.78, again less than unity.

If society is only concerned with the amount of energy obtained from a fossil fuel in relation to the external energy that must be provided to extract it, the ratio R_1 is of greatest interest. All processing sequences yield much more energy in their products than must be externally supplied for the conversion. Coal mining is the most attractive, with nearly 40 times as much energy in the extracted coal as in the external energy. Gas production has the next highest ratios, with natural gas and coal gasification to fuel gases each being in the same general magnitude (R_1 is from 24.2 to 25.4).

The conversion of petroleum to gasoline is only about 40 percent as effective in external energy requirements (R_1=9.6) as natural gas recovery (R_1=24.21) or coal gasification to syngas (R_1=24.75). Coal or oil shale (with R_1 in the range of 6 to 6.4) are about two-thirds as energy-effective as sources for gasoline as is petroleum, in terms of external inputs.

The production of electric power by (a) mining and burning coal directly, (b) first converting the coal to syngas, or (c) first producing a coal liquid, all have about the same range of external energy input ratios (R_1 is from 8 to 9.2). Petroleum and natural gas for power generation are also within this energy ratio range. However, if the sequence "oil shale to shale oil to electric power" is used, R_1 drops to a range of 3.6 to 3.9.

The ratio R_2 is a more significant measure of net energy yield than R_1 because it accounts for all inputs and outputs and losses, except for the efficiency of resource recovery. Coal mining still has the most favorable ratio (25.8 to 28.2) under this method of energy accounting. Natural gas recovery is again second highest, although only about one-fifth as energy productive as coal mining. Coal gasification (R_2=1.46) is only about 30 percent as "efficient" as natural gas recovery due to greater processing "losses"; the R_1's for these two trajectories were the same.

Gasoline production from petroleum is comparable to natural gas recovery if this energy accounting method is used. But to produce gasoline from coal liquefaction or from shale oil is only one-third as energy-efficient as is petroleum-derived gasoline.

The processing sequences which are least attractive solely from an R_2 energy ratio viewpoint are those which involve electric power generation from any fossil fuel source. The electrical energy produced is only 0.2 to 0.4 of the total energy losses in the system. These low ratios, of course, in part reflect the low thermodynamic efficiency of electric power generation (35-40 percent) inherent in producing electricity by burning a fossil fuel or one of its derived products (syngas, synliquids, shale oil.) The R_2 ratios indicate that electricity from coal gas, oil shale, or coal liquefaction are about 55 percent as "efficient" as electricity from coal.

It is not to be concluded from the foregoing, however, that electric power should not be obtained by fossil fuels combustion. Rather, it is necessary to accept the fact that if modern society prefers (or requires) electric power, it must accept the lower energy efficiencies involved if it chooses to generate such power from fossil energy resources, given today's economics and technologies. Improvements in efficiency by using combined cycles or MHD will change the picture. Similarly, air quality may be more important than net yeilds, and coal gas to electricity may be desirable on that basis compared to conventional coal-electric plants.

In a real sense, proceeding from R_1 to R_2 to R_3 type energy ratios is a quantitative means to extend a net energy analysis from a short, almost immediate time frame, to those larger-scale outlooks which encompass society's concern for the maximum utilization of its finite energy resources, and with depleting the fossil energy supply of future generations. The R_3 energy ratio, therefore, with its emphasis on "unrecoverable" (lost and "damaged") resources in-place (i.e., the efficiency of resource recovery), has the greatest long term resource management orientation of the energy ratios. It is also the least pragmatic in its response to short-term "1985-type" goals of increased energy independence. This is partially due to the fact that "R_3" improvements will require changed economics and technology from today's.

As might be expected, the most favorable R_3 ratios are those for strip mining of coal (8.18) and recovery of natural gas (4.84), each of which have minimum unrecoverable resource losses. The two sequences involving the strip mining of coal and its subsequent (a) gasification to SNG (R_3=1.28), or (b) liquefaction to gasoline (R_3=1.13) have the next highest R_3 energy ratios. These again are primarily due to the associated high efficiency of coal resource recovery.

The surface mining of oil shale and its processing to gasoline has the next most attractive energy conservation ratio (R_3=0.78), reflecting the high resource recovery possible by open-pit mining. It is interesting to observe that this ratio is in the same order of magnitude as the underground mining of coal (R_3=0.64).

All of the remaining trajectories shown in Table 2 have R_3 ratios considerably less than unity (varying from 0.08 to 0.40), thus indicating that substantially less energy is obtained than is used and left in "unrecoverable" resource in place. Again, however, this does not mean that some of these processing sequences are not attractive for other reasons (e.g., conversion of a solid to a "cleaner" gaseous or liquid fuel, or to a more versatile form: electric power), or that improved technology will not change the picture.

It is pertinent to observe that all processing sequences which convert a fossil fuel to electric power have very low R_3 ratios. These vary from 0.35 or 0.36 for power generation directly from strip-mined coal or natural gas, to 0.10 to 0.13 for burning underground-mined coal or petroleum products to produce electricity. And yet, it is these latter four trajectories that, in spite of their apparent unfavorable energy ratios (a result of low resource recovery efficiencies and efficiencies in electrical conversion) are currently the major processes for electrical energy production in the United States. This may aid in illustrating the care which must be taken in interpreting all energy ratios, especially those of the R_3 type. From a resource-management viewpoint, however, the "high electrification" scenarios which are often proposed for the U.S. might be examined in light of net energy data. End use needs for space heat and many industrial processes can be met by using natural gas (which is in short supply), coal syngas, fuel oil or electricity. "High electrification" scenarios usually include large amounts of nuclear power, which has not been examined in this study.

All trajectories must be considered in light of other social needs. For example, the need to reduce sulfur dioxide emissions is very real. However, if this need is met with surface coal-liquefaction-electricity instead of conventional surface coal-electricity production, the "total external and process losses" increase to 489 from 279 units per 100-unit output.

C. Conclusions

General conclusions are as follows. Net energy analysis should be further developed and tested as a planning tool to provide an additional type of information to supplement economic, technologic and environmental information. It should be explored cautiously, so that its value and best uses are ascertained before there is wholesale application of net energy analysis. It is probably most applicable for Federal decisions. Indsutry may find it is most applicable when carried out in greater detail on specific processes, to identify means of improving net yields or to avoid possible pitfalls in energy decisions based primarily on economics.

Specific comparisons can be made between various types of fossil fuel production processes, as discussed in Section II-B above. Care must be exercised in avoiding confusion between ratios.

Indirect external inputs of energy and energy needed to produce the materials of fossil fuel systems are quite small (see Column 14 of Table 3). Therefore, expensive and sophisticated techniques to refine this data for net energy analysis are not warranted, (although such data may be more useful for non-energy process analysis).

The CERI investigators feel that the confidence level of the data which is presented here is sufficient for the general purposes and typical processes which are described, although this confidence level may not always be adequate for analysis of a specific "nontypical" module at a given site.

There do not appear to be any significant "hidden subsidies" in direct or indirect external inputs. Some "subsidies" or impacts on energy flows could be identified in site-specific studies by changing the boundaries of the system being analyzed, but they will change the results presented here by very small amounts.

There does not appear to be any reason for either definitely halting or definitely stimulating major synfuels programs strictly or primarily on the basis of net energy yield data. With major programs involving synfuels research, development, demonstration and commercialization, however, net energy analysis can be used. Its use should be in engineering and planning to improve net energy yields, and to compare processes and alternatives.

A conclusion could be drawn that surface-mining of coal should be emphasized, and that underground mining should be de-emphasized. This would leave the underground coal to be recovered by future generations. However, several factors must be considered. Underground coal mining is important right now as for energy. It is a source of employment and income for many people. It is geographically located near where large amounts of energy are needed. A primary consideration should be continued research and development of better means of underground coal recovery, so that less coal is left behind in mining. Further, it may be desirable to get a maximum amount of coal into production rapidly to reduce the consumption of natural gas and imported oil. Surface mines can be established more rapidly than underground mines, and some Western surface mines can produce enormous amounts of coal.

D. Recommendations on Specific Applications

Although this study was not designed or funded to actually apply or test the use of net energy analysis in actual decisions, comments are offered regarding its potential applications.

1. Specific Applications at Federal Level

The Energy Research and Development Administration (ERDA) operates under specific legislation concerning net energy analysis. Public Law 93-577 of 1974, the "Federal Non-nuclear Energy Research and Development Act of 1974", refers to net energy as follows:

> Governing Principles
>
> Sec. 5(a) The Congress authorizes and directs that the comprehensive program in research, development, and demonstration required by this Act shall be designed and executed according to the following principles;
>
> (1) Energy conservation shall be a primary consideration in the design and implementation of the Federal non-nuclear energy program. For the purposes of this Act, energy conservation means both improvement in efficiency of energy production and use, and reduction in energy waste.
>
> (2) The environmental and social consequences of a proposed program shall be analyzed and considered in evaluating its potential.

> (3) Any program for the development of a technology which may require significant consumptive use of water after the technology has reached the stage of commercial application shall include thorough consideration of the impacts of such technology and use on water resources pursuant to the provisions of Section 13.
>
> (4) Heavy emphasis shall be given to those technologies which utilize renewable or essentially inexhastible energy sources.
>
> (5) The potential for production of net energy by the proposed technology at the state of commercial application shall be analyzed and considered in evaluating proposals.

It is our view that ERDA should consider the following in using net energy analysis.

In all major research, development and demonstration leading to commercialization, ERDA could conduct, or require the use of, net energy analysis. The objectives should be to find engineering improvements to reduce the external energy inputs (improve Ratio R-1), to minimize "lost" energy and utilize such energy to the maximum feasible extent (improve Ratio R-2), and to improve resource recovery and reduce resource degradation (improve Ratio R-3 for surface and underground recovery of fossil fuels.) Technological research efforts could have those objectives, along with other objectives, as quiding principles. The engineering analyses should include economic analyses so that the costs of improving net energy yields can be determined.

ERDA could organize planning approaches to utilize net energy analysis, especially data for Ratios R-1 and R-3, in developing alternative scenarios. Such analysis could use data for Ratio R-1 in net yields over time for alternative growth patterns, some of which might require high energy reinvestments to achieve the desired outputs. The Reference Energy System model used by ERDA perhaps could be adjusted to show net yields and losses. Resource depletion rates could be examined, using data for Ratio R-3, for various scenarios.

If a proposed commercial application has a highly unfavorable net energy yield, it should not be encouraged unless there are strong reasons for so doing due to other considerations (economics, national import problems, environmental factors, etc.) By "unfavorable", we mean that its net energy yields are substantially lower than other processes which can meet end use needs, and that there is little evidence that significant improvements in net yields could be achieved. From data of this study, it would appear that commercialization of oil shale for electricity generation, should this be proposed, is not a favorable use of oil shale compared to other uses of shale oil or options for electrical generation. Oil shale should be used for gasoline, fuel oil and other liquid products. Technologies involving direct combustion of coal, such as the fluidized bed, should be stimulated because all three ratios for direct heat for end use from coal are favorable compared to other fossil fuels.

Research on improved recovery of resources should definitely be stimulated, so that presently unrecoverable fossil fuel resources can be utilized by future generations.

The studies at commercialization should be detailed and confined to a module, as discussed in Section VI of this Report. Energy-intensive aspects of the module balance could be traced in this way.

It might be advisable for ERDA to codify net energy analysis and adopt a consistent methodology to avoid confusion and non-comparable results.

Further research and testing of net energy applications, especially in integration with economics and other factors, should be funded. Section V discusses some concepts in this respect.

Other agencies could use net energy analysis in various decisions. The uses warrant more exploration, but the following suggestions are offered.

The Department of the Interior should examine major projects and programs in which significant energy quantities are involved, using net energy analysis. The Alaska gas pipeline alternatives could be compared. The pipeline data of this report could be used and adjusted for lengths of pipelines. The energy inputs and losses of terminals and tankers could be identified. We do not wish to comment, at this time, on what weight should be given to net energy analysis compared to economics, environment and other factors. Net energy analysis could be considered as a discrete parameter or as modifier to economic analysis, as discussed in Section V. Other major programs could be treated in a similar way. Also, the Department of the Interior could use net energy analysis in any overall resource management planning in the Bureau of Mines, U.S. Geological Survey, and Bureau of Land Management.

The Department of the Interior should explore how net energy analysis could be used in its energy minerals leasing program. Our cursory examination of the Energy Minerals Activity Recommendations System (EMARS) for coal leasing indicates that net energy analysis may be difficult to apply in the decisions and studies made at field level under the currently-proposed EMARS operation. However, it may be feasible for application at the Department level in leasing programs, because efficient use of resources is a factor to be considered at policy and program level. If it is to be used in the field offices, it appears that the Environmental Impact Statement may be a vehicle for its use. However, further examination of this concept is needed before it can be determined if net energy analysis should be applied in minerals leasing, and how to apply it.

The Federal Power Commission could use net energy analysis in choices involving major alternatives, similar to the approach discussed above for the Alaska Pipeline. The discussion at the end of Section V about an FPC off-shore gas decision illustrates the type of decision in which net energy analysis may be useful. It appears that net energy analysis would be more useful than the "Second Law Efficiency" approach used by FPC.

The Federal Energy Administration and the Environmental Protection Agency should continue efforts to match natural gas to end uses for which the highest Ratio R-2 is obtained, rather than permitting its use in electricity generation, which has lower net yields.

The Council on Environmental Quality could consider requiring net energy analysis in certain decisions. One could be an analysis of comparative energy yields in resource decisions. Another could be in the analysis of environmental impacts from "waste heat". The Environmental Protection Agency also could be interested in similar matters.

Regardless of which agencies are involved, a wide variety of information can be derived from the data of this study. A number of questions can be asked and answered using the data of the study. As one example, coal-electric trajectories can be re-analyzed for trajectories not included in our tables and figures to give information on mine-mouth versus load-center plants. For 1.00 x 10^6 output, tracing inputs only to, but not including, the mine, indicates the following for Case A, with a 500-mile rail haul and 150 miles of transmission line, and Case B, with no rail haul but 650 miles of transmission line:

Case	Initial Process Input	Total External Losses	Total External & Process Losses	Output	R-1	R-2
A	337 x 10^4	11.03 x 10^4	251 x 10^4	100 x 10^4	9.1	0.40
B	435 x 10^4	2.58 x 10^4	355 x 10^4	100 x 10^4	13.0	0.28

This tells us that Case A requires about three-fourths as much coal as Case B, but it requires an external energy investment which is 1.5 times that of Case B. However, the external energy investments are very small in either case. Case A requires movement of more energy units, and one must consider other factors in comparing physical movement of coal versus transmission of electricity. Other situations could be analyzed, and of course. the above example and others could be extended back to the resource in the ground.

The small outputs of the selected trajectories of this study can be evaluated to realistic quantities for actual end use patterns forecasted for future years.

For example, suppose that someone could encourage a single surface-mine 250-million-cubic foot/day coal gasification plant to deliver 74 x 10^{12} Btu/yr, enough to provide 146 x 10^6 Btu/year to 429,000 homes for heating and hot water heat; this is Case C. Compare this with Case D: 429,000 homes requiring about 100 x 10^6 Btu/year with electrical heat from surface-mined coal-electric generation. (The assumed end-use efficiencies are 60 percent for gas heat and 100 percent for electric resistance heating.) For Case D, about 42.9 x 10^{12} Btu must be delivered to end use. Comparing these, we have:

Case	Initial Resource Required	Total External Losses	Total External & Process Losses	Total External, Processes Unrecovered Resource Losses	End Use Energy
C	126 x 10^{12}	3 x 10^{12}	51 x 10^{12}	58 x 10^{12}	74 x 10^{12}/yr
D	152 x 10^{12}	4.7 x 10^{12}	108 x 10^{12}	120 x 10^{12}	42.9 x 10^{12}/yr

(All Figures at Btu/yr.)

Converting into coal at 10,000 Btu/lb., the first column equals 6.3 million tons/year for Case C, 7.6 million tons for Case D. The "payback periods" for external energy are 15 days per year for Case C, and 40 days per year for Case C. Other factors will enter the decision, of course. This example shows the importance of end use efficiencies.

2. Specific Applications Other Than at Federal Level

Industrial use of net energy analysis, both for specific modules and for entire trajectories where appropriate, should be encouraged. The engineering analysis of specific modules should be at a quite detailed level. It will probably indicate means of reducing energy losses (and possibly improving economic factors) and source problems of energy inputs (such as changeable economics or availability).

State government use of net energy analysis should be explored in greater detail before it can be recommended. It may be most useful at broad-brush state energy flow analysis, where states could consider policies to affect energy flows in their states. However, the type of applications will vary from state to state.

Multi-industry research organizations should consider using net energy analysis. The Institute for Gas Technology is conducting studies. These organizations have a variety of interests to which net energy analysis can apply.

3. Constraints in Using Net Energy Analysis

There are opportunities along with problems and caveats in using net energy analysis; problems of institutional and decisional structures are included. These are discussed in greater depth in the body of the CERI report. However, there are several key points to be made.

In applying the analysis to any decisions, the boundaries of the compared trajectories should be identical. If end uses have substitutability, comparisons can be made between trajectories which yield different qualities of energy. Fossil fuel trajectories can be compared with non-fossil fuel trajectories in terms of meeting end uses. (example: coal-electric vs. hydro-electric.)

In using net energy analysis, one must consider the sensitivity of the assumptions and variables. If the application is to be broad policy planning, large scenarios of alternatives, siting, or major R, D & D policy, the data of this study should be sufficiently detailed and valid for application. If one is looking at some systems, site-specific conditions, or particular processes, however, he should make sure that the conditions approximate those of study before he applies the data of this study. (A lower-efficiency power power plant might have a low net energy yield, but if it is used only for peaking power, its presence in the electrical system may be warranted, for example.) The indirect external energies and materials are of sufficient precision that they do not warrant reanalysis of a specific process, especially one which may be a major technological departure from those presented here.

The transportation and transmission data herein are for assumed distances. These can be adjusted for other studies simply by multiplying the CERI data by the appropriate ratio of distances.

If one wishes to adjust the boundaries to reflect specific conditions such as human energy, this could be done. However, it is our opinion that such adjustments will generally add complexity without adding precision. We have excluded such factors because their energy quantities are numerically insignificant. In other words, we do not feel that overall trajectories, as presented here, are sensitive to the numerical quantities of the factors excluded as shown in Figures 4 and 5.

The use of ratios involves a greater sensitivity than the use of numerical net yield data. Ratios are very sensitive to small changes in the denominator. Ratio R-1 is sensitive to changes in the process where internally-generated energy can replace external energy. If a process has this option, it may be wise to develop two accounts for it, with and without the recycling of internal energy.

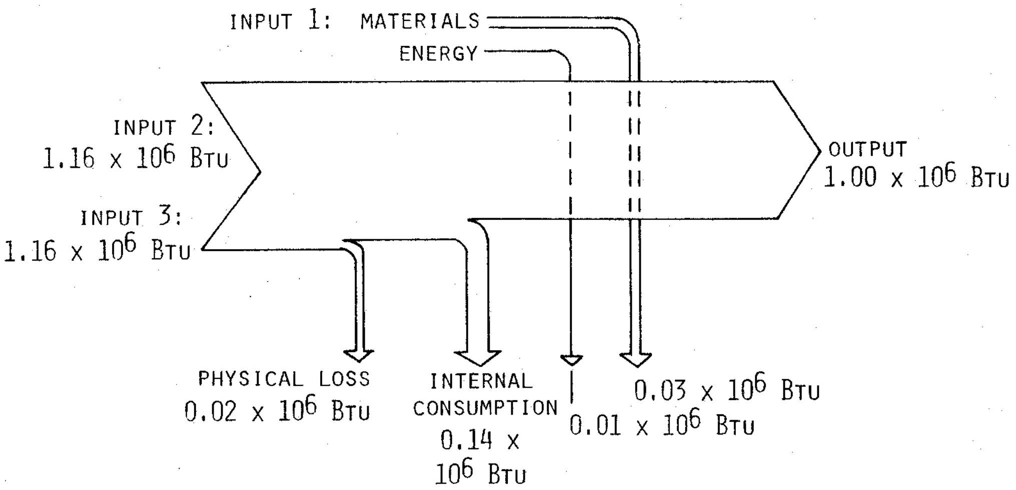
Finally, it is clear that factors other than energy balances must influence responsible decisions and they will generally carry more weight. These factors include: (1) economics, (2) environment, (3) national security, (4) energy mix, end use efficiencies and substitutability, (5) lead times, (6) transportation capacities, (7) institutional restraints such as governmental regulations and incentives, (8) availability of needed materials, (9) available water, (10) local attitudes and socio-economic impacts, (11) employment needs, and (12) needs for energy.

Short Glossary

Selected Trajectory:	A series of extraction, process, and transportation modules arranged to form an integrated energy-producing system. The trajectories selected for this table are typical of western energy-producing systems. They are constructed using representative energy requirements and energy losses of current commercial technology.
Primary Final Product:	The trajectory product for which the energy-producing system is developed.
Percent of Trajectory Products:	The portion of total trajectory output that is sequestered in the primary final product, calculated on the basis of heat content. The remainder of the trajectory energy is the heat content of byproducts.
Initial Resource Required:	The heat content of in-place resource which must be exploited in order to produce 100 units of Final Output.
Unrecovered Resource(1):	The heat content of energy resource unextractable due to current economics and commercial technology.
Initial Process Input(1):	The heat content of resource subsequent to extraction by current commercial technology, which is processed to produce 100 units of Final Output.
Physical Losses(1):	Process losses due to spills, leaks, vents, flares, disposal,etc.
Internal Consumption(1):	Process losses due to use of some Initial Process Input to provide power, heat, etc.
Process. Losses(1):	Loss of heat content from the Initial Process Input during energy production.
Direct Losses(1):	Heat content losses due only to energy directly associated with the energy-producing Selected Trajectory, i.e. goods, fuels, and electricity consumed by the Trajectory Modules.
External Losses(1):	Heat content of energy supplied to the Selected Trajectory from other systems as (a) fuels and electricity and (b) energy sequestered in materials (energy of manufacture and/or heat content of material goods).
Indirect Losses(1):	Heat content losses from other energy systems used to support or supply the Selected Trajectory.
Total Losses(1):	Sum of Direct Losses and Indirect Losses.
Final Output(1):	Primary Final Product at the point of end use.
R_1 - External Ratio(2):	Ratio of Final Output to Total External Losses.
R_2 - Process Ratio(2):	Ratio of Final Output to Total External and Process Losses.
R_3 - Resource Yield Ratio(2)	Ratio of Final Output to Total External and Process Losses, and Unrecovered Resource.

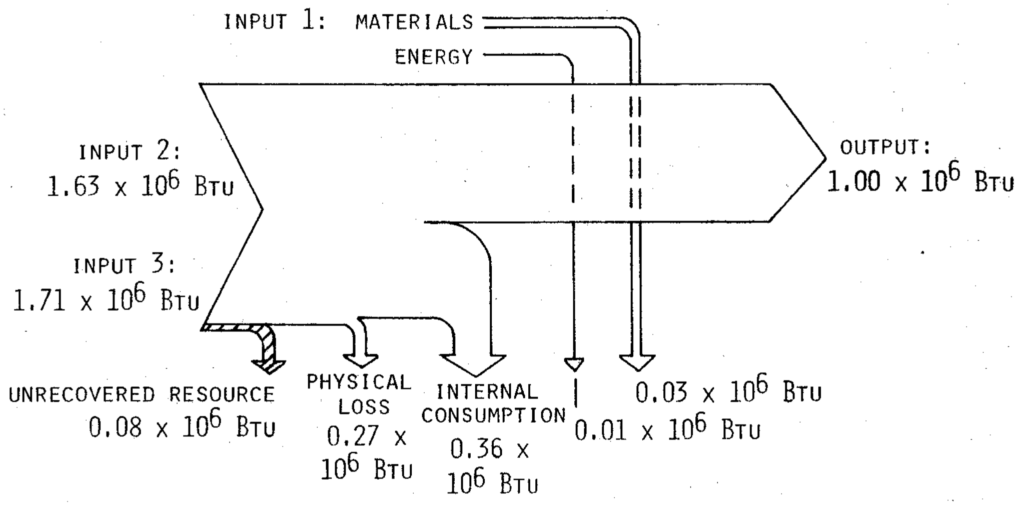
(1) For this item any energy unit (Btu, Joule, calorie, etc.) may be used. However, all items must be assigned consistent units. Numbers are standardized to 100 units of Final Output.

(2) See text for fuller explanation of net energy ratios.



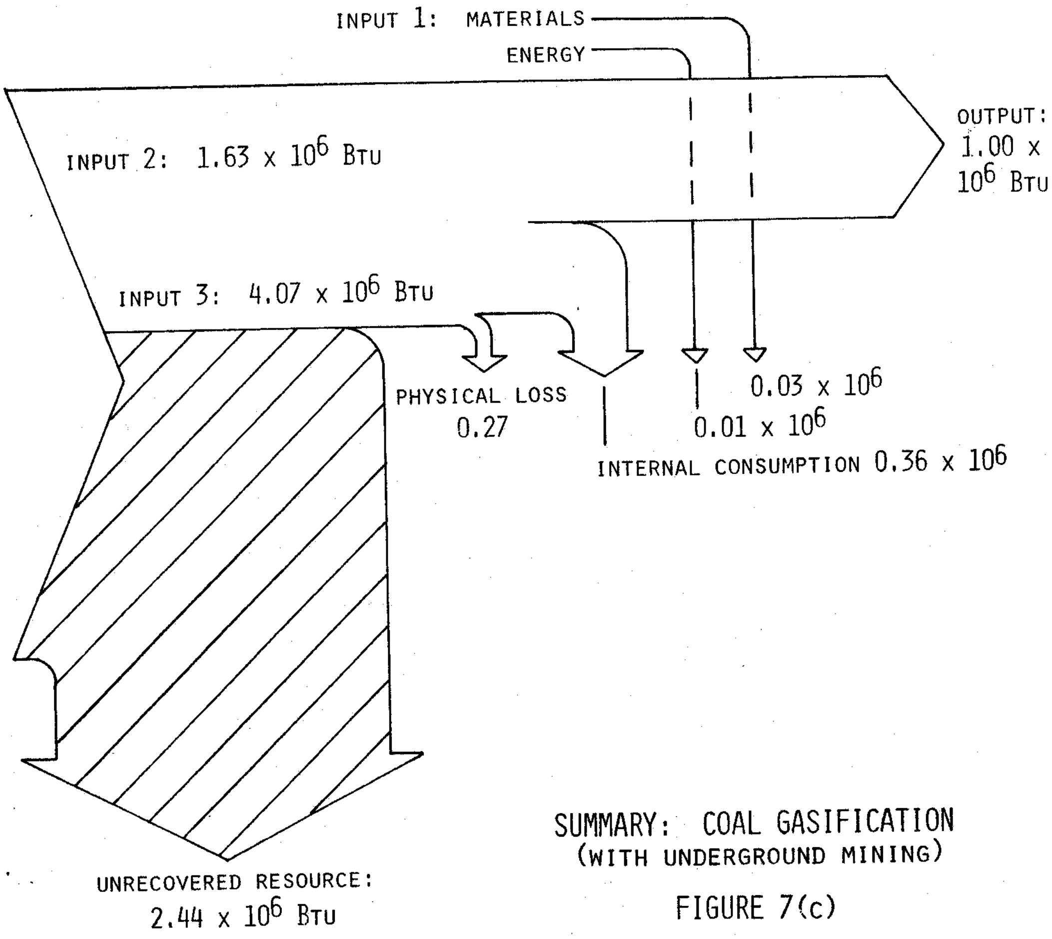
SUMMARY: NATURAL GAS

FIGURE 7(A)



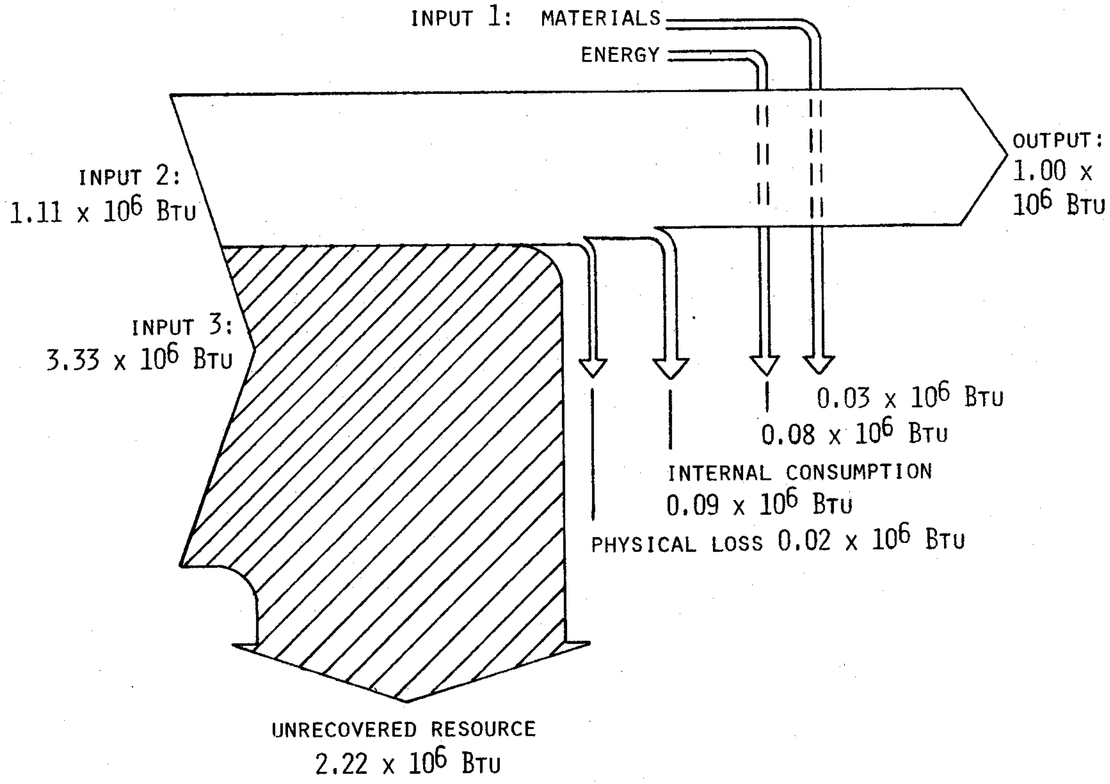
SUMMARY: COAL GASIFICATION (WITH SURFACE MINING)

FIGURE 7(B)

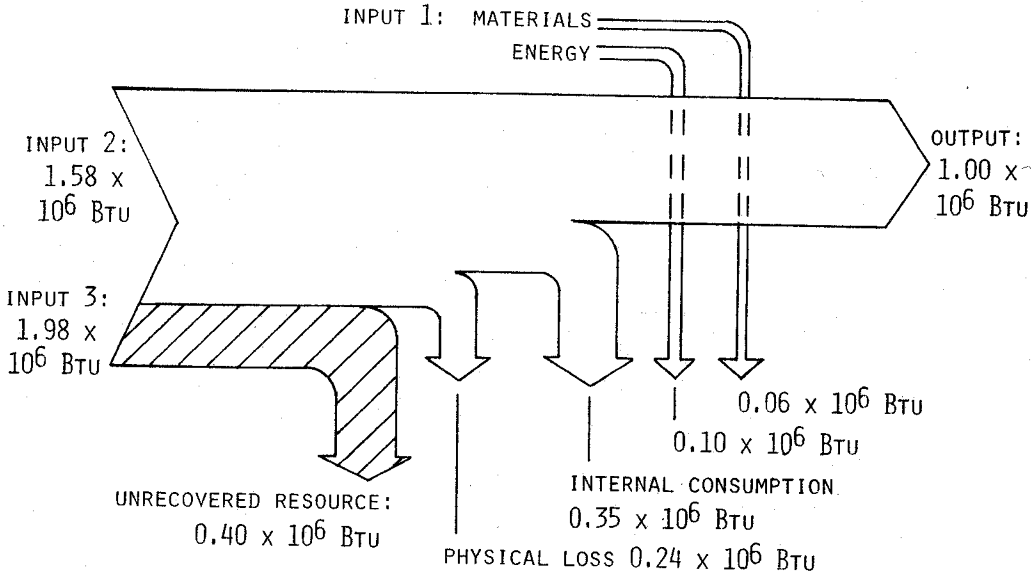


SUMMARY: COAL GASIFICATION
(WITH UNDERGROUND MINING)

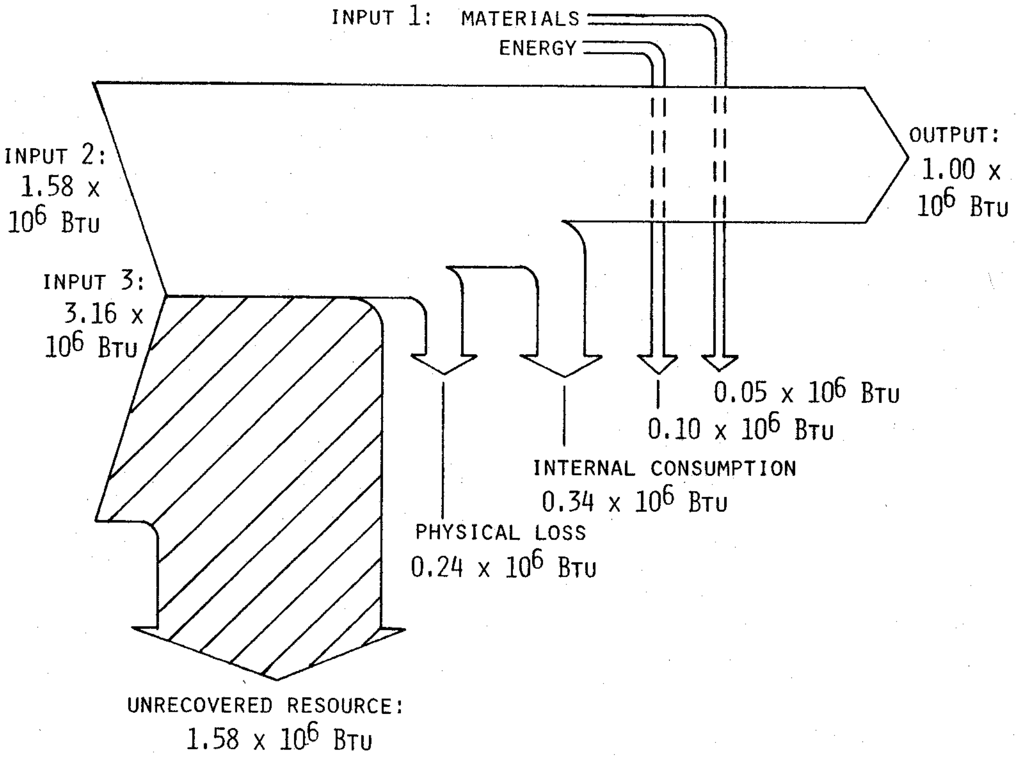
FIGURE 7(C)



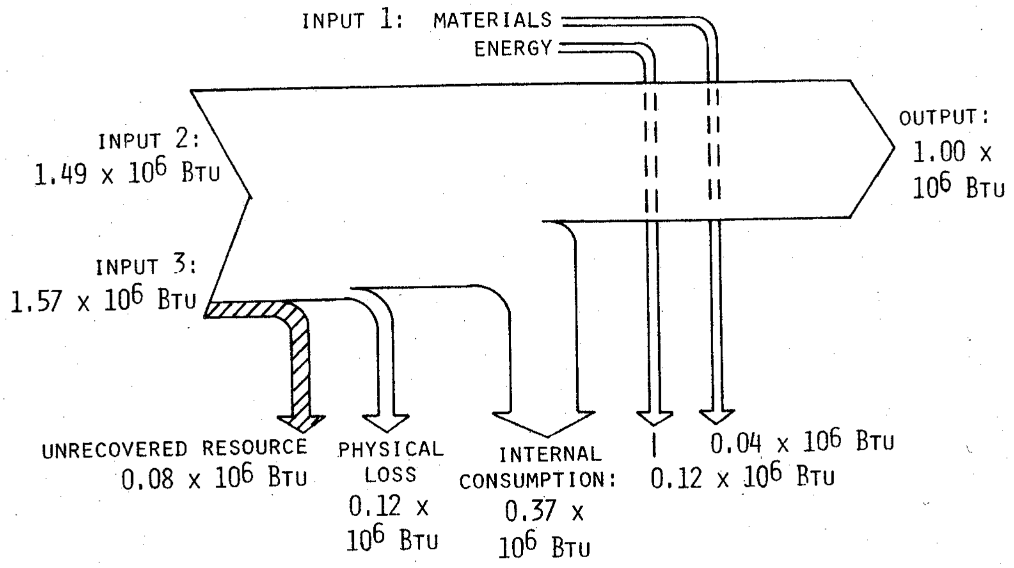
SUMMARY: PETROLEUM - GASOLINE
FIGURE 7(D)



SUMMARY: OIL SHALE - GASOLINE (WITH SURFACE MINING)
FIGURE 7(E)

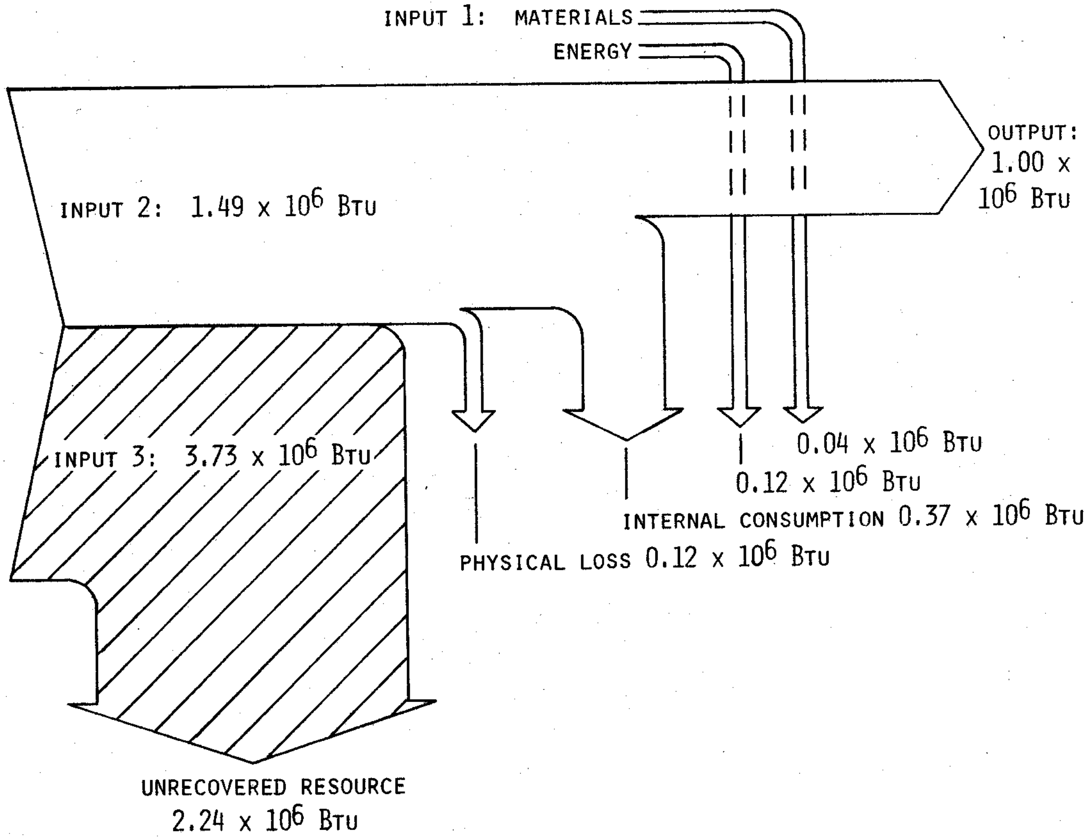


SUMMARY: OIL SHALE - GASOLINE (WITH UNDERGROUND MINING)
FIGURE 7(F)



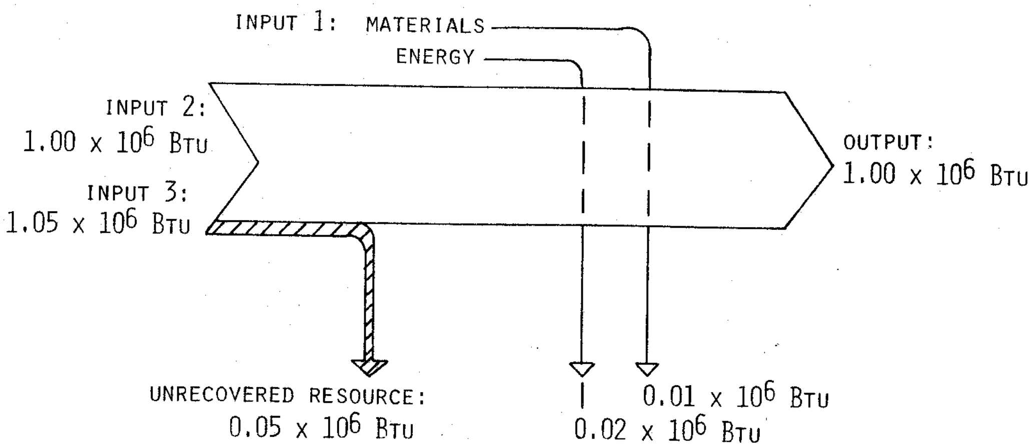
SUMMARY: COAL LIQUEFACTION - GASOLINE (WITH SURFACE MINING)

FIGURE 7(G)

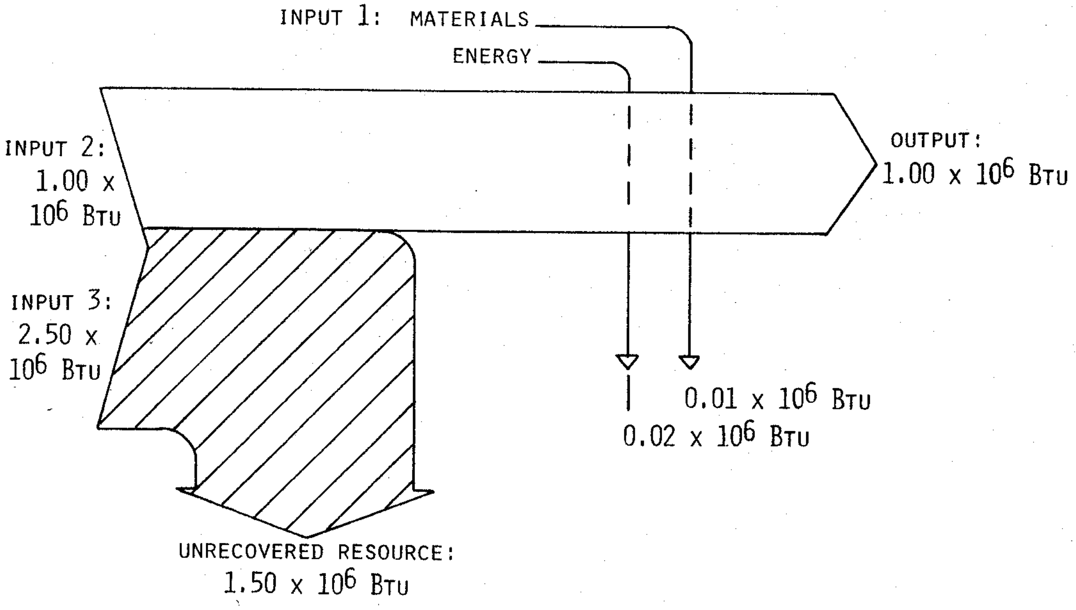


SUMMARY: COAL LIQUEFACTION - GASOLINE (WITH UNDERGROUND MINING)

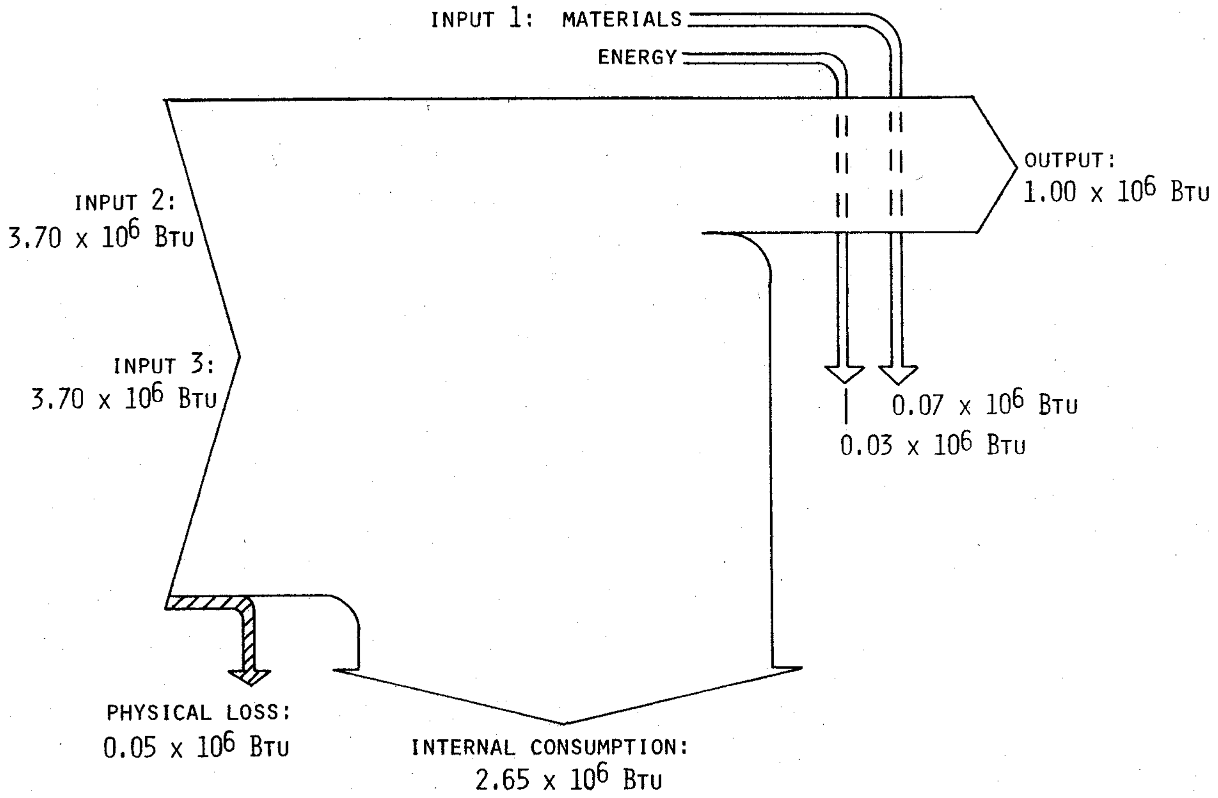
FIGURE 7(H)



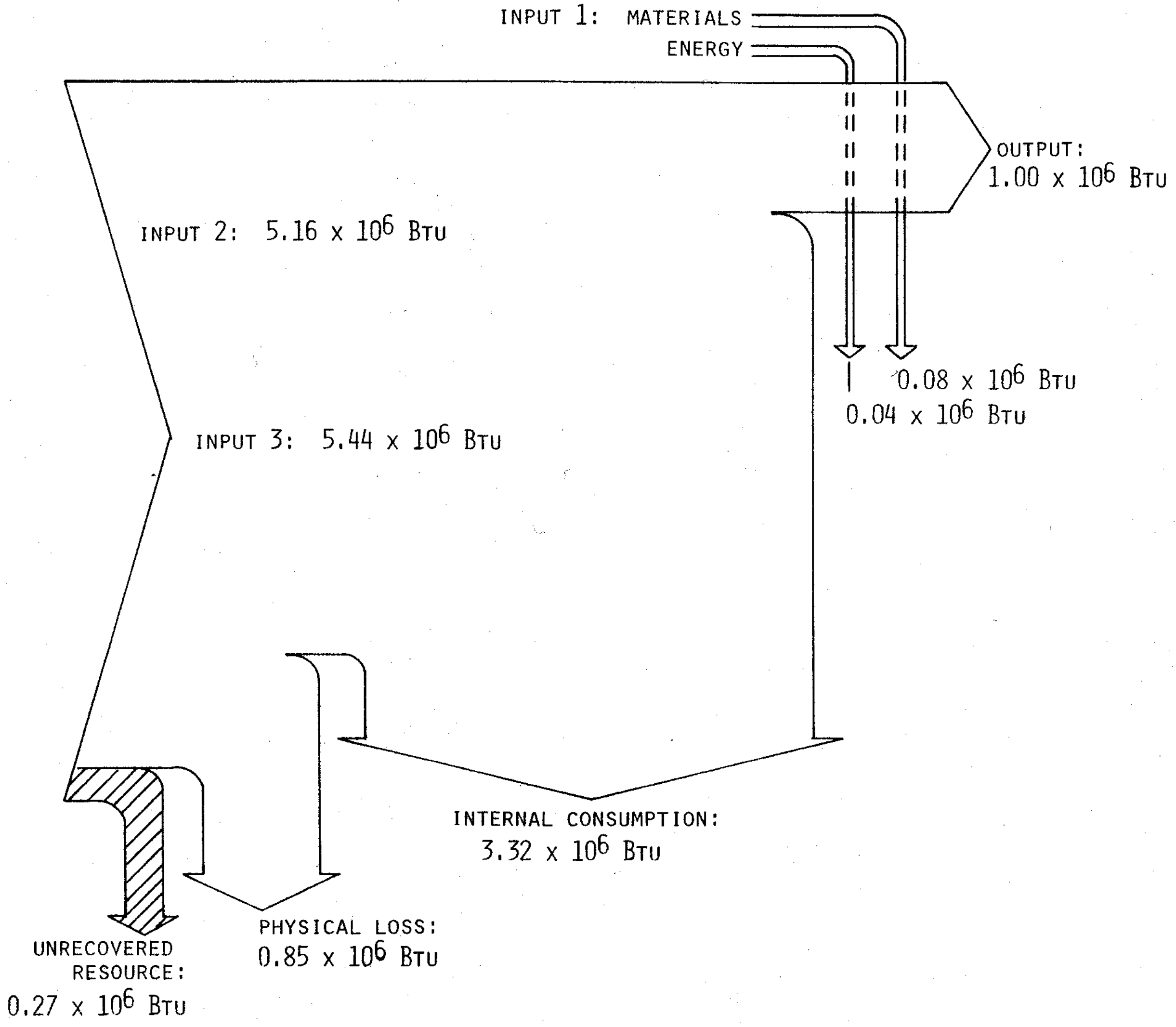
SUMMARY: COAL (WITH SURFACE MINING)
FIGURE 7(I)



SUMMARY: COAL (WITH UNDERGROUND MINING)
FIGURE 7(J)

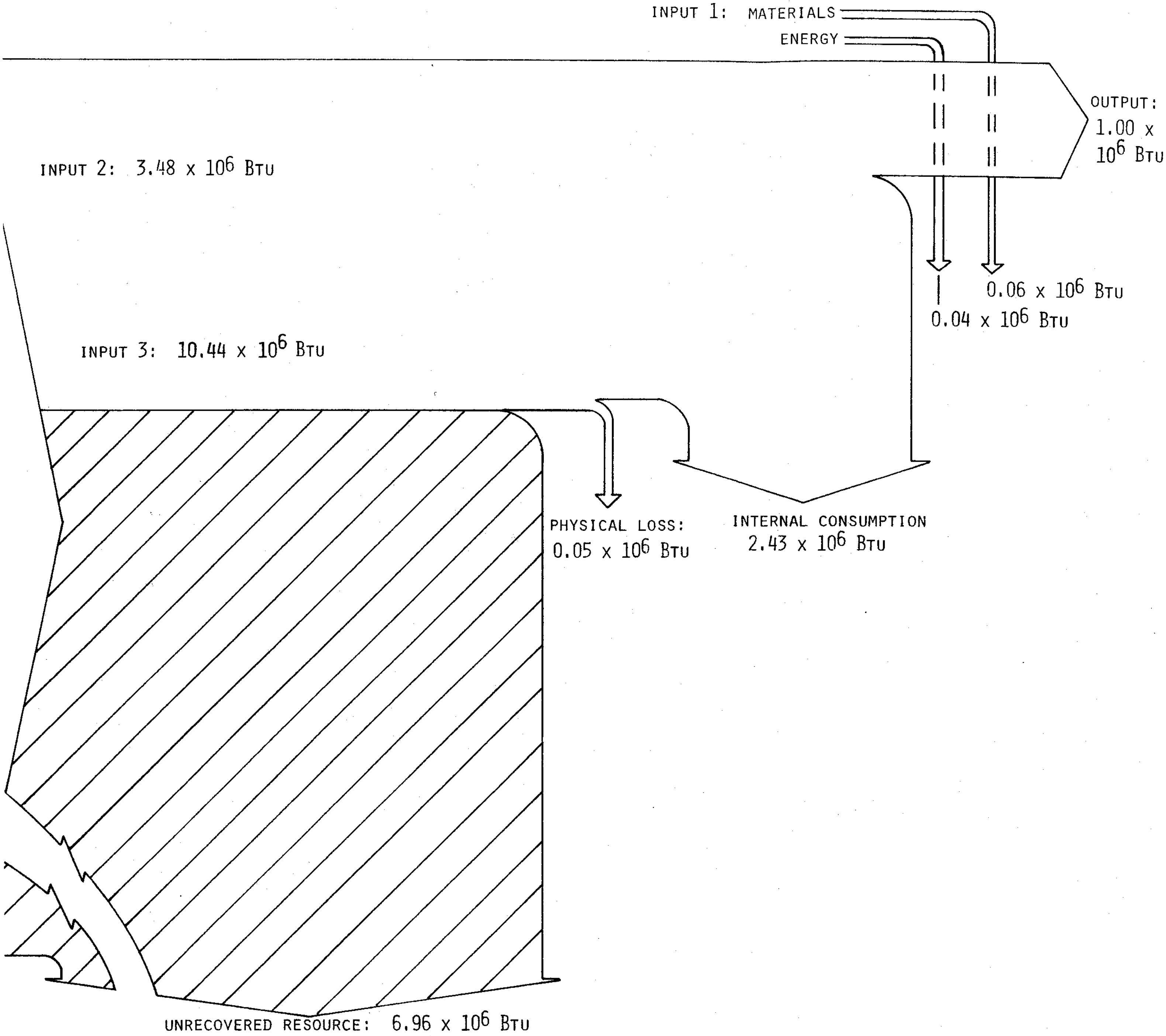


SUMMARY: NATURAL GAS - ELECTRIC
FIGURE 7(K)

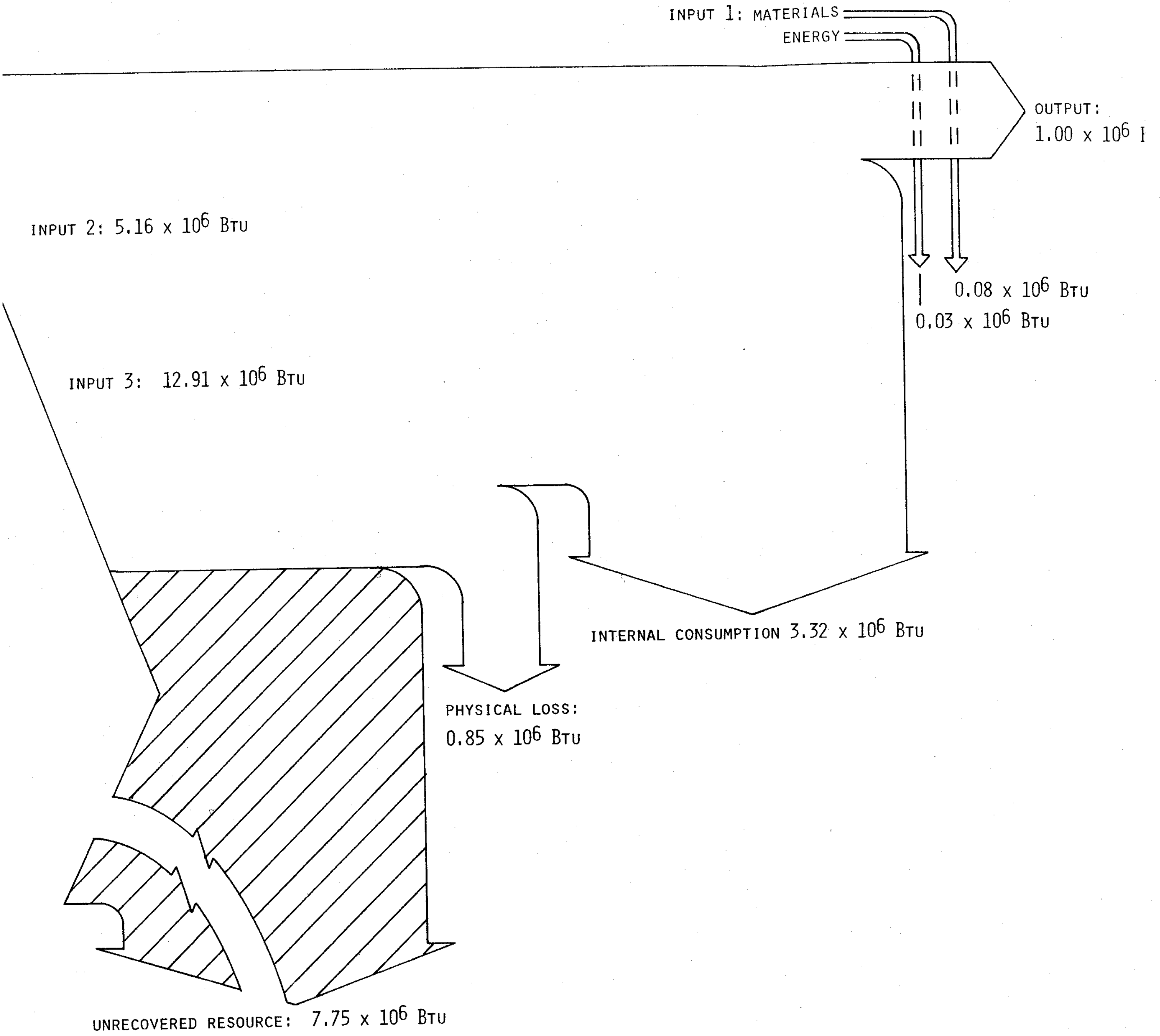


SUMMARY: COAL-GAS-ELECTRIC (WITH SURFACE MINING)

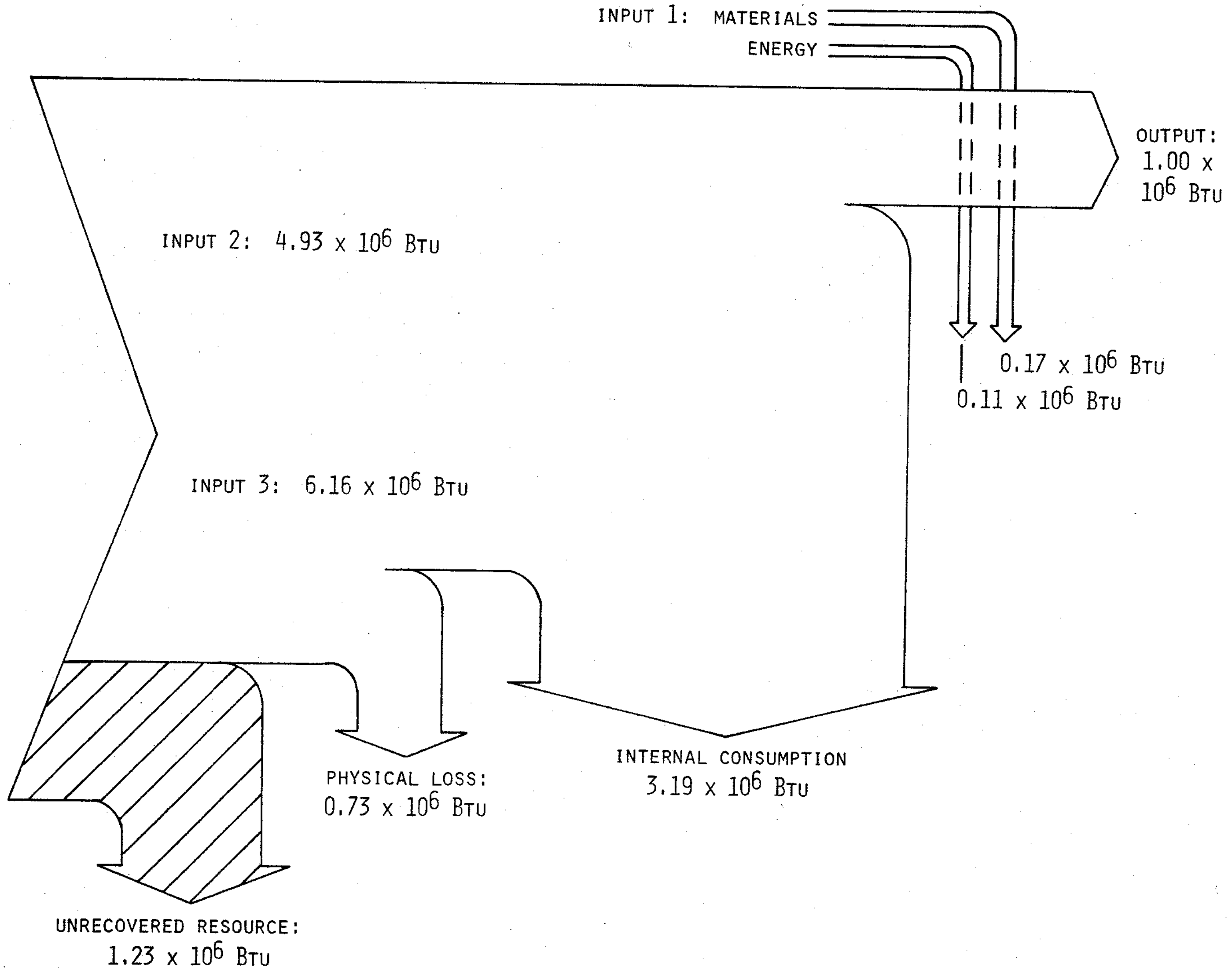
FIGURE 7(L)



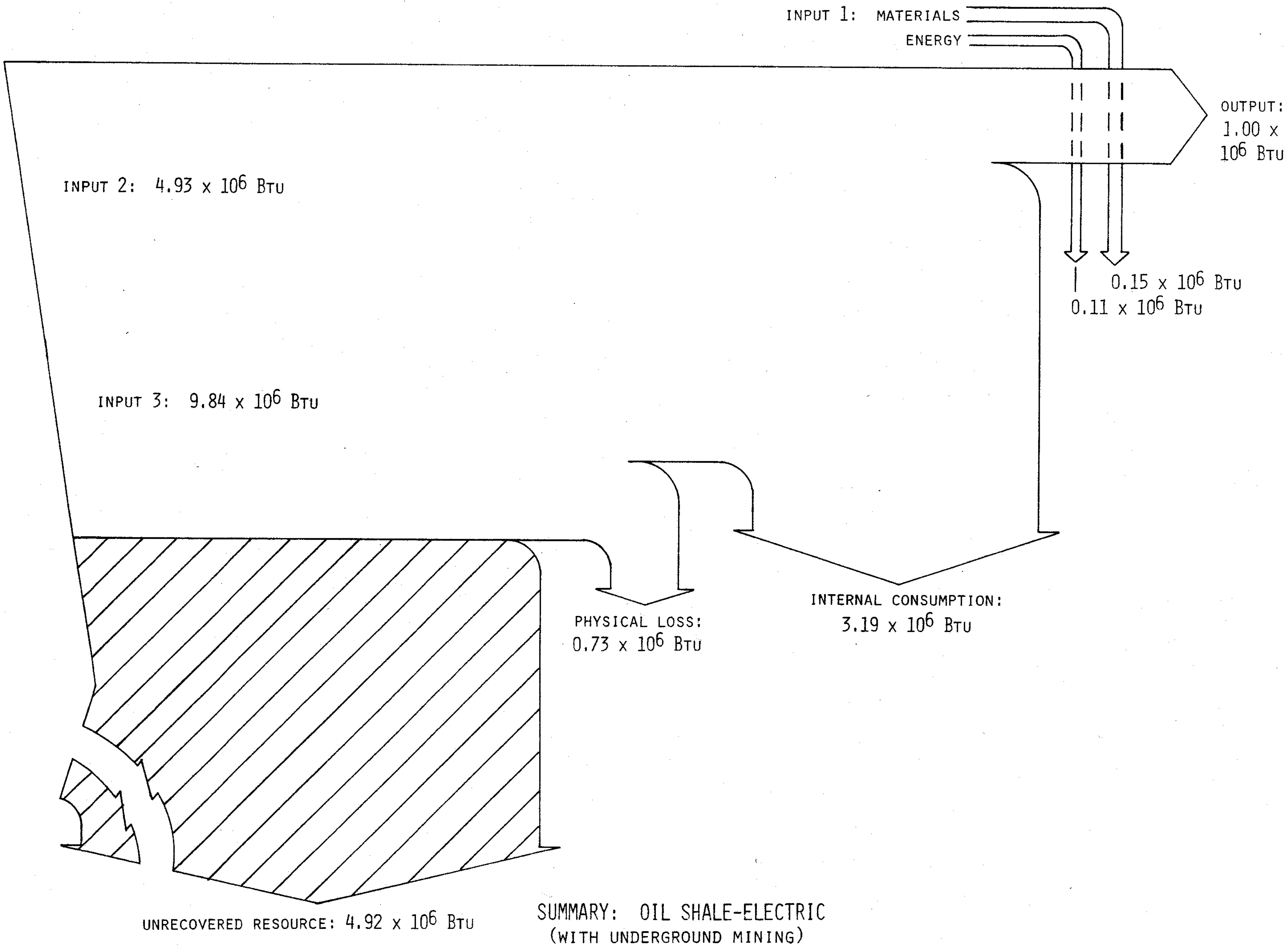
SUMMARY: PETROLEUM-ELECTRIC
FIGURE 7(N)



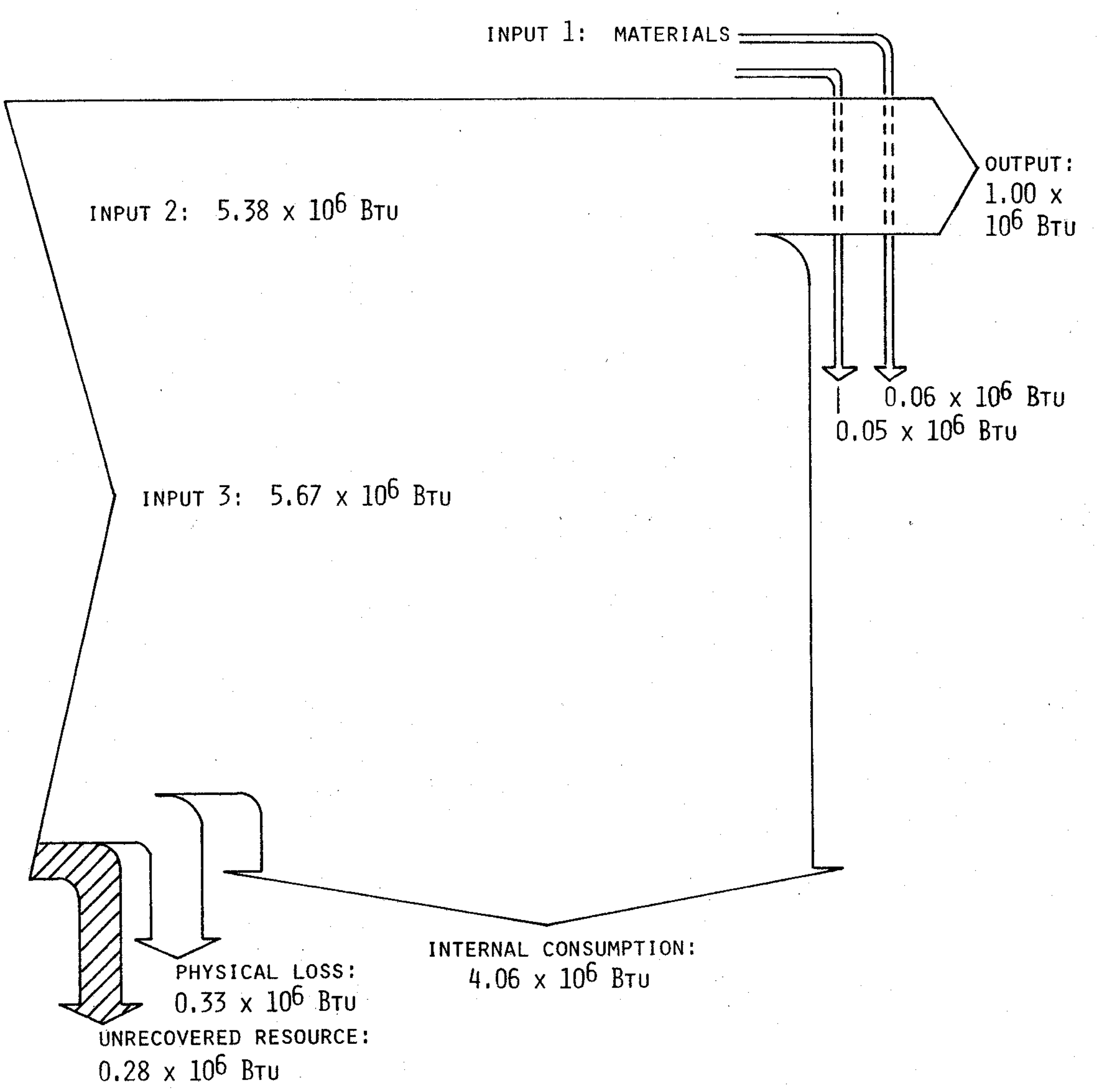
SUMMARY: COAL-GAS-ELECTRIC (WITH UNDERGROUND MINING)
FIGURE 7(M)



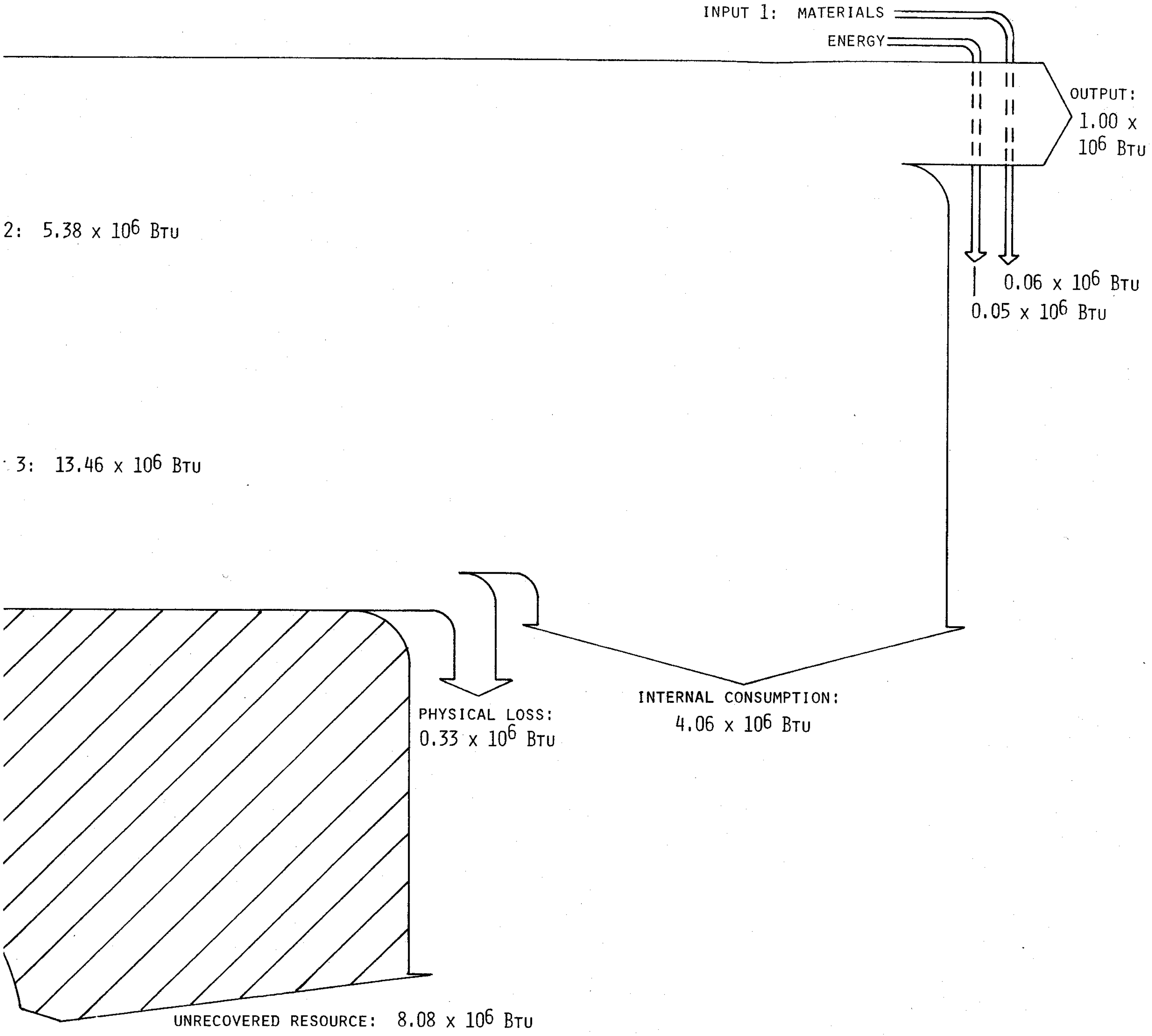
SUMMARY: OIL SHALE-ELECTRIC (WITH SURFACE MINING)
FIGURE 7(o)



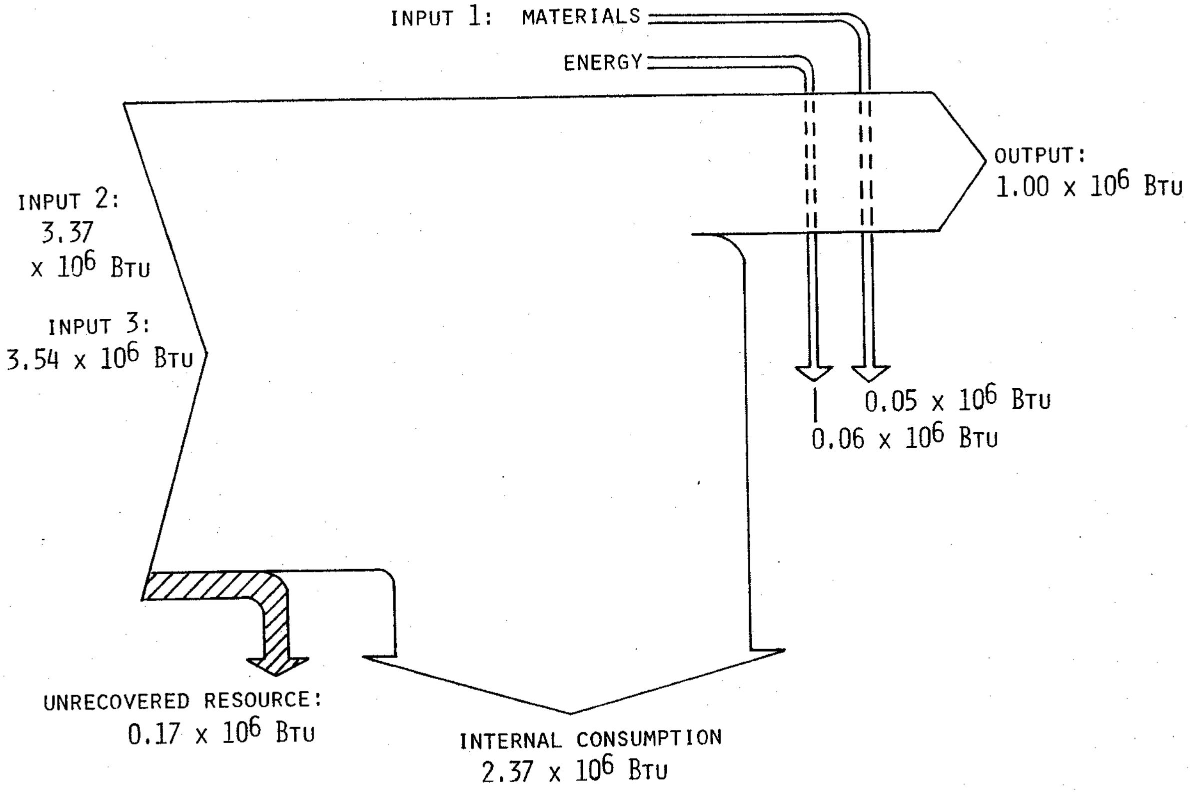
SUMMARY: OIL SHALE-ELECTRIC
(WITH UNDERGROUND MINING)
FIGURE 7(P)



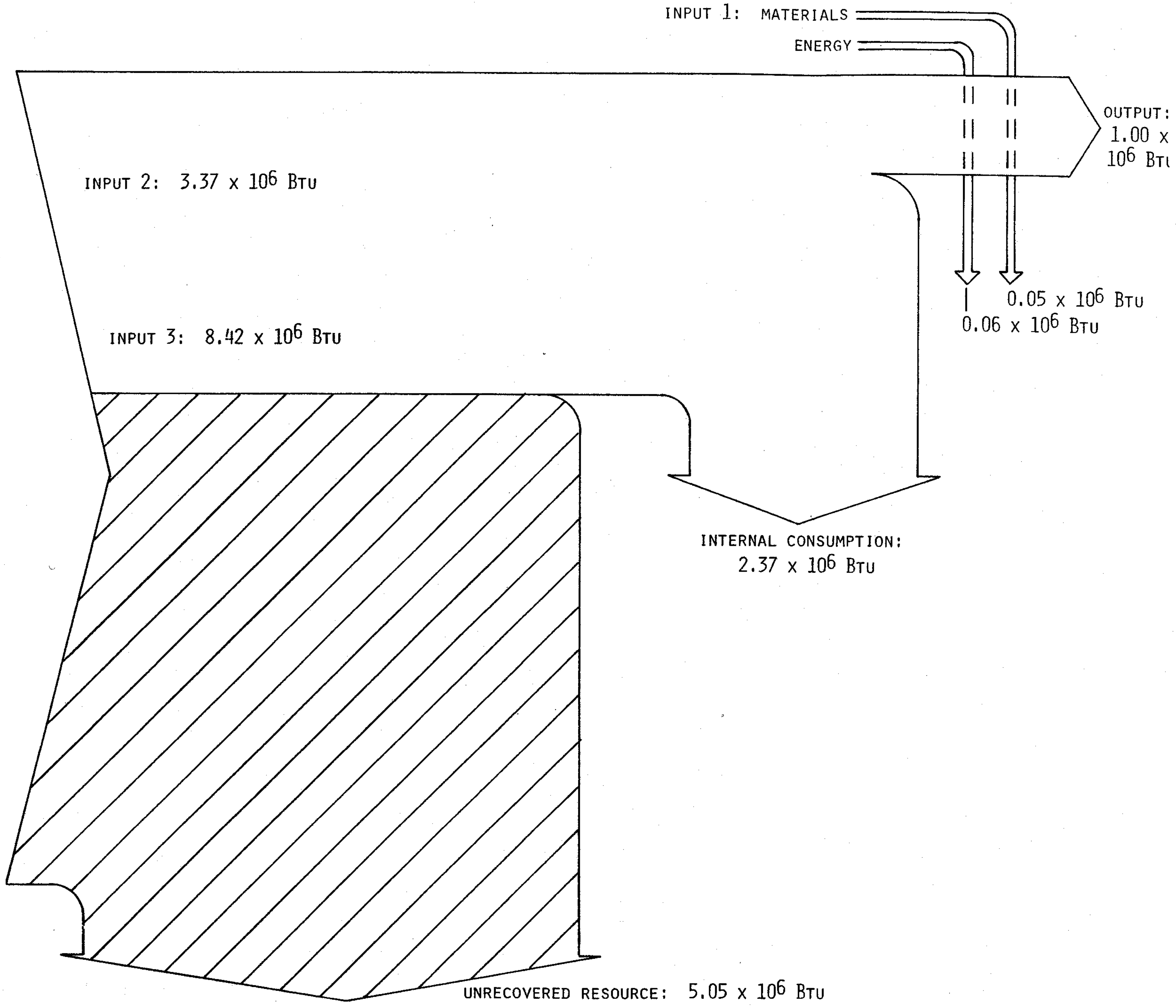
SUMMARY: COAL LIQUEFACTION - ELECTRIC (WITH SURFACE MINING)
FIGURE 7(Q)



Y: COAL LIQUEFACTION - ELECTRIC (WITH UNDERGROUND MINING)
FIGURE 7(R)



SUMMARY: COAL - ELECTRIC (WITH SURFACE MINING)
FIGURE 7(s)



SUMMARY: COAL - ELECTRIC (WITH UNDERGROUND MINING)
FIGURE 7(T)

III. DISCUSSION OF NET ENERGY ANALYSIS AND THE CERI APPROACH

A. Definition of Net Energy Analysis

Because it is a new concept and analytical technique, "net energy analysis" does not have a history to help in understanding what it is and what it is not, or what it tells us.

In the simplest terms, net energy analysis is an analytical tool for assessing the amount of energy required to produce and deliver energy.

"Energy analysis" is a broad term which we can apply to a number of types of energy studies. These could include national, regional or state flows and systems of energy production, distribution and consumption. They could include manufacturing processes to determine the quantity of energy sequestered in products, such as steel or automobiles. Examples of national energy analysis include the Reference Energy System and the Project Independence Evaluation System. The former, developed by Brookhaven National Laboratories and used by the Energy Research and Development Administration, traces energy from resource to consumption through the many intertwined pathways which comprise a total system.(1) It quantifies flows and efficiences in energy conversion and transportation. The Project Independence Evaluation System is a linear programming model which has been developed by the Federal Energy Administration to assess domestic energy production, consumption and import alternatives for a comprehensive array of energy types under varying assumptions of price.(2)

At the state government level, a number of analytical tools have been developed, and assessments made of state energy flows. These latter studies are sometimes called "input-output analyses."(3) Usually, they examine imports, production, exports and consumption patterns of the total energy flows of a state.(4) States have analyzed the dollar transactions of their economies for a long time. Now, it is recognized that they must know more about their energy. However, these studies have not, in general, examined indirect flows or "net yields" of energy. Many types of energy analysis models exist.(5)

Net energy analysis does not apply to the manufacturing of non-energy products. For this purpose, various people have developed an approach known as "process analysis." It examines the entire sequence of steps leading to a product, and accounts for the energy used in each of these steps. For example, the manufacture of aluminum uses energy in: bauxite mining, caustic mining and steam production in the Bayer process; cryolite and anode preparation in electrolytic reduction; transportation of materials, etc. All of the energies involved in these steps are identified and quantified in "process analysis."(6,7)

Energy analysis also covers the study of ecological energy flows, many of which are becoming more useful to industrial society. These include solar, wind, ocean, biological and other "natural" energies. It is also an analytical tool used in ecology and environmental analysis.(8) Energy transactions between the human population and its total environment are the concern of this type of energy analysis.(9,10,11)

Energy analysis has developed in the last few years as society suddenly became aware that the days of cheap and plentiful energy are numbered. The energy costs, in monetary terms, of goods and services and "life styles" has been only a small percentage of overall costs in the past. The finiteness of fossil fuel resources has not been widely recognized until recent years.(12) Now, as energy analysts have noted, "Energy may become a real limiting factor in many vital sectors of society because the resources are limited and because the extravagant use of energy may have unbearable consequences. The continuing energy crisis is leading to a new awareness that we need to know how much energy is used in producing goods and services".(13)

In contrast, "net energy analysis" has a narrower definition. It is limited to energy production and conservation. The "Stanford Workshop" on Net Energy Analysis, noted that the field of energy analysis generally is directed to the computation and measurement of energy flows in society.(14) Net energy analysis is more restricted, being directed to the energy required to deliver a specified energy product to a selected point or stage of use.

Net energy analysis deals with the total energy investment which society must make to produce energy. Using physical units instead of monetary units, it leads to the identification of all the inputs, direct and indirect, involved in every step of the process of extracting, converting and distributing energy.

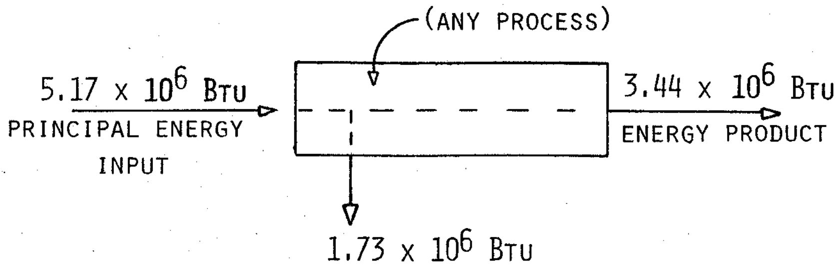
The indirect energy which must be drawn from society and nature to produce energy has attracted the attention of net energy analysts. The direct energy to operate a process in the production of energy may be readily discernible. For example, a refinery requires energy from some source for cracking, pumping, etc. But that energy alone does not enable petroleum products to be made available to society. Also required was energy to build the refinery. Energy was used to produce the steel from which the refinery was built, and to produce the catalysts needed for continuous operation of the refinery. Also, energy was used to extract, mill and smelt the ores which were the sources of the steel and the catalysts.

Net energy analysis asks questions such as these: Are indirect inputs large or small; do they vary significantly between alternatives which may be available for delivering various forms of energy to the end users? Recognizing the finiteness of some energy resources, and the possibility that the output of energy may require increasingly large total inputs of energy, can the net energy resource made available to society be analyzed?

The monetary costs of all the direct and indirect inputs into the refinery can be accounted for, but what percentage of these dollar purchases are labor or materials, and what amounts are allocated to direct or indirect energy? What energy occuring in the ecosystem is involved in the refinery example cited above?

The difference between net energy and efficiency are important. The difference can be illustrated by a simple analysis. Figures 8(a) and 8(b) show the energy efficiency and the net energy analysis of a hypothetical process; the process is represented by the box, with inputs and outputs. The first figure, "efficiency," shows only the ability of the process to change energy from one form (or place) to another. It measures the direct output as a percentage of the direct input of the energy which is processed. This

EFFICIENCY:



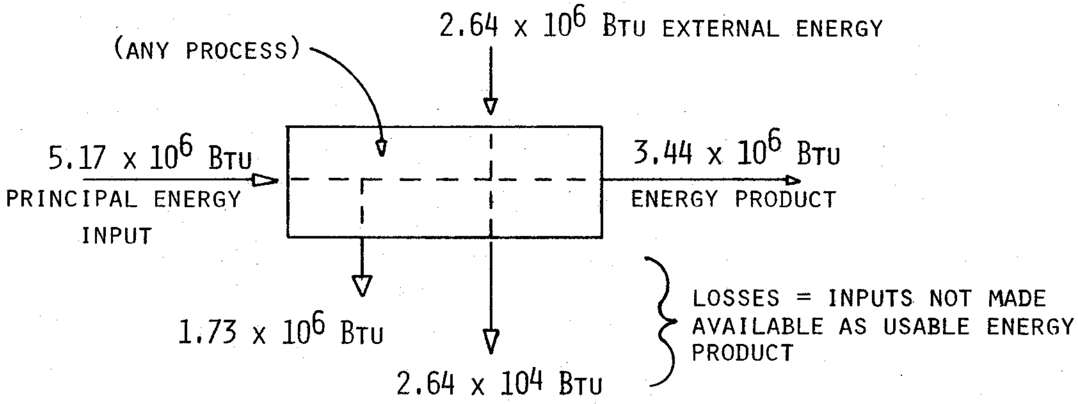
$$\text{EFFICIENCY} = \frac{\text{ENERGY PRODUCT}}{\text{PRINCIPAL ENERGY INPUT}}$$

$$= \frac{3.44}{5.17} = .655 \text{ OR } 66.5\%$$

EFFICIENCY CAN NEVER EXCEED 1.00 OR 100%

FIGURE 8(A)

NET ENERGY



ENERGY BALANCE: INPUTS = OUTPUTS, OR (INPUTS) - (OUTPUTS) = 0

NET = OUTPUTS - LOSSES

$$(3.44 \times 10^6) = [(1.73 \times 10^6) + (2.64 \times 10^4)]$$

OR

$$\text{RATIO} = \frac{\text{OUTPUTS}}{\text{LOSSES}} = \frac{3.44 \times 10^6}{(1.73 \times 10^6) + (2.64 \times 10^4)} = 1.96$$

NET ENERGY AND EFFICIENCY
FIGURE 8(B)

of goods and services are under consideration. We cannot compare apples and oranges directly, but when we know that oranges are worth $.05 and apples $.10, we know that the value of an apple is the same as that of two oranges. (We hope that economics and energy analysts will not be disturbed by the use of "apples and oranges" in this example.) Furthermore, if we had 10 oranges and five apples we could say we have one dollar worth of fruit. This one-dollar worth of fruit could then be compared to other items measured in dollar terms and used to judge the options available for spending or not spending the one dollar.

We say that prices reflect the "value" of things because, in a smoothly functioning price system, the resources which are devoted to the production of one item could have been directed to the production of other items. Resources devoted to apples could be reallocated to produce oranges and vice versa. This may not always be the case and to the extent that it is not, problems creep into the price system. Given the example above when we say that two oranges are worth one apple, we are saying that we could reallocate resources from orage production to apple production. In the process we would lose two oranges and gain one apple. If this were not the case the prices of each item would change so as to make it the case. For example, suppose that resources were reallocated from oranges to apples and in the process only one orange had to be sacrificed for each apple gained. Remembering that oranges cost $.05 and apples $.10, persons performing this reallocation are able to gain something (one apple) worth $.10 by giving up something worth only $.05. The incentive is there to perform the reallocation. But it can't go on forever. As fewer oranges are produced they become in short supply in orange markets and their price rises due to the simple forces of supply and demand. Similarly, as apple supplies expand their price falls. If nothing else happens, the price of oranges will rise and that of apples will fall until they are equal. At that point the price ratio (one:one) becomes the same as the technological relationship in production (also one:one).

Incentives for the reallocation of resources might originate in a change in society's tastes rather than in a mere discovery that gains can be had from a reallocation alone. For example, assuming the original prices used above for apples and oranges, suppose that people changed their tastes so as to prefer more apples to oranges than was formerly the case. A shift in demand has occurred so that at the old apple price of $.10 more apples are demanded. This is an indication that the social value of apples has risen and by expressing value in dollars we can say by how much the social value has risen. Since it takes time for more apples to be supplied the price of apples rises, to say $.15 each. Producers look at the old technological situation where resource reallocation allows a gain of one apple when two oranges are sacrificed. Now the sacrifice of two oranges (worth $.10) is justified to gain one apple (worth $.15). As more apples are thereby produced, and fewer oranges, the price of apples falls, and that of oranges rises until they again are in a 2:1 relationship to each other <u>both</u> in terms of price and technological possibilities.

This example is complicated, but not changed, by what economists refer to as increasing costs. That is, as resources are transferred it may become more and more difficult to produce apples from the resources which formerly were used to produce oranges. In any event, it is the technology of production combined with the forces of supply and demand which keep the system in balance.

We should note here that while supply is determined by technical relationships (which give rise to costs), demand exists either in the minds of final consumers (in the case of final consumer goods) or in the need for the items as inputs into further production. But, since further production is eventually determined by the consumer demand for goods and services which require higher levels of processing we can say that demand is a reflection of the tastes and preferences of society. This is where social values come in. These values can only come from the minds of the people who make up society, and in the economic realm these values are reflected in demand. One should note that demand for something may exist even though the item is not produced. This is a result of high costs on the supply side. So, it is a combination of technology and the tastes and preferences of society combined which determine the economic value we place upon something. Changes in either can change the price charged for any given item in the market place.

Energy flows within an economy reflect mainly technological relationships relative to tastes and preferences. We must clearly distinguish between demand for energy per se and demand for the things that energy provides. For example, people demand clean and convenience home heating systems. The cleanest and most convenient happen to be those powered by natural gas or electricity. The demand for natural gas and electricity is therefore (in part) determined by people's demands for certain types of heating systems and not because they have some innate love for natural gas, etc. Further, the preferences of the public for a clean environment, and the willingness to pay something for it, have entered the decision process. If other fuels provided exactly the same quality heat, at the same cost, people's attitude would be indifferent among these fuels and the primary ones in current use. We should also note that price makes a difference. Electric heat is somewhat more convenient and cleaner than natural gas heat. Despite its higher cost, some people prefer it because they prefer the added quality. Others compare the costs with the relative merits of both and choose the cheaper natural gas. The point remains that it is the final product (heat with certain qualities) that is demanded and it is technology that determines how the final product is produced.

On occasion, technological changes which involve energy, and relative changes in tastes tend to move in opposite directions. In agriculture, for example, production has become much more energy-intensive over the recent past as chemical fertilizers and machinery have become much more important in that sector. Nevertheless, the prices paid for many agricultural commodities are lower now than they have been for thirty years. At the same time the proportion of National Income (similar to GNP) generated in the agricultural sector has declined in dollar terms dramatically -- from about 9 percent in 1940 to about 3 percent now. Thus, in the case of agriculture we see, over time, an increase correlation between energy content and either relative value of output or price.

Net energy studies are new and thus definitive statements are difficult to make about how net energy yields and economic costs have correlated in the past. There is intuitive appeal and some scattered empirical evidence that the energy "subsidy" to energy production has grown over time.(18,19) That is, as increased demand is coupled with reserve depletion, increasingly poorer quality reserves must be brought into production. The energy input into extraction of power from these reserves must therefore rise to offset this poorer quality.

Economic or dollar costs of energy and other natural resources, however, appear to have declined at the same time that the amount of energy needed to exploit that resource or energy has risen. Barnett and Morse attempt to determine whether, during periods of rapid growth in the U.S. economy, resource scarcity effects were felt in the form of rises in the relative prices of the products of extractive industries.(20) Their statistical procedures show that with few exceptions technological change has continually outpaced deteriorating resource quality. Prices not only did not rise, but actually fell. Similar findings by Krutilla and by Nordhaus confirm the observation that since 1900, the relative direct cost of production of natural resource products - including coal and petroleum - have fallen over time despite diminishing resource quality.(21,22) Nordhaus raises the question as to whether this trend can be expected to continue and projects that relative prices for energy in the long-run (50 years) are likely to rise on the order of 2.2 percent per year. (By relative prices, we mean the price of energy relative to the price of other things - in this case relative to the general price level.)

The ratio of energy consumption to GNP has fluctuated since 1900, according to Cook.(23) It increased rapidly from 1900, has generally declined since, and has risen slightly since 1965. Cook notes that the ratio tends to be low when GNP is large and energy is being used efficiently, as was the case during World War II.

Over a relatively long period of time therefore a negative correlation appears to have developed between energy cost and the economic cost of energy production. This has been possible through the rapid technological progress that has taken place in the U.S. economy. It is entirely possible that technological progress has permitted the extraction of energy from poorer quality natural resources and at a lower energy cost. No systematic research has been done on this point, and the argument presented by Odum (1971) that energy subsidies are on the rise cannot be fully acceptable until it is done. Failure to recognize this point has led some persons concerned with energy to attribute economic feasibility to energy costs. Gilliland makes this error in attributing economic feasibility in oil shale to the energy subsidy required in production from shale as opposed to other petroleum sources.(24) Her reasoning that shale is now becoming an economically feasible source of oil because the energy subsidy required in other forms of petroleum production has risen is clearly erroneous. Only recently has shale approached economic feasibility because of the jump in oil prices caused by the OPEC activities. However, the amount of energy required to produce a fixed amount of Mideast oil has not changed significantly, even though the price of the product has gone from $2.00/bbl to $12.00/bbl. Rising prices have made all forms of energy production more economically feasible.

While over time there is little reason to expect energy content to correlate closely with price or total value, there is even less reason to expect goods ranked in order to total value to correspond to goods ranked in order of energy content. All different goods are produced by combining a wide variety of resources in different ways and energy is just one of the many resources. Some goods are indeed more energy-intensive than others; but since they all require inputs other than energy, it is not possible to say whether or not energy-intensive goods will have higher or lower value, relatively or absolutely, within the economy.

While economic analysis is much more comprehensive than energy analysis, it nevertheless has weaknesses which are inherent in any measure which in some way expresses the impact of a variety of forces. One of the main weaknesses of the price system as an indicator of social value is that there occur what economists call "externalities."

Externalities are changes in the costs or benefits felt by some secondary elements of society due to the production and/or consumption of the externality-producing item. For example, our use of the services of our automobile produces pollution, an externality because it imposes a social cost (an "external cost") upon other members of society who have to breath the exhaust. The value of the external cost or benefit is not reflected in the price system. We are not forced to compensate persons who are bearing part of the social cost of our driving a car. Similarly, firms hiring skilled labor, trained by someone else, are not forced to pay for the entire "cost" of that labor since they avoid the cost of training that labor themselves. Therefore in the cases where externalities exist, the price of an item which is established by some market mechanism does not necessarily represent a true social valuation of the items concerned. The market-determined cost of driving a car appears too low in relation to social cost, and the cost of labor appears too low to firms hiring ready-trained workers. In the case of these "market failures", information in addition to market prices is needed to arrive at an estimate of what the true social value of an item is.

Prices which do not represent true social value can evolve for reasons other than the existence of externalities. So-called "market imperfections" can be present which permit neither the free allocation of resources nor the smooth adjustment of prices as was used in the earlier apples/oranges example. Government regulation, labor contracts, minimum wage laws, etc., all act so as to limit the extent to which prices are allowed to vary. An example was the recent administered price system for "old oil" produced domestically. While the legal price was $5.25 per barrel, the true social value is closer to twice that amount since if the oil was not forthcoming from old wells it would have to be pumped from new wells or be imported. The price of oil from the latter sources (which is much freer to fluctuate) is in the range of $11-$12 per bbl. Indeed the oil prices determined by the OPEC membership represent another form of market intervention which does not permit free price adjustment. Other forms of "market imperfections" can result from the existence of some monopoly power on the part of producers or consumers, imperfect information, technical inability to substitute productive inputs for each other or merely tradition.

How do economists concerned with public policy handle the appraisal of projects which entail market imperfections? Market prices are only a starting point, and must be adjusted up or down depending upon whether the true social value is determined to be higher or lower than the market price. The most commonly used practice is to determine what are called "shadow prices" or "accounting prices." These are the prices which, if they existed, would represent true social value.(25) We will use the term "accounting prices" to refer to these rather than the other, more ethereal term.

How do we arrive at accounting prices? Unfortunately, at this point, we must resort to procedures which combine science with judgment. On occasion we do have rather precise information which allows us to estimate what prices would be in the absence of market failures. On other occasions we must make judgments based upon whatever information is available to determine the true social costs and benefits of a project. In the recent past we were presented with the ever more costly pollution produced by our economic development projects. Ten years ago public projects were evaluated without making any adjustments for the social cost of pollution. Now all projects are evaluated, in part, with this consideration in mind. Concern with pollution led to the incorporation of the costs of all forms of environmental degradation in the calculation of the accounting prices used in public projects. How economic values are placed on considerations which normally have their impact outside the economic system, and therefore have no market established prices, is described by Kneese et. al.(26) Assignment of non-market recreational values are described by Capel and Pandey(27) and Pope(28). These are no works which are comparable for the subject of net energy analysis. Society may choose, in the future, to incorporate into economic decisions certain energy considerations which have no market mechanisms for their establishment.

The above discussion leads to the conclusion that there is no reason to expect dollar and energy flows to coincide. By knowing only the dollar flow within an economy or within say, an industrial project, we cannot say much, if anything, about the flow of energy through the system. To determine the latter, we need to know much more about the specifics of the case. What kind of project (or economy); what technology; what cooperating resources are, etc. are all relevant questions (and, in fact, the ones being asked by CERI necessary to the determination of what energy flows are. Energy flows are an integral part of the technological interaction of all productive inputs in any given production process. Dollar flows not only help coordinate the combination of energy and other resources, but facilitate the coordination of society's tastes and preferences with the technological possibilities that society has at its disposal. Dollar flows are more comprehensive than energy flows as indicators of social value and quality since their eventual magnitude is a result of a wider variety of interacting forces. Money gives a measurement of both quantity and quality (including the social value of energy quality); the physical unit of energy measurement does not do this.

Could a process which has a small energy yield be economically feasible? Clearly, the answer is yes. This is due to the basic fact that all Btu's are not equal in their social or economic value. It is also true because of arbitrary price controls imposed by governmental actions. Every day we produce vast amounts of electrical power (high value) from other sources of power (coal, oil, etc.). In the process we use up many more Btu's than we produce, but the process is economically feasible because each Btu input is worth much less than each Btu of electrical power produced.

Questions have arisen which relate to how energy balance corresponds to economic feasibility in the empirical sense; how net energy has influenced past energy development, etc. None of these questions can be answered in anything more than a speculative way since energy balance studies are just now being done. Thus, we are only starting to have the empirical evidence upon which to base a statement. Also, as we have found in this study, intensive analysis of economic-energy flow and value relationships would be needed to make correlations for all the modules of this study.

C. Issues in Net Energy Analysis

There are a number of issues associated with net energy analysis. These can be categorized as:

- Energy and resource issues to which net energy analysis might be applied;
- Issues within the confines of net energy analysis itself, such as boundaries, analytical techniques, and accounting systems.

These two broad categories obviously relate to each other. Each will be discussed, and an effort will be made to correlate the internal analytical issues with the broader issues. In some of the discussion which follows, it will be quite apparent that the CERI team has arrived at certain findings or opinions. These then form part of the framework for the analytical methodology of this study.

1. Net Energy Analysis Relative to Energy Issues

As stated in the Introduction and in the discussion of the definition of net energy analysis, there are several general issues to which net energy analysis relates. Indeed, the existence of the issues has led to the concept of net energy analysis. At the broadest level, these are:

- Resources are limited; extravagant use of resources will lead to very serious consequences;
- Technological-industrial societies are becoming very energy-intensive without adequate regard for efficient use of energy;
- Human communities, industrialized or not, are part of ecosystems involving a complex network of energy flows with vast amounts of natural energy which has potential application for human use;
- Socio-political economic decision processes heretofore have not paid adequate attention to energy, its flows and its social costs; as a result, society now faces "energy crises" of various kinds and magnitudes.

Resource depletion has received a great deal of attention in the last five to ten years. Some of the studies dealing with the problem have been controversial. However, there appears to be general acceptance of the conclusion that present trends of resource consumption will result in effective exhaustion of global supplies of petroleum and natural gas, sometime within half a century to a century. Coal supply may be available for a much longer time period but is still finite. Uranium ores in North America may be in potentially short supply, depending on given prospective demands, at reasonable price levels. The rationale for synthetic fuel development is given as the need to develop a replacement for U.S. petroleum, partially to reduce dependence on foreign supplies.(28)

Environmental impacts associated with resource extraction and production are of concern along with depletion. These impacts are directly related to the amount of resource extraction and production activity.

The total use and use rates of resources are of concern. Given a certain level of end-use of energy, and a certain mix of energy products (gaseous, liquid, solid, and electrical energy) for final consumption, the amount of energy resources used could vary with the net energy of the overall system. A numerically significant change in resource use could occur if the final mix were varied. For example, simple analysis reveals that massive electrification using fossil fuels would require about three times as much fossil fuel resources as direct combustion of those fuels for heat, if end-use efficiencies were equal.

However, end-use efficiencies are not equal, and there are possibilities for major improvements in them.(29) Furthermore, the end-use objective is not the consumption of a particular form of energy per se, but the result of the use of energy. Warm buildings, removal of heat by air conditioning and refrigeration, heat for smelting or melting, power and motion in machines, light, information - these are some of the reasons for the transformation of energy. Changes in end-use patterns, traced back through production systems and considering direct and indirect energies, will obviously have major consequences on resource depletion.

Resource extraction results in some of the resources becoming lost or effectively unavailable to society. If the resource in the ground is viewed as capital stock, the mere process of bringing it into productive use may cause a partial loss of the stock. It could be said, then, that the "net" of the system varies with the amount of loss at the capital-stock end of the system. This concept considers the quantity of the resource in the ground (in the case of energy minerals) or the potential energy in hydrological resources as an integral part of the overall human system of energy. Inasmuch as wastage or recovery of this "capital stock" enters into economic decisions about energy production, it seems logical that it sould enter into energy analysis of energy production. The fossil fuel resources in the ground are the "gross energy" from which we get a net yield.

A host of questions arise. Can the mix of production trajectories from resource extraction to the point of end-use be affected with the result being less resource consumption? Can the net energy yields of the overall system, including the raw resource, be improved by reducing the amount of raw resource which is lost, wasted or made unrecoverable as a result of extraction? The National Environmental Policy Act calls for "wise stewardship" of the nation's resources; can net energy analysis help achieve "wise stewardship"?

Technological efficiencies, and efficiencies of energy use by industrial societies, have not represented a major concern until the last few years. Engineers have devoted attention to the problems in design, to a limited extent. However, decisions are generally made on an economic basis, and if a more energy-efficient process has been less economical, it generally has not been adopted. As has been noted, the energy sequestered in products or services are not explicitly identified.(30) A major cause of this situation is the low cost of energy relative to labor, materials, interest and other costs in the production of goods and services. In some cases, the energy costs may be artificially low because of regulation, or because their true social costs (such as environmental impacts) are not internalized. Given the possibilities and limitations in our capabilities to substitute end-uses of energy, can the overall system of industrial society be altered to produce a given amount of goods and services with less total energy consumption and resource impact? Are there theoretical maximums of efficient use of energy which can be achieved in accomplishing tasks or improving net energy yields? Do geographic and locational parameters affect net energy yields, i.e., are facilities situated because of economics, labor supply and politics to the detriment of the net energy yields of the system? Are there net energy benefits or disbenefits due to the scale of facilities? In energy production systems, how can the direct and indirect "driving energies," whether procured from outside the processes or from inside them by tapping produced energy, be reduced?

There are additional issues relating to time relationships, and flows over time, called "intertemporal flows." Does discounting, as is done in economics to determine present worth of future benefits, also apply to net energy analysis? What are the time and reinvestment relationships for diverting energy into energy production instead of into goods and services?

Ecological relationships of man and his environment involve energy flows. This is true for all organisms, as energy is the essence of life. Primitive societies depend almost entirely on rather short-time flows: solar energy to vegetation to man, or vegetation to herbivore (and sometimes thence to carnivore) and to man. Industrial man now multiplies energy through machines. He obtains most of the energy to build and operate the man-made part of his complex environment from fossil fuels - the solar energy of hundreds of millions of years ago. Just as his economics have ignored energy accounting, his economics have not always included transactions between man and his natural environment. The technological and population explosions have caused man/environment transactions which have overstressed the environment in places. Hence, in recent years, "environmental accounting" has found its way into decision-making to compensate for deficiencies in the economic system, and to identify the means by which man can develop a sustainable relationship with his environment.

Because this sustainable relationship includes the depletion and impacts resulting from the consumption of energy resources - especially the "paleosolar" energy of fossil fuels - and because energy transactions or flows link all living organisms together, there is some thinking that the energy should be the dominant unit to represent all transactions. This school of thought is called "energetics" and is based on a theory, sometimes called the "energy theory of value."

The concepts and methodologies of the school of "energetics" are not widely accepted either by ecologists or by students of net energy analysis.(32) However, it is well recognized that industrial energy production involves natural energy flows. A conspicuous problem has been waste heat from power plants, with some examples of severe disruptions of the ecosystems of receiving waters caused by waste heat. The ecological principle of "limiting factors" is one reason why disruption occurs: organisms have a limited range of tolerances. Other disruptions from pollutants and usurpation of habitat occur as well. If the ecosystems are producing food for man, the energy flow relationships become more direct. This would occur if a power plant disrupts an estuary, or a mine takes agricultural land out of production. There are potentials and actual examples of using "waste heat" to increase food production.(33) These ecological energy transactions are legitimate issues, and are being examined in the better studies being conducted according to the requirements of the National Environmental Policy Act. Now, there are many studies underway to utilize ecological energy to replace our diminishing supply of fossil fuels.

These issues of resource depletion, technological efficiency and ecological energy flows can involve net energy analysis. If this analytical tool is useful, we must consider how to use it, and how government should apply net energy analysis. Should government foster or discourage various energy systems, developments or policies using net energy yields as a consideration? This is the obvious implication of PL 93-577 of 1974, "The Federal Non-Nuclear Energy Research and Development Act of 1974," and an implicit concern of PL 93-438, the "Energy Reorganization Act of 1974" with its phraseology about efficiency in energy extraction, conversion, transmission and utilization. There may be other areas of Federal decisions which could produce benefits by the use of net energy analysis. State governments could bring net energy analysis into their decisions. California requires the analysis of net energy in consideration of the issuance of siting permits.

There could possibly be established a minimum threshold of net energy yields which would provide a cut-off point for any sort of governmental approval. Guidelines could be established for actual use by various agencies of government. Or, perhaps all aspects of net energy analysis should be left to industry, which is making rigorous efforts to improve its energy efficiency. Factors other than net energy must be considered in decisions; how much weight should net energy yields have relative to these other factors?

Last, but not least, should the entire matter of "energy costs," in whatever form, be left to traditional economics?

2. Issues Internal to Net Energy Analysis

In August, 1975, The Institute for Energy Studies of Stanford University, and the TRW Ssytems Group, conducted a Workshop on Net Energy Analysis, sponsored by the National Science Foundation. The Report states: "...(This summary's)... lack of specifics is probably a fair reflection on the state of energy analysis as an emerging discipline. Persons looking to this report as a 'cookbook' of instructions on how to do it may be disappointed. The participants, however, knew from experience the pitfalls of simple recipes and were very reluctant to proliferate them."(34)

The gist of that statement is that there are unresolved issues about the methodologies of net energy analysis. In general, these are:

- what are the boundaries of the system to be analyzed?
- what "accounting methods" are appropriate?
- to what extent should the analysis be made using the properties of chemistry and thermodynamics?
- what data, including the use of economic data as a surrogate for physical energy data, are needed and available?
- how are time dynamics to be handled in the methodology?

This section will discuss some of these issues and will present some recommendations and our findings.

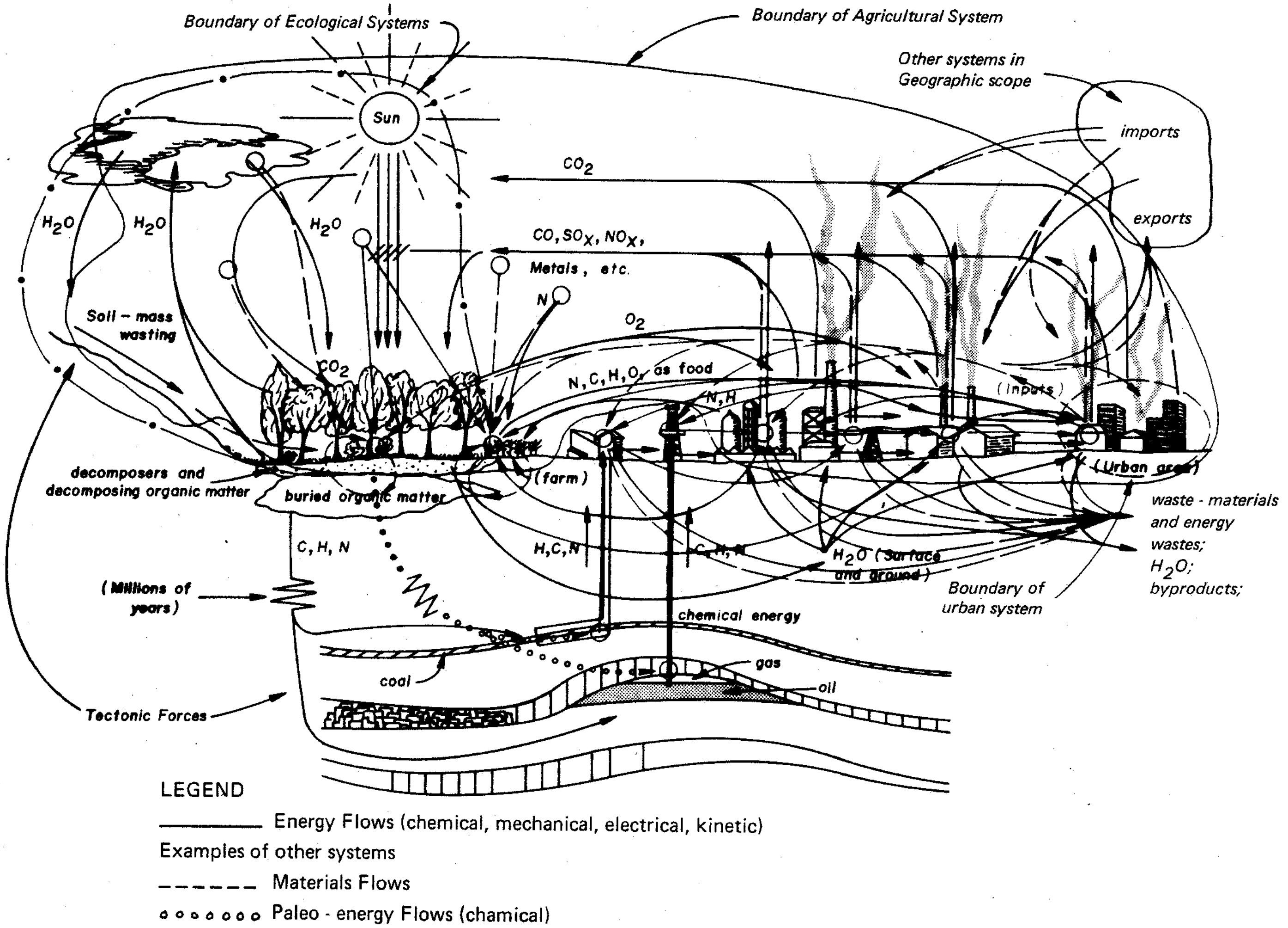
D. Boundaries

1. General

System boundaries have varied in different studies which have been made. The CERI team has spent considerable time in discussions of this problem in this research project. Imprecise boundary definition, and public misunderstanding of the boundary issues, has caused a lot of confusion about energy analysis. Whether one approaches the question from the purely technical side or the philosophical side or the "policy issue" side, this central problem of boundaries becomes a critical matter.

Boundary identification must deal first with the comprehensiveness of the system, and second with some specific inclusions and exclusions if a less-than-comprehensive system is defined. The concept of "net energy analysis" does not preclude the examination of very large systems including a variety of types of energy flows.

Dealing first with the larger systems, refer to Figure 9, which shows a number of components of an industrial culture. All of these components are related: farm, factory,



ENERGY FLOWS INVOLVING INDUSTRY AND ENVIRONMENT

FIGURE 9

forest, field, fossil fuels, housing, highrise offices, hydrological cycles, and the sun. Energy is one of the flows which link the components. Figure 9 shows some energy flows along with some materials flows. Figure 4, presented earlier, is a simplified representation of Figure 9. The following discussion will address boundary problems pertaining to this comprehensive system relationship.

2. Ecological Boundaries

An issue in boundary definitions is the question of whether to include all of the important components of the entire ecological system. One school of thought in net energy analysis states that the boundary must include all of the linked components of the entire system to be valuable in decision-making; ergo, other approaches will not be valuable. It is worthwhile to examine this approach.

This school of thought generally considers energy to be the sole "numeraire" or unit of valuation of the system. This approach is called "energy theory of value." Within the urban-industrial component of the system, for instance, money would be replaced by energy as the numeraire for transactions. The premise is that the only <u>common</u> flow within and between all components of the universe is energy. Money flows and energy flows would be related, but <u>energy</u> would primarily describe the system behavior.

However, energy flows as energy are not the only linkages. Materials cycle through these components. Some combine to fix energy as chemicals, and other materials may be disruptive of energy fixation. Some of the material cycles are related to energy flows only in an extremely indirect way. An example of a disruptive material flow is the SO_2 from burning of coal, which may cause "acid rain" that alters the environment to which certain primary producers are adapted. Changes in the alkalinity of crop environments are another example of a materials flow which disrupts energy flows. The biogeochemical cycle of the entire Colorado River Basin, where alkali from upstream causes downstream crop losses, is one example; it also illustrates an indirect relation of two energy flows linked by materials flows.

Energy flows are critical throughout the system; but they do not, as a "single numeraire," describe or define the functioning of a system.

Ecosystems have many functions such as transformers, materials cyclers and sinks, habitats and climate and hydrology modifiers. They have many values, tangible and intangible, to humans. When an industrial system depends on these ecological factors, the inputs from ecosystems are sometimes called "subsidies." Obviously, for a primitive society, this ecological "subsidy" is practically the entire total energy subsidy. For an industrial society, it is much lower and may be less than the "subsidy" returned from indsutry to further energy production (see Figure 4). However, the matter of "energy quality" still must be considered. As the system becomes larger and more diverse, the "qualities" of energy become more varied and diverse. Therefore, the reduction of all qualities to a single numeraire leads to more and larger distortions of reality. These problems exists even in analyzing a system such as the industrial fossil fuel production system. A Btu of electricity is not equivalent to a Btu of coal or a Btu of natural gas in thermodynamic properties, utility, or social value.

There are a number of pragmatic reasons for excluding ecosystem energy flows from a generalized study of industrial energy production. First, energy flows in ecosystems may be numerically insignificant. For example, consider the 10-year loss of primary production of an irrigated alfalfa field if it is disturbed to recover a 15-foot seam of coal and then restored to alfalfa production. This loss is, in a sense, a social subsidy of the fossil fuel system. However, as in Figure 5, the fossil fuel system also "subsidizes" the agriculture system. The energy from the coal is about 100,000 times that lost in the 10-year disturbance of the alfalfa (f0r coal at 13,500 Btu/lb.).(35) This quantity will be lost in the numerical "noise" or deviations in the industrial system numbers. (Decision-making based on energy values alone would always lead to the loss of the alfalfa field, thus ignoring the need for the energy qualities of alfalfa and the other values associated with the alfalfa field.)

Second, ecosystem energy disruption is highly site-specific. Primary production varies from 0.5×10^3 Kcal/m^2/year in a desert to 20×10^3 Kcal/m^2/year in some estuaries and wet broadleaved evergreen forests.(36) Changes in ecosystem energy flows should be analyzed in site-by-site ecological studies associated with specific energy development proposals. The energy flows should be analyzed in the context of the ecological analysis, and concepts such as beneficial use of "waste" heat could be considered.(36) Detailed process and ecological studies of the site and a specific proposed energy industry would be needed.

Third, distance and time factors are highly variable. An energy industry in the Piceance Basin of Colorado may cause energy disruptions in Mexico due to ecological links; this disruption could be minimized by manipulating farm-caused salt loads from a completely different tributary of the Colorado River. Disparities in time as well as in large geographical boundaries are difficult to deal with.

Fourth, ecosystem energy disruptions may be the result of cumulative effects from many sources. Also, they can be assessed for different conditions: for existing conditions, for conditions under ecosystem management for increased productivity, or for natural successional or climax stages of the ecosystem.

Lastly, the energy produced from a mine or power plant will vary greatly per unit of land surface affected. Coal seams vary significantly, for example. Thus, site specificity becomes highly important to any meaningful analysis. This problem becomes infinitely complex when an entire trajectory of energy production is examined from the mineral resource to the point of end use.

Environmentalists and humanists have worked diligently to expand the factors in decision-making from a single numeraire - the dollar - to a more comprehensive set of values, including intangible values. For example, water resource planning procedures have departed from strict dollar benefit-cost calculations to the new "Principles and Standards" issued in 1973 by the Water Resources Council. These new guidelines require quantitative and qualitative description of a number of social and ecological parameters. No single numeraire is relevant to all these parameters. For example, the dollar as numeraire cannot describe the value of a rare and endangered species such as the Peregrine Falcon. The use of an energy unit would be no more appropriate as a numeraire for such values.

The findings and conclusions of this discussion are as follows. If there are various factors of major significance (materials cycles, energy qualities) in analyzing links between components of a system, or values associated with a system, then a single numeraire is unrealistic. If this is the case, then:

- It will be more helpful to limit analytical boundaries to a discrete subsystem where an assumed numeraire is of primary significance;
- It will be unwise to use large system boundaries without a workable analytical process which includes all the major variables relevant to the operation of the system.

Further research on large systems involving many flows is needed. Models of such systems should replicate the real world and should be aimed toward assistance in decision-making. At present, it appears that the best use of analysis of ecological-industrial systems may be to:

- Find how renewable energy can replace or supplement non-renewable energy;
- Avoid or minimize impacts of industrial processes;
- Use industrial heat to augment natural heat in ecosystems.

3. Human energy

Human energy is another factor which must be included or exclused from the system boundary. Similar considerations apply in this case as in the matter of natural ecosystems.

The energy assignable to a given energy alternative should be the metabolic energy of the workers allocated to that alternative in proportion to the difference in its net energy from that of the alternative to which it is compared. (Metabolic energy is that which is used directly and internally by the human organism.) In other words, if Process A needs 50 workers'energy output, and a less labor-intensive Process B has 40 workers for the same output, then the human energy assigned would be that of 10 workers. (The metabolic energy, rather than "life style" energy, should be assigned. The "life style"energy of an individual should not be assigned entirely to his job.) Life style energy includes the entire urban infrastructure and services consumption of energy.

As with ecosystem energy, the human energy will be insignificant compared to industrial energy. One study states that the inputs to an ammonia process may be 40,000 Gigajoules (GJ) per day compared to the worker household energy use of 0.22 GJ/day (80 GJ/year) per worker; for 200 workers, this is 44 GJ/day.(38)

For a strip mine with 50 men producing 1 million tons/year, or say 2.2 x 10^{13} Btu/year, the metabolic energy would be 50 men times 12,000 Btu/day x 365 days/year = 2.2 x 10^{8} Btu/year. This assumes 100 percent of the human energy assigned to mining and none to any other aspects of the workers' lives, such as recreation or procreation. Therefore, the coal energy output exceeds the human energy by five orders of magnitude.

Another estimate of the magnitude of energy consumption is the following example: In 1967 gross energy consumption divided by value added for all U.S. manufacturing was 59,223 Btu/dollar. Labor accounts for approximately 23 percent of the cost of manufactured goods. Personal energy usage per dollar in excess of the poverty income level is approximately

17,000 Btu/dollar. Approximately 50 percent of an average worker's income is in excess of the poverty level.(39) Therefore energy consumption by labor due to employment is on the order of 0.23 x 50 x 17,000 Btu/dollar or 1955 Btu/dollar. This is only 3 percent of the gross energy consumption in Btu/dollar identified above.

Energy analyses are often employed for comparison of activities. Thus the energy requirement differences and ratios of products or of services are unlikely to be much altered by omission of small and probably similar labor-energy consumption.

Energy equivalents for other effects, such as interest on borrowed money, taxes and basic research are essentially economic transactions divorced from physical transfers. In each case one can follow money flows throughout society, but the result does not seem useful for energy analysis.

One further point concerns the problem of separating producers from consumers. People "wear both hats." All energy which is consumed by society is in some sense produced by society, either by extracting fuel reserves from the earth (mining coal, producing oil) or by harnessing energy which is available on the earth's surface (hydropower, animal labor). Thus while on the average one person consumes a certain amount of energy, he also, on the average, directly or through the stimulus which his activities provide, produces the same amount of energy. The money which he pays may be regarded as buying energy, a consumption, or as indirectly stimulating energy production. We arrive at an impasse from which no useful information can be obtained.

On the other hand, there does appear to be a justification for examining the human energy associated with certain energy production. The Alaska pipeline construction, for example, will undoubtedly require a higher per capita energy use than a comparable Texas pipeline. The difference between per capita Texas energy consumption and per capita Alaska consumption, times the worker-years, could be assigned. However, the ratio of this energy to the energy delivered through the pipeline would probably be very small. We have not examined this in our project.

4. Research Energy

One more boundary inclusion or exclusion matter which has been controversial is research energy. Energy research per se is not directly intended to produce energy. It is usually intended to lead to an energy production improvement or a new process; these latter are then intended to produce energy. Much research is dead-end; that is the nature of research. Also, research results are transferred. For instance, Rankine cycle engines were not thought up for "bottoming cycle" use in solar thermal-electric plants, but they may be so used. The fluidized bed was invented for making coke,(40) but is used in many other processes such as refineries (fluid-bed catalytic cracking). How much of the fluidized bed research energy should be assigned to coke and how much to other processes? Further, if such an assignment were made, the amount of energy would probably be negligible compared with other energy inputs and outputs.

Also, if research energy is to be allocated to some ultimate production, then one must have some idea of what the ultimate quantity of that future production will be.

For these reasons, it seems proper to exclude research energy costs.

5. Indirect Industrial Energy

The above discussions on ecological flows, human energy, and research energy can relate to both the direct and indirect flows into the energy production system. As previously discussed, net energy analysis by definition deals with the indirect and direct energy required to produce energy. Therefore, it is necessary to trace this and include it in the accounting methods. The means of accomplishing this are discussed in Section IV. The basic approach for accomplishing this analysis is becoming known as "process analysis."(41)

An example of the reason for examining indirect energy in general has been developed by Dr. Kenneth P. Maddox, of this research team, in a recent publication.(42)

> A first attempt at energy analysis considers only the fuels and the electricity directly used in the process studies. This is defined as first-order analysis. For example, the energy requirements for an electric wall clock can be estimated by multiplying the clock's wattage by the amount of time the clock operates. This calculation indicates energy consumption in watt-hours, an energy unit which can be converted to any other energy unit (e.g., 1 watt-hour = 3.412 Btu).
>
> The advantages of using direct energy inputs are (1) simplicity and (2) accuracy of input data. For our clock example, the energy consumption calculation is easily made by multiplying wattage by operating time. According to published information (Rocky Mountain Electrical League 1975) an average clock requires 2 watts during 8760 hours per year, or about 17,500 watt-hours (17.5 kilowatt-hours) per year.
>
> Has our calculation accounted for all the energy required for the clock? No. We have neglected the energy which was used to manufacture the clock and we have also omitted the energy lost during the generation of electricity. Both these energy requirements are significant. Electricity is generated at efficiencies of less than 33 percent, that is, more than 2/3 of the energy from coal, petroleum, natural gas, or uranium that is used to power steam-electric turbines is lost. Therefore, in order to calculate the total energy for running an electric clock, we must consider what energy is required to generate electricity. Also, we should determine how much energy is used to make the clock materials and to fabricate the clock. If we fully account for all the energy that went into making and running the clock, we find the total energy requirements to be more than 4 times our original calculation, or more than 75 kilowatt-hours (almost 256,000 Btu) per year.
>
> This example illustrates the errors inherent in using a direct energy-use methodology. There are serious omissions. Direct energy accounting is like computing the cost of owning an automobile as only the amounts paid for gasoline and oil (other important costs - depreciation, taxes, insurance, and maintenance - being neglected). In energy accounting, the omission of secondary energy requirements can lead to poor results. Consequently, directly energy methods have limited value and cannot accurately address most of the problems for which energy analyses are useful.
>
> A refinement of the first-order (direct) energy method is to consider one more step in the manufacturing chain - the energy required to produce directly used energy and the energy required to produce materials directly employed in the final process. This type of analysis is defined as second-order analysis (Fig. 1). In our wall clock analysis, we now include the energy required to generate electricity and that directly used to make the clock.
>
> According to data of the Federal Power Commission (1974), electricity is generated at fossil-fueled steam-electric plants with an efficiency of about 32 percent. Of the electricity generated, about 91.5 percent is sold to ultimate consumers, that is, 8.5 percent either is lost during transmission of represents an excess of supply over demand. Therefore the percentage of electricity actually received by a consumer to fossil-fuels energy burned at a power station is 32 percent x 91.5 percent = 29.3 percent. Thus for 293 energy units received by a consumer, an additional 707 units are expended during electrical generation and transmission. For the approximately 60,000 Btu (17,500 watt-hours) of electricity directly used by the clock, 145,000 Btu more were needed at the power plant.

A completely accurate account of the energy required to manufacture an electric clock would require a thorough energy analysis. For the purpose of this illustration, we shall use an approximation. According to a recent study (Herendeen and Bullard, 1974), an electric clock requires about 49,000 Btu per dollar of purchase price. If we assume a cost of $10 and a lifetime of 15 years, the clock's yearly energy consumption attributable to its manufacture is 49,000 Btu/dollar x $10 ÷ 15 years = 32,667 Btu/year, or approximately 33,000 Btu/year.

At the second order of analysis we find:

Direct electrical energy	60,000 Btu/year
Energy loss to power plant	145,000
Energy used to make the clock	33,000
Total	238,000 Btu/year

Our first-order analysis calculated an energy requirement of about 60,000 Btu/year. The second-order analysis has yielded 238,000 Btu/year, or nearly four times as much energy.

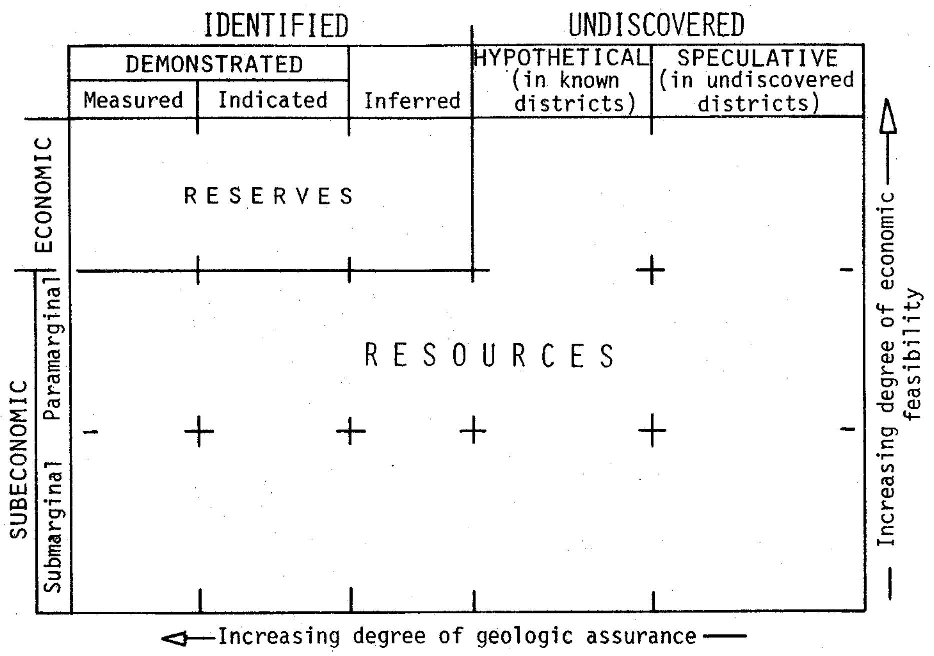
6. Resource to End Use: The "Length" of the System

A number of special-purpose "net energy" studies have dealth with a single and specific process such as an oil-shale plant in isolation.(43,44) The boundary begins and ends immediately at the fence of the module. This leads to a study of limited value. It may be useful in a process analysis of a specific process to identify potential energy inefficiencies or high-Btu direct and indirect inputs. This may assist in pinpointing some potential energy input problems or costs which could be masked by pure economic analysis.

However, it ignores the fact that a single process does not stand by itself in the "assembly line" of energy production. To bring a mineral resource to the end users, it must be extracted, processed to produce different qualities and forms of energy, and moved about quite a bit to get it to the various processers, distributors, and end users. Each step requires energy. Also, since one resource may move through several different trajectories, any comparison of alternatives or options must consider the entire trajectory.

The inclusion of the resource which is effectively lost due to production is another boundary problem. Does the unrecovered or lost resource lie within the system boundary or not? A case can be made for either point, depending upon which issues one is addressing. However, it is diligently incumbent upon the analyst who includes gross resources within his system boundary to advise his audience of his assumptions and of some hazards which he has created in comparisons of different trajectories. An "unrecovered resource" assumes that present technologies and economics will prevail. Changes in economics and technologies may lead to the future recovery of some of the resources which are unrecoverable. An example might be future in-situ recovery of shale oil in the pillars left in place in oil shale room-and-pillar mining.

The resource not extracted may not be damaged or permanently lost to future generations. In petroleum extraction, that amount left in the ground after primary and secondary recovery is still petroleum. The U.S. Geological Survey identifies it as a "resource", but it is not a "reserve" according to the U.S. Bureau of Mines classification system. See Figure 10. It is subeconomic, but it is there. Even if tertiary recovery were to become economical and lead to the production of about half the petroleum of the field, the remainder is still petroleum. It might be "lost" to this generation because of our



RESOURCE CLASSIFICATION DIAGRAM BY THE U.S. GEOLOGICAL SURVEY AND THE U.S. BUREAU OF MINES

FIGURE 10

economics and technology, but it might not be lost to future generations. The only petroleum which is lost to all generations is that which has been extracted and consumed.

This issue is sufficiently important to warrant adequate discussion. The following quotation from the report prepared by the Committee on Natural Resources and the Environment (COMRATE), of the Commission on Natural Resources, National Research Council, is relevant.(46)

> ### TWO POINTS OF VIEW
>
> Minerals are the staff of civilized living, and growing concern with their continued availability and efficient use was the impetus for this report. In the course of its study, the Committee on Mineral Resources and the Environment (COMRATE) recognized that two increasingly polarized schools of thought are becoming entrenched concerning the future adequacy of the world's mineral resources and the environmental costs of winning them. The study of the general issues involved -- demand, supply, technology, and environmental impact of production -- by the four COMRATE panels has resulted in findings which may go some way towards reconciling the two extremes.
>
> The "doomsters" see a future in which catastrophic exhaustion of resources is inevitable unless drastic measures are taken to reduce economic growth. In opposition, the "cornucopian" view maintains that mineral resources are economically, and, for any future that may concern us, physically infinite. This unresolved conflict in economic thought was represented within COMRATE panels as well, and is illustrated by the dissenting opinion attached to the Report of the Panel on Demand for Mineral Resources (Section IV).
>
> There are fallacious assumptions and potentially dangerous consequences inherent in both extremes. The "doomsters" pay too little attention to the adjustment potential of the market mechanism, and generally fail to understand the distinction between "reserves" and "resources." Their gloomy outlook is based on a "fixed" supply of materials and fails to recognize that the supply available changes as price rises and technical advances make lower grade resources economically and physically more accessible. The danger of this approach lies in its encouragement of alarmist overreaction on the part of policymakers, which may in turn have unnecessarily disruptive effects on the economy and society as a whole.
>
> The "cornucopians," on the other hand, rely too heavily on the market mechanism for inducing the transformation of "infinite" resources into almost infinite reserves, and on the technological miracle for providing the physical wherewithal. Their hypothesis insufficiently represents the increasingly large capital costs of technological advance, the long lead times involved, the "net energy" factor (the energy cost involved in the technology of increasing production), and the fact that although technology has always come up with an answer in the past, its solutions have always had their social, environmental, or economic costs. These costs can no longer be ignored and are in fact setting a practical limit to the economic/technologic transformation of resources into reserves. More importantly, the economic/technological basis of the cornucopian argument is derived from the very assumption its adherents are concerned to disprove: it is shortages and public awareness of shortages which provide the incentive for increased production, technological solutions, and increased efficiency of use. The paradoxical result of the cornucopian message may thus be the fulfillment of the Cassandras' prophecies: in the relaxed climate fostered by anticipation of plenty, there will be no apparent urgency for setting in motion the economic and technological machinery for maintaining that plenty. This is a particularly important problem for the United States where maintenance or attainment of self-sufficiency in mineral resources is concerned. COMRATE believes that the United States will face serious difficulties in attempting to increase some supplies of energy and mineral raw materials from domestic sources. Indeed, COMRATE believes it is doubtful whether even current levels of supply can be maintained for all materials.
>
> To view the problem moderately, we must draw together the valid arguments of both schools of thought. The overall conclusion that has emerged from this study is by no means a counsel of despair. But separate consideration

> of the complex problems involved underscores the need (1) to husband resources, (2) to generate information in areas where it is inadequate, and (3) to tackle immediately problems where there is adequate information to form a basis for new action or for augmenting existing efforts. Such actions should always be designed to conserve resources and increase efficiency in their use.
>
> GENERAL CONCLUSIONS
>
> Some general conclusions emerged from the panels' separate deliberations. Although the time span for this first COMRATE report has not allowed all-encompassing conclusions to be drawn, those conclusions that have been drawn have many implications for policymakers.
>
> 1. Mineral resources become available for man's use by a complex and lengthy process which, on a worldwide scale, related intimately (a) natural process, (b) man's knowledge and technological ingenuity, and (c) man's economic, social, and ethical concerns. Efficiency in use and avoidance of waste in both mineral resources and their end products are essential if we are to avoid preempting the resources needed for future generations. Policymaking at all levels should recognize interdependencies within the materials cycle, among nations, and among the various users of mineral commodities. But, above all, we should adopt a conservation ethic that has at its heart avoidance of waste and more efficient use of materials.
>
> 2. Widely divergent methodologies, based largely on individual judgment, are used both in forecasting demand for, and in estimating supplies of, mineral resources. There are currently no standardized techniques for making either long-term demand forecasts or resource estimates nor are means available to assess adequately the accuracy of the existing methods."

A recent net energy analysis by Development Science Inc., has dealt with the subject as in the following selected quotations.(46)

> "The following report is written with the objective of defining a methodology for making net energy estimates and applying them to several technologies to see if the law of diminishing returns applies to the technologies over the near time horizon. As will be seen in the report itself, the answer is that the next technologies and fuels America will call on, for all their other problems, do not yet cost more energy subsidies from other fuels than they give in return. The so-called diminishing return occurs, in effect, as an accelerated depletion of reserves, not in subsidies from other sources.
>
> "The method chosen here avoids a single number to describe net energy in favor of a disaggregated set to give information for a number of decisions. In so doing, the really quantitative energy impact isn't that net energy is negative, but that the amount of unused resource left behind by extractive technologies is several times what can be economically taken today. Of course, this is not a new fact and as prices go up, more complete use of the reserve will also go up. While it takes more than twice as much energy to use tertiary crude oil extraction techniques, there still is a net energy benefit on that incremental investment. If the rate of depletion of fossil resources is considered, the new and proportionately larger penalty may be justified in the name of using more of the resources in the ground.
>
> "If we have a policy of husbanding the remaining fossil fuels, then the questions raised by the in situ resource affected analysis need to be applied to the scheduling of resource utilization over time, to R&D priorities, to additional information on technological forecasting in the extractive industries, and especially with an assurance that there will be fossil fuels enough to make a transition to other sources. The comparative resource affected data should fit into these additional contexts."

The "unrecovered resource boundary" is analogous to the Second Law of Thermodynamics, which states that energy is degraded (or increased in entropy) as work is preformed by that energy. The increase in entropy can be theoretically defined; the <u>usable</u> work achieved varies with technology and economics. By analogy some energy is used and some is degraded, given today's technology and economics of the in situ fossil fuel when it is exploited by man. We are not saying that the second law applies to resource extraction efficiency, but that an analogy exists.

The maximum recovery of reserves is both a social and economic issue. There are serious research and development efforts in underground mining to improve the amount of coal recovered, for economic reasons if for nothing else. Social issues may prevail if surface disturbance is involved. Given a certain level of demand for coal, if more coal can be recovered per unit of surface area (be it auger mining or strip mining), fewer acres of surface disturbance will occur. Appalachia is grim testimony to this issue. Montana has enacted a law which gives articulation to this social concern. If the surface is to be disturbed, every effort must be made to recover all seams of coal under that surface. As few acres of surface as possible are to be disturbed, and even then, the disruption should never be inflicted on the land and its ecosystems more than once.

In general, it is safe to assume that more energy will be required by future generations to recover the "lower grade" or presently uneconomical resources. Cheap and readily available resources are exploited first. This is one of the basic philosophical concerns which helped to start the concept of net energy analysis. But few people have proposed any deliberate interference with normal market economics to force the immediate recovery of expensive reserves, so that future generations can have cheap and readily available energy or better net energy yields than we have in this generation.(47)

7. Internal and External Energies

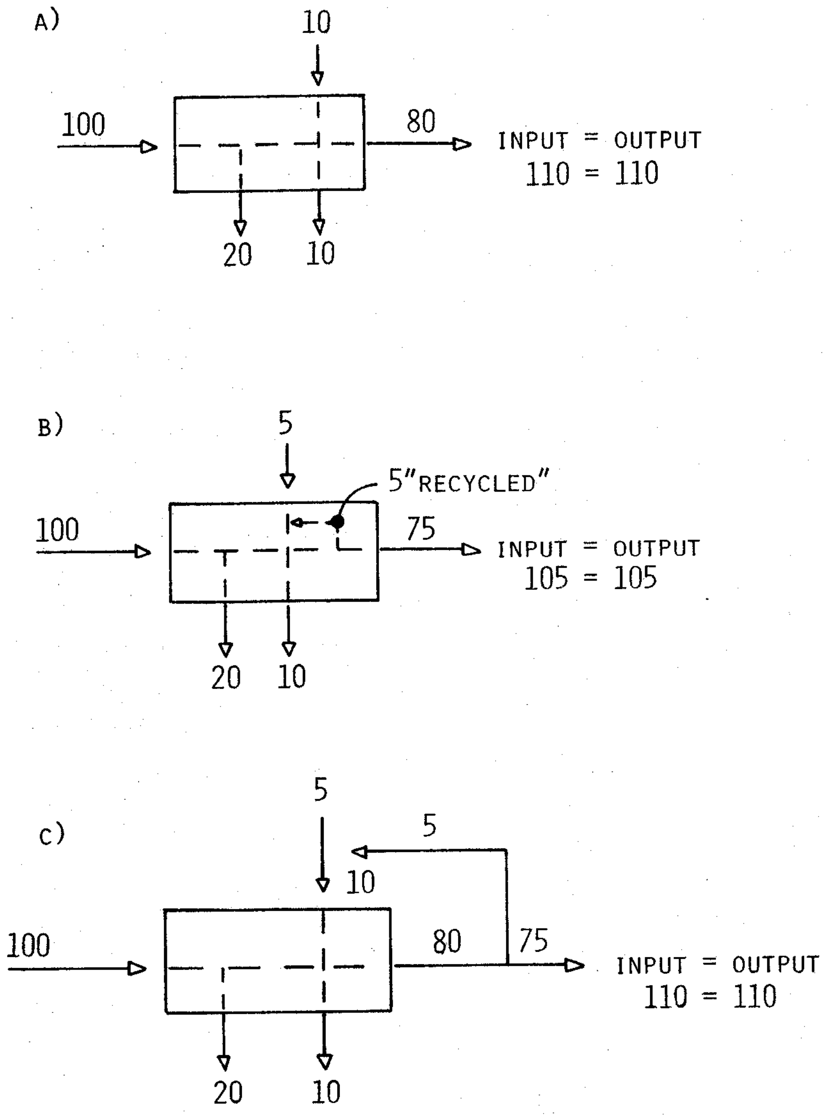
A refinery can be run on process gases generated in the refining of petroleum, or it can be run on natural gas purchased from outside. This same condition applies to a number of the steps and processes which are part of the trajectories of energy production. Coal trains could run on the energy which they are transporting, as they did 50 years ago, rather than on oil from outside of the coal transport process.

Some of the previous studies have utilized different boundaries regarding internal and external energy.(48) The difference is illustrated in Figures 11a, 11b and 11c. The first process, Figure 11a, is driven with external energy. The second, Figure 11b, is operated on internal energy. It never appears outside the boundary and therefore is not accounted for. This makes the net energy yields look very favorable, because it reduces the external energy which is acquired to drive the process. Figure 11c, in effect, takes this same internal driving energy outside the boundary and then returns it as a net energy deduction.

This is a problem of accounting methods as well as boundaries. In all the cases of Figure 11, the same amount of energy is needed to operate the system. Figure 11b merely disguises the driving energy by hiding it inside the boundary; also, if one wants a "balance", this energy must be shown as the loss shown in Figure 11c. The CERI accounting method avoids this particular pitfall of boundaries.

8. Air and Water Inputs

Some energy-producing systems require combustion air, cooling air and water, water for hydrogenation and other purposes. Inasmuch as they have no enthalpy of combustion, it is realistic to exclude them from the calculations.(49) However, it is proper to include the energy required to move them so that the production process can operate.



INTERNAL AND EXTERNAL ENERGIES:
BOUNDARY OPTIONS FOR MODULE
FIGURE 11

9. Time Boundaries

Time, the fourth dimension, can be considered as another boundary. Referring back to Figure 4, the many flows do not all occur at the same time. The energy which produced the industrial plants, produced the materials which have gone into our specific power plants that process energy may have occurred decades ago. The energy output from our plant which is recycled back into future energy production will involve additional time flows. One can display a "static" condition which recognizes and accounts for various time flows and boundaries. On the other hand, there are ways in net energy analysis to deal explicitly with the time dimension and to display it. The essence of the point is that in net energy analysis the fourth dimension boundary is a very real matter and can be handled in several ways. Some issues cannot be handled only with static analysis. This will be pursued further in Sections III-E and III-G. This CERI study has utilized only a static method.

10. Miscellaneous

Byproduct outputs may be included or excluded from the boundary and the accounting of energy. Some processes may be intended to put out only one product; others may be deliberately designed to produce various energy products. For example, a power plant could supply heat from its boilers to a number of buildings for house heat and hot water heating. This "waste heat" would be a valuable by-product in this case. It would be feasible to use it because of the proximity of the plant to potential end users of heat of lower quality.

If all energy by-products, or materials by-products which represent the sequestering of energy in their manufacture, are not included in the analytical boundary and accounting, then the energy inputs proportional to their share of the total output should be excluded. The data and accounting problems which apply to net energy analysis in general are also applicable to by-products.

11. Criteria for Selecting the Boundary

In summary, the person conducting a net energy analysis will have to select a boundary. He might apply the following criteria to the boundary options previously discussed:

- Social issues involved;
- Desired level of specificity;
- Potential use in decision-making;
- Limitations in time and cost of study;
- Decay of effects and magnitudes of inputs and outputs of system selected;
- Availability of data methodologies;
- Comparability, compatability of data;
- Ability to make valid assumptions on real world behavior within system boundary and about limitations of inputs and outputs;
- Speculation about future technologies, life styles, politics, economics;
- Realism of time frames in terms of technological and other dynamics (the "fourth dimension" boundary);
- Site-specificity of concerns and proposals to be analyzed.

E. Accounting Methods: Energy Quantity and Quality

Net energy analysis can present quantitative results in several ways. Each way will relate to certain broad social or policy issues, and each will give different numerical answers. There is no single standard accounting system at present, and those involved in net energy analysis recognize that different accounting methods are all appropriate. As a result, it becomes extremely important for the accounting to identify what method he has used in arriving at numerical results, and what issues are addressed by the particular accounting scheme.

Acceptance of several accounting methods, and rejection of a single scheme, was evident at the Stanford Workshop: "Focusing on a single value or ratio was compared in one subgroup to attempting to assess the economic viability of a corporation from a single number, such as an accounting profit."(50) The CERI study team arrived at a similar conclusion early in their research.

As has been discussed, the accounting method must account for all indirect and direct energy inputs into, and "driving" energy of, an energy-producing process or string of processes. It must account for the energy sequestered in the direct and indirect materials which are utilized. The data and analytical approaches of the study must identify and quantify these energies; the accounting methods must display them. This becomes apparent in referring back to Figure 4.

A single unit must be used to describe quantities. The question of energy quality has been previously raised and will receive subsequent discussion in this report. The single, assumed unit of measurement has the disadvantage of masking various energy qualities in the direct and indirect energy. The quality of energy has significance in a thermodynamics sense: a Btu of heat at 1000°F is not of the same quality as a Btu at 80°F. It is a Btu, but when it is degraded or dissipated at ambient environmental temperature, it no longer represents the same potential for work. Quality also has significance in a social sense as well: its location, form, time, convenience, substitutability, transportability, storability, resource scarcity, and several other factors affect its social and economic value, as has been noted. Hence, we construe quality to connote more than the thermodynamic concept of quality and more than the limited engineering concept of "Available Work."

Regardless of the use of the narrow engineering definition or broad social definition of "quality," there is a problem of concealing energy qualities in accounting. This is true for both inputs and outputs. If one takes a common descriptor such as "electricity" for a qualitative catch-all identifier, the one who is even slightly knowledgeable about energy can visualize quite a bit about the quality. If his net energy analyst tells him that the output of a process is "electricity," qualitative connotations are evident to him.

The inputs, however, may be very complex and the masking of quality by the use of a single quantitative numeraire may have some hazards. A power plant may obtain direct energy from gas or coal; the former has significantly different social quality because of relative scarcity. The single numeraire does not reveal the form of the various inputs. This hazard has not been surmounted by energy analysis in general. The accountant should make this problem clear to his client.

Quantitative designation may be any common unit of energy" the British Thermal Unit (Btu), the joule, the equivalent of a fossil fuel (such as barrels of oil), are all acceptable. The "Quad," (one quadrillion Btu's, or 10^{15} Btu) is becoming common in national energy planning. (A smaller unit, one billion Btu's, or a "microquad," might be a manageable unit in net energy analysis.)

The following quote is an excellent statement of the problem of quantitative measurement.(51)

> ### What is Energy
>
> Like money, the unit of energy account is not as simple a concept as it might at first sight appear. We can, of course, speak of some physically definable energy unit like the joule or kilowatt-hour, but we are still left asking "a joule of what?" For many workers it has been enough to define "what" as the calorific value of a given fuel, that is, the enthalpy of combustion of the fuel. Enthalpy is the thermodynamicist's description of heat, but to analyze the production of a good or service in terms of heat can in certain circumstances be dangerously misleading. There is almost certainly more heat in the Atlantic Ocean than in the enthalpy of combustion of the oil in the middle east. It is some other quality than heat that makes oil an attractive fuel for driving the economic process. That quality is "free energy."
>
> As is clearly enunciated in the first law of thermodynamics, Energy is always conserved. It is never lost. Its quality is merely degraded. The driving force for transformations, however, is not heat but thermodynamic potential, Free Energy. Free Energy is irrecoverable, and diminishes every time a fuel is burnt or a nucleus fissions.
>
> The workshop considered what should be the relevant unit of account, examining Enthalpy, Free Energy and Availability. It concluded that there was no unique input, and that it was necessary to adopt a convention. It was agreed, however, that the unit that best expressed the objectives of Energy Analysis is Free Energy (G) rather than enthalpy (H) but noted that for most intensive fuels (high free energy potential/unit mass)(oil, coal, etc.) the error in taking Enthalpy rather than Free Energy was of the order of 10%. For many processes it is rather difficult to compute the Free Energy changes."

At the NSF-Stanford Workshop, the following two statements were submitted by participants:

> "Not all forms of energy are equal in quality. There exists a chain of increasing energy quality with the low quality, dilute energy of the sun developing food in plants which is subsequently upgraded to wood that is in turn converted into coal and then through power plants into electricity, etc. A few calories of higher quality energy have the ability to determine the time and place of work of a layer flow of low quality energy through feedback pathways."
>
> "The question of consistency in units naturally arises when considering transformation within the system, or inputs and outputs of the system. This must be handled by assuming an equivalency (e.g., the mechanical equivalent of heat, or electrical equivalent of heat) and an efficiency of conversion. This assumption of efficiency becomes arbitrary, but may be based on prior experience and will be related to the particular system and its elements. The use of consistent units -- by common practice, a thermal unit of energy -- will, by providing a common denominator, permit more ready comparison of the performance of one system against another."

Accounting can be done through summations, ratios, percentages, or intertemporal relationships such as "payback period." Various possible accounts relate to <u>issues</u> and therefore to <u>boundaries</u>. As has been stated, accounting systems must at least differentiate between the major types of inputs and outputs of a process. Based on the generalized process in energy production which is shown in Figure 4, various types of accounting systems and the boundaries and issues relevant to them are described in Figures 12, 13 and 14.

The energy flows through the boundaries include the "lost" energies. The external "driving" energies flow into and out of the process boundaries without becoming part of the usable energy product in general. This is not universally true, as some processes actually retrieve a portion of the external energy as usable output. The energy being processed flows in two directions: out as usable energy product, and down (in the figures) as unusable loss or waste. To account for all energy flows, and to simplify the expression of ratios, it is necessary to use the lost energy as a term in the accounting.

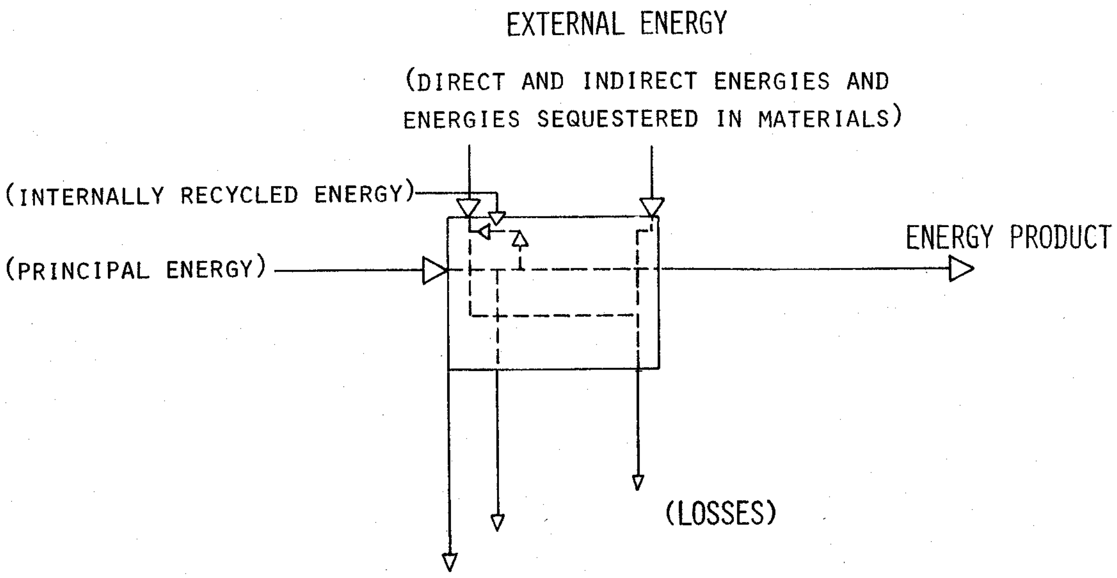
As shown, the figures deal only with static, not dynamic or intertemporal conditions. Factors which involve a time flow or time disparity are shown as a static condition. For example, if a plant has a 20-year life, the figures display the external energy of the initial capital investment as a single-period "amortization payment" at the year "x", which is an average of the production life of the plant. Some of the indirect flows of energy sequestered in indirect materials may have occurred years ago, but are shown as occurring in year "x".

F. Data

Some of the problems with net energy analysis methodologies are associated with quantity and quality of data. In theory, net energy analysis should utilize only actual energy data for all indirect and direct inputs and outputs. In practice, this is not possible. It may be necessary to infer some data, such as indirect energy sequestered in materials from national energy consumption statistics related to output of various industrial sectors. An assumption might have to be made that industry-wide or geographic averages can be applied to a geographic-specific industry. It may be necessary to assume that certain data represent a realistic average when, in actual fact, the determination of a technically accurate average (and deviations) could be a major project in itself. It is impossible, given constraints of time and money in any net energy study, to trace all the direct and indirect energy flows, and especially, it may be impossible to normalize them all to a qualitative-quantitative unit of measurement and description.

The types of data needed include:

- Energy produced;
- Byproducts produced and their energy content, for equivalency of "sequestered energy";
- External "driving" energy required;
- Direct materials for construction and operation;
- The energy sequestered in the manufacture and transport of those materials;
- The materials sequestered in the production of direct external energy inputs;
- The energy sequestered in the materials and transport of (6) above;
- The further indirect energies sequestered in the materials and transport of (7) above, and so on in indirect levels of input until these become insignificant;
- The inputs of energy which is to be processed by the step in question;
- The actual measurement of all losses would be good data to have.



ISSUE: THE AMOUNT OF INDUSTRIAL ENERGY WHICH MUST BE INVESTED IN A PROCESS RELATIVE TO ITS OUTPUT.

ACCOUNTING:

(1) AS RATIO: $R_1 = \frac{\text{ENERGY PRODUCT}}{\text{EXTERNAL ENERGY}}$

(2) AS SUM: $S_1 = \text{(ENERGY PRODUCT)} - \text{(EXTERNAL ENERGY)}$

$= \text{NET YIELD}$

COMMENTS:

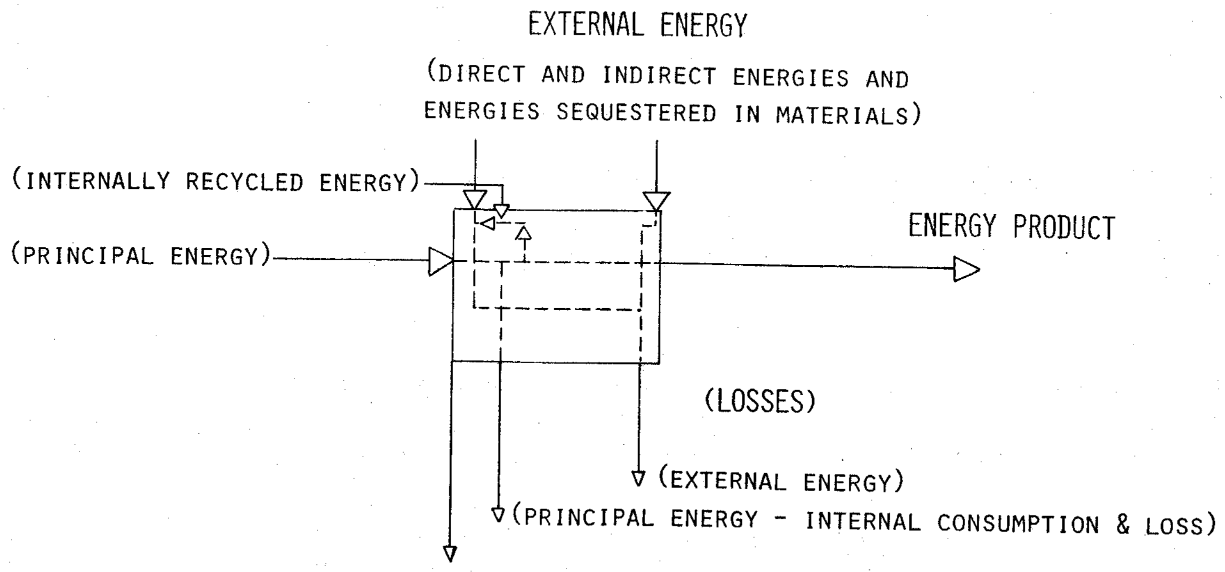
(1) EXTERNAL ENERGY CAN BE REDUCED BY RECYCLING ENERGY WHICH COMES FROM PRINCIPAL ENERGY AND IS PRODUCED BY THE PROCESS; THIS ACCOUNTING METHOD DOES NOT SHOW THIS SITUATION.

(2) THIS ACCOUNTING METHOD CAN BE USED IN FURTHER ANALYSIS OF INTERTEMPORAL FLOWS SUCH AS "PAYBACK PERIODS" OR "REINVESTMENT RATES" FOR ENERGY REINVESTED TO ACHIEVE NEW GROWTH IN ENERGY PRODUCTION FACILITIES.

(3) S_1 IS NOT A COMPLETE ENERGY BALANCE.

ACCOUNTING METHOD 1

FIGURE 12



ISSUE: WHAT FINAL YIELDS OF ENERGY PRODUCT DO WE GET RELATIVE TO THE TOTAL SOCIAL LOSSES OF RECOVERED RESOURCES AND INDUSTRIAL ENERGIES FROM OUTSIDE THE PROCESS?

ACCOUNTING:

(1) AS RATIO: $R_2 = \frac{\text{ENERGY PRODUCT}}{\text{LOSSES}}$

(2) AS SUM: $S_2 = \text{(PRINCIPAL ENERGY)} - \text{(LOSSES)}$

$= \text{NET YIELD}$

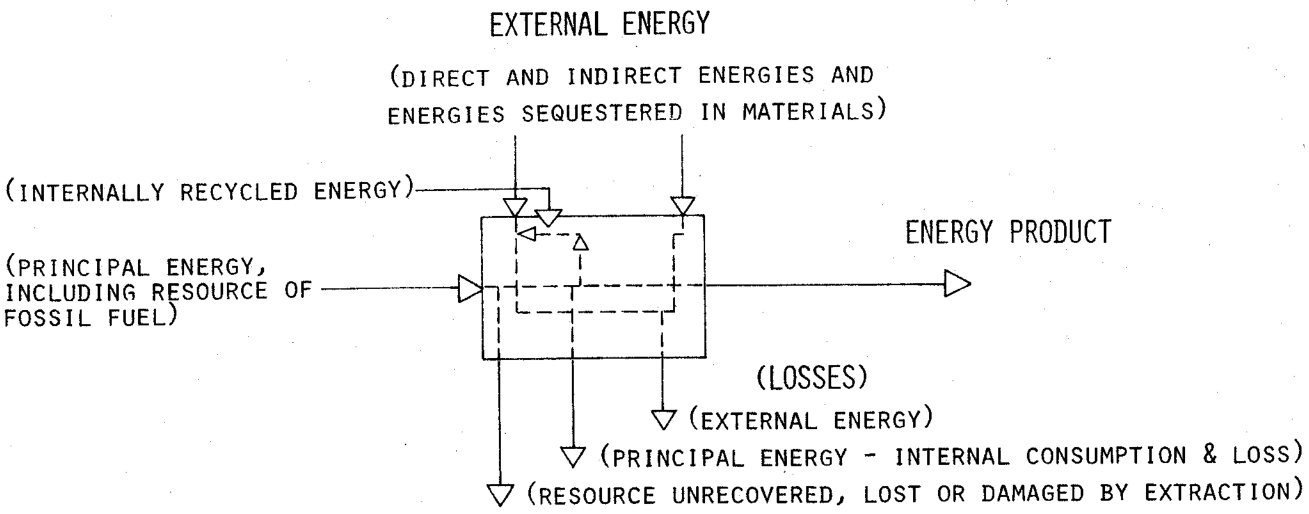
COMMENTS:

(1) VARIATION BETWEEN EXTERNAL ENERGY AND RECYCLED INTERNALLY-GENERATED ENERGY DOES NOT AFFECT THE ACCOUNTING, AS BOTH OF THESE ENERGIES END UP AS LOSSES.

(2) THIS ADDRESSES IMPACTS ON RESERVES OF FOSSIL FUELS, AND COULD BE USED IN INTERTEMPORAL ANALYSIS WHICH EXAMINES DEPLETION RATES.

ACCOUNTING METHOD 2

FIGURE 13



ISSUE: WHAT TOTAL LOSSES OF EXTERNAL ENERGY AND FOSSIL FUEL RESERVES AND RESOURCES OCCUR TO ACHIEVE A CERTAIN OUTPUT OF ENERGY PRODUCT?

ACCOUNTING: (1) AS RATIO: $R_3 = \frac{\text{ENERGY PRODUCT}}{\text{LOSSES}}$

(2) AS SUM: $S_3 = (\text{PRINCIPAL ENERGY}) - (\text{LOSSES})$

$= \text{NET YIELD}$

COMMENTS: (1) THIS GIVES A MORE ACCURATE PICTURE OF RESOURCE STRESS THAN METHOD 2, AS IT DISPLAYS THE RESOURCE WHICH IS NO LONGER AVAILABLE TO SOCIETY, <u>GIVEN TODAY'S ECONOMICS AND TECHNOLOGY</u>, ONCE THE PROCESS IS IN OPERATION.

(2) COMMENTS (1) AND (2) FROM METHOD 2 APPLY.

ACCOUNTING METHOD 3

FIGURE 14

It is evident that this poses an immense data problem in real life. An important tool is the economic input-output (I-O) matrix. I-O analysis in economics tells us, normally in dollar terms, not only the inputs which are directly required to produce a given output of something, but also the inputs into the inputs, etc. For example, if we are examining the output of cars, I-O analysis allows us to see how much input in the form of plastic is needed to produce a given number of cars. Also, we can note the petroleum input (and all other inputs) into the plastic; machinery input into the petroleum, etc., etc. Inputs produced and used within one industry can also be seen,some plastics might be used in the production of other plastics, for example. I-O analysis calculates automatically the limit to this process, allowing us to see all inputs, no matter how far removed from the final production of machinery.

The CERI study has made use of I-O data developed by Dr. Robert Herendeen and Dr. Clark Bullard.(53) The Department of Commerce I-O data are expressed entirely in 1967 dollars. Herendeen and Bullard's task was to obtain similar data in energy terms (Btu's). Thus, they performed mathematical manipulations which allowed them to observe the energy inputs into all 357 sectors (five sectors are energy sectors). These energy inputs include both primary or direct energy inputs, as well as the secondary, tertiary, etc. inputs or indirect inputs. Dollar figures which were then converted to physical units using 1967 price indices, then conversion was made from physical units to Btu's. As a result, they present a matrix which shows the Btu input (direct and indirect) from five energy sectors, into each of 357 major industrial classifications in the U.S. Their data appear in terms of Btu/$ of output in 352 sectors and Btu/Btu in the five energy sectors.

This provides assistance in net energy analysis. However, it does not supplant the need for accurate engineering data for direct inputs and outputs. Because indirect inputs decay rapidly in magnitude, the less-accurate I-O data is suitable at an indirect level of application.

In actual practice, the collection of data may involve the investigator in a number of minor assumptions and professional judgments. He must be careful of a number of pitfalls, such as "double-counting." The discussion by the CERI investigators in Section VI illuminates some of these matters.

G. Intertemporal Flows: Energy Flows Over Time

Although the CERI team decided not to analyze time flows and time relationships of energy, the subject is very important. Some have concluded that intertemporal considerations lie "outside the discipline of net energy analysis," and that the "sole intertemporal objective of net energy analysis is to provide as clear and complete an accounting of the energy inflows and outflows over the life-cycle of a particular technology as possible."(54) Others recognize the time spacing of inputs and outputs which occur in real life. They feel that net energy analysis should examine these factors, especially when energy quantities and mixes are in a dynamic situation. In a policy context, it is legitimate to ask, "if we do this now, what are the net energy implications in year n?"

Intertemporal flows can be dealt with in various ways. A relatively simple question is a life-cycle matter of the payback period of an energy investment. How long does it take in production to recover the energy investment which establishes the process, deducting energy operational inputs during the operations phase? This relates to the accounting issue ratio R-1 previously discussed. Figure 15 shows the concept of payback period. For the fossil fuels examined in this study and reported on herein, it is obvious that the payback periods will be very short.

A second and related approach would be concerned with the investment to feed new growth in a situation which found energy production increasing rapidly. There must be a certain increment of energy production assigned to establish the next unit of energy production. If growth is very rapid, in theory, all energy production could be devoted to building additional units for production. No energy would be available for end uses. One could even hypothesize a situation where an outside energy subsidy plus the full increment of each new unit of production would be needed to sustain energy growth. Figure 16 displays the concept.

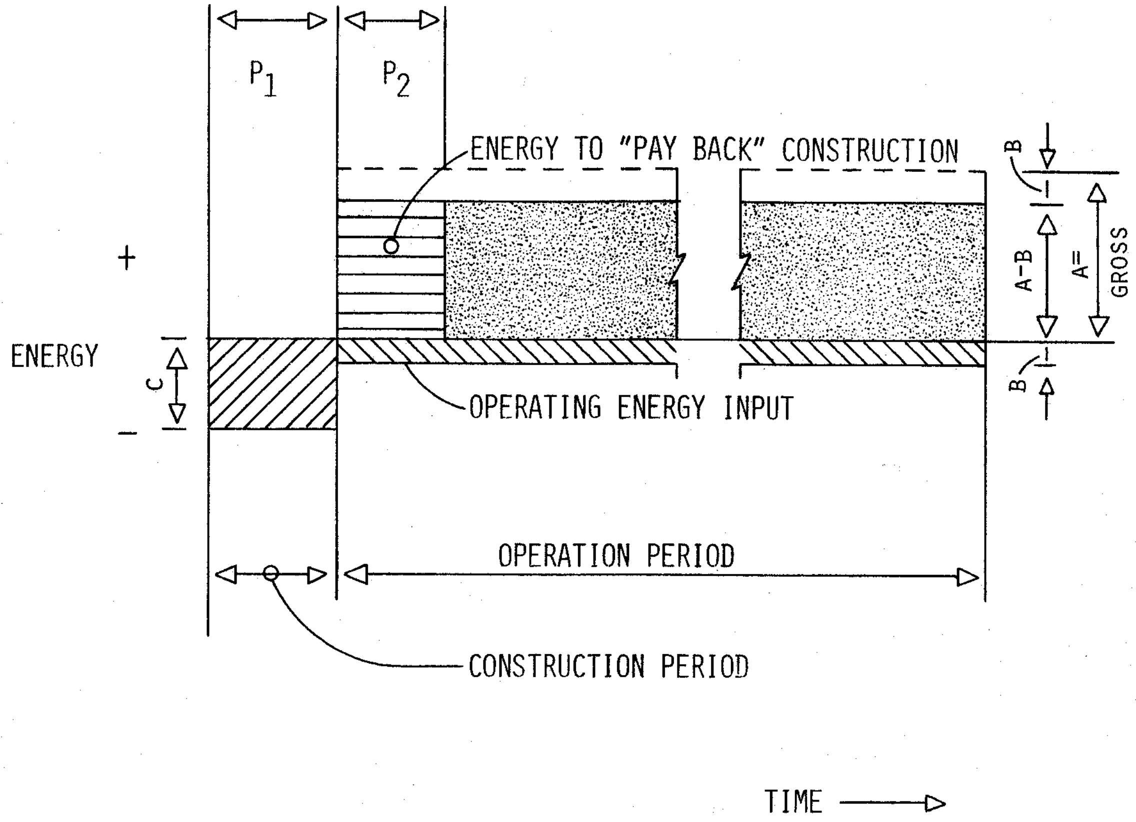
As a corollary, technological improvements in energy production could change the shape of a time-net yield curve. A Btu of shale oil used as "driving" external energy for present shale processing may not generate the same net yield as a Btu of shale oil after the technology is improved. Curves of anticipated improvements versus time yields could be constructed to compare technologies.

Dr. John Price of England has examined this situation for nuclear energy in England.(55) Critical factors, he found, are the ratio of output/input and the rate of plant construction. He concluded that the doubling times for production capacity of perhaps four years cannot be sustained for nuclear power, due to its low output/input ratio. This situation could occur, he felt, if continued exponential energy growth and a shift from fossil fuels to nuclear energy were to occur. It is not our purpose here to examine Dr. Price's methodology or conclusions, but we wish merely to invite the reader's attention to the subject.(56) The problem of how much productive capacity to devote to capital increases versus consumer goods is a classic problem of every developing country.

A third type of analysis deals with discounting: determining the present worth of future benefits or costs. Section V of this report deals with this concept. It is essential to note that some students of net energy analysis are willing to assign <u>values</u> to energy units, i.e., a Btu at present is not <u>valued</u> the same as a Btu at some other time. However, a Btu is a Btu; human preferences and economic practices may change its <u>value</u> but will not affect the enthalpy or free energy.

A fourth intertemporal consideration deals with depletion of resources. The accounting methods of Ratio R-2 and Ratio R-3 relate to this type of concern. The previous discussions on accounting methods, and the quotation from The National Academy of Sciences COMRATE report, illustrate this general point.

A fifth intertemporal consideration concerns ecological flows and analytical systems which attempt to integrate energy flows throughout many subsystems into a single system. In the environmental study of a site-specific power plant or mine, there are a number of intertemporal flows, such as ecological succession or cooling rate/time/distance of cooling water, which may have to be analyzed. These relate to industrial facility life and operations; for example, it may be desirable to inflict a small reduction in the net



$P_1C = P_2 (A-B)$

TIME FLOWS OF ENERGY:
THE "PAY BACK PERIOD"

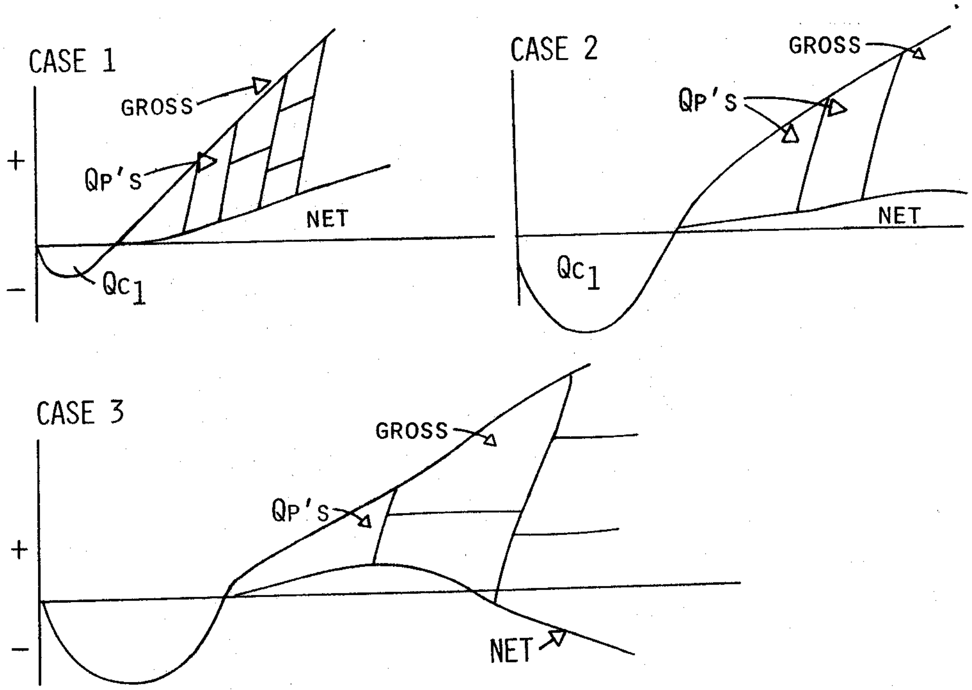
FIGURE 15

Q = ENERGY QUANTITY
Qc = CONSTRUCTION ENERGY
Qp = PRODUCTION ENERGY TO PAY OFF Qc

CASE 1: Qc_1 IS SMALL, BUT GREATLY INCREASING TOTAL Q REQUIRES A LARGE NUMBER OF Qp'S TO BE ASSIGNED TO NEW Qc'S. THIS REPEATS FOR EACH NEW Qc.

CASE 2: Qc_1 IS LARGE, NUMBER OF Qc'S IS SMALL: THE MAGNITUDE OF Qp MUST BE LARGE FOR A POSITIVE YIELD.

CASE 3: Qc IS LARGE AND NUMBER OF Qc'S IS LARGE.



INTERTEMPORAL FLOWS:
THREE CASES

FIGURE 16

energy yield of a power plant by using to a cooling tower instead of flow-through cooling if the heat dissipation rate of the receiving waters cannot tolerate the higher heat load without unacceptable ecological change. In the larger "energetics" system, time dynamics are important. Again, our purpose is merely to identify that intertemporal considerations exist, rather than to deal with the substance of them.

References and Footnotes - Section III

1 Bronheim, Harold; Nathans, Robert and Palmedo, Philip F.; "Users Guide For Regional Reference Energy Systems," Brookhaven National Laboratory, Upton, N.Y., September 1975.

2 Federal Energy Administration; "Project Independence Report," Washington, D.C., November 1974; see Appendix A-IV.

3 This is an unfortunate use of the term "input-output" analysis, as it is easily confused with economic Input-Output (I-O) models of the Leontief type which are common in economic analysis and are now finding application in energy studies. State studies are sometimes called "state energy flow balances."

4 Colorado Energy Research Institute; "Future Energy Alternatives for Colorado," Golden, Colorado, February, 1976; see also studies by the States of Florida, Kansas, Iowa, Texas (The Energy Institute, University of Houston), Arizona and others.

5 Searl, Milton F., Editor; "Energy Modeling," Resources for the Future, Inc., Washington, D.C., March, 1973.

6 IFIAS, op.cit, pp. 60-66.

7 Berry, S. and Fels, M.; "The Production and Consumption of Automobiles," Illinois Institute for Environmental Quality, Chicago, Illinois, 1972.

8 C-b Oil Shale Project; "First Year Environmental Baseline Program Report, Oil Shale Tract C-b," Denver, Colorado, 1976. This is a good recent analysis of the existing energy flows in ecosystems which may be affected by oil shale production.

9 ✓ Odum, Howard T.; "Environment, Power and Society," Wiley-Interscience, New York, 1971.

10 Odum, Eugene P., op.cit.

11 Kendeigh, Charles S., op.cit.

12 Hubbert, M.K.; "The Energy Resources of the Earth," Scientific American, 1971, Vol. 224, No. 3, pp. 60-70.

13 IFIAS, op.dit., p.6.

14 The Institute for Energy Studies, Stanford University, and TRW Systems Group; "Report of the NSF-Stanford Workshop on Net Energy Analysis," sponsored by the Office of Energy R&D Policy, National Science Foundation, August 25-28, 1975. This workshop was a key event in the development of net energy analysis, as it brought together, for the first time in the United States, practitioners of energy analysis.

15 IFIAS, op.cit., pp.17-18.

16 ✓ Slesser, Malcolm; "Energy Accounting," A Report to IFIAS, 1974.

17✓ Sanghvi, M.K., "Limitations and Usefulness of Net Energy Accounting," July 28, 1975; Background paper for Annual Meeting, American Chemical Engineers Institute, Los Angeles, 1974.

18 Odum, Howard T.; op.cit.

18 Clark, Wilson; op.cit.

19 Gilliland, Martha; op.cit.

20 Barnett, H. S., and Morse, C.; "Scarcity and Growth," Johns Hopkins Press, Baltimore, 1963; Chapter 8.

21 Krutilla, John V.; "Conservation Reconsidered," American Economic Review, 57:4, September 1967, pp.777-786.

22 Nordhaus, W.; "Resources as a Constraint on Growth," American Economic Review, 64:2, May 1974, pp.22-26.

23 Cook, Earl; "The Flow of Energy in an Industrial Society," Energy and Power, Scientific American, W.H. Freeman and Company, San Francisco, 1971.

24 Gilliland, Martha; op.cit.

25 Little, I.M.D., and Mirrlees, J.A.; "Project Appraisal and Planning for Developing Countries," Basic Books, New York, N.Y., 1974.

26 Kneese, A.V., Ayres, R.V. and D'Ange, R.C.; "Economics and the Environment," Resources for the Future, Washington, D.C., 1970.

27 Capel, R.E., and Pandey, R.K.; "Evaluating Demand for Deer Hunting: A Comparison of Methods," Canadian Journal of Agricultural Economics, Vol. 21, No. 3, November 1973, pp.6-14.

28 Subcommittee on Energy of the House of Representatives Committee on Science and Astronautics; "Energy from Oil Shale: Technical Environmental, Legislative and Policy Aspects of an Undeveloped Energy Source," Congressional Research Service, Library of Congress, Washington, D.C.,1973.

29 American Physics Society; "Technical Aspects of Efficient Energy Utilization," American Physics Society, 1974. This is but one of many good references on efficiency in end uses of energy.

30 IFIAS, op.cit.

32 Stanford, TRW; op.cit.

33 Odum, Eugene P., op.cit.

State of California; "Energy Resources Conservation and Development Act," 1974.

34 Stanford-TRW; op.cit.

35 Kendeigh, Charles P., op.cit., for energy production in ecosystems.

36 Odum, Eugene P., op.cit.

36 Odum, Eugene P., op.cit.

38 IFIAS, op.cit.

39 U.S. Department of Commerce, 1974, data.

40 Dr. Charles Prien, Source.

41 IFIAS, op.cit.

42 Maddox, Kenneth P.; "Energy Analysis," Mineral Industries Bulletin, Vol.18, No. 4, July, 1975, Colorado School of Mines, Golden, Colorado.

43 Clark, C.E., and Varisco, D.C.; "Net Energy and Oil Shale," Proceedings of the Eighth Oil Shale Symposium, Colorado School of Mines, April, 1975.

44 Kunchal, S. Kumar; "Energy Requirements in an Oil Shale Industry," Proceedings of the Eighth Oil Shale Symposium, Colorado School of Mines, April, 1975.

46 Committee on Natural Resources and the Environment, "Mineral Resources and the Environment," National Academy of Sciences, Washington, D.C.,1975.

46 Development Sciences, Inc.; "A Study to Develop Estimates of Merit for Selected Fossil Fuel Technologies," E. Sandwich, Mass., 1975.

47 This problem might be viewed as "The Conservation Paradox."

48 Clark and Varisco, op.cit., and Kunchal, op.cit. Also, Penner, S.S.; "Report on Net Energy in Shale-Oil Recovery," University of California, San Diego, La Jolla, California, January 1975.

49 IFIAS, op.cit.

50 Stanford-TRW, op.cit.

51 IFIAS, op.cit.

52 Stanford-TRW, op.cit.

53 Herendeen, Robert A., and Bullard, Clark W. III; "Energy Cost of Consumer Goods, 1963 and 1967," Center for Advanced Computation, University of Chicago at Urbana-Champaign, Urbana, Illinois, 61801.

54 Stanford-TRW, op.cit.

55 Price, John; "Dynamic Energy Analysis and Nuclear Power," Friends of the Earth Ltd., London, England, 1974.

56 Rotty, Ralph M., Perry, A.M., and Reister, David B.;"Net Energy from Nuclear Power," Institute for Energy Analysis, Oak Ridge Associated Universities, November, 1975. This Report also discusses the time flows of energy.

ADDITIONAL REFERENCES:

Beardsworth, Edward; "A Perspective on Energy Accounting," paper presented at the 68th Annual Meeting, American Institute of Chemical Engineers, Los Angeles, California, November, 1975.

"Fuel Processes Must Consider Energy Costs," Chemical and Engineering News, June 2, 1975.

Conservation Foundation; "Net Energy Analysis Can Be Illuminating," Conservation Foundation Letter, Washington, D.C., October 1975.

Council on Environmental Quality, "Energy and the Environment: Electric Power," Washington, D.C., 1973.

Darmstater, Joel; "Energy Accounting vs. the Market," paper given at the Pacific Science Congress, Vancouver, B.C., August, 1975.

Muskie, Edmund S., Senator; "Energy or Environment: An Echo, Not a Choice," Chemical Engineering Progress, Vol. 71, No. 2, February 1975.

Office of Energy Research and Planning, Oregon: "Transition," Salem, Oregon, 1975.

Steele, Robert V.; "Net Energy Analysis of Synthetic Fuels Production," Stanford Research Institute, Palo Alto, California, 1975.

IV. METHODOLOGY OF STUDY

A. The CERI Process

The basic approach of this study was to have specific investigators deal with specific fossil fuels, with other members being responsible for overall integration and attention to such matters as economics and the environment. The team met frequently as a group. A one-day workshop was held with outside participants several months into the study. At this time, the methodology, philosophy and initial data approaches were discussed with the workshop participants and input was obtained. The team members, individually or in groups, attended or participated in other conferences on net energy analysis, including: the Eighth Oil Shale Symposium of the Colorado School of Mines in April, 1975; the NSF-Stanford Workshop in August, 1975, and the Americam Institute of Chemical Engineers Annual Conference, November, 1975. Also, team members, individually or in groups, met with other people involved in net energy. The team reviewed a great deal of literature, and met in small groups to exchange data common to the more than one investigator.

After the team agreed upon the overall methodologies, boundaries and approaches, individual members collected data, primarily from various industries which are actually processing or transporting energy. The data were aggregated and the report was drafted and reviewed. The great majority of the time and expense of this study has been devoted to data acquisition and analysis, which is summarized in Table 3 for the methodology discussed in this section.

B. Assumptions and Ground Rules

Prior to commencing the study, the CERI team spent some time in reviewing literature and in team meetings to define the study scope and general methodology. As a result, the ground rules and assumptions were established as follows.

1. Entire trajectories or pathways from resource extraction to the point of end use should be examined;
2. End use efficiencies, or energy analysis of end uses, should be excluded; the study should be confined to the production system. End uses are highly important regarding efficient resource use, but this can be separated in terms of studies. End use analysis is very complex, and it was decided to limit the scope for reasons of time and budget. This does not imply that attention to the consumption of energy may not be much more important than analysis of energy balances in production;
3. The study should analyze energy flows in scientific and engineering terms, and should obtain the best technical data on energy flows;
4. Indirect, as well as direct energy inputs should be included:
   - Energy needed throughout the various sectors of industry to ultimately produce and operate the energy production system should be included;
   - The energy needed to produce materials used throughout the various sectors of industry to ultimately produce and operate the energy production system, or enable direct and indirect energy to be delivered which ultimately enables the energy production system to operate, should be included.

- An examination should be made early in the research as to the rationale and feasibility of interrelating many other forms of energy; ecological flows, human labor or "life style," research, and other types.

5. A Western focus would be emphasized as it regards fossil fuels. It was assumed that a national importance could be attached to such a study because of the increasing significance of Western energy production.

6. Technologies which exist or which may be on line by the early 1980's should be included. Technologies for which research and development is in early stages should be excluded at this time, because data are weak and decisions on their implementation are not imminent. This assumption is an important one, and has obvious ramifications to the use of a boundary which includes "unrecovered or lost resource."

7. The energy inputs and outputs of the production system should include environmental control equipment as an integral and necessary part of the system. Environmental quality control should be a requirement in all aspects of energy production.

8. The study should not examine other concepts such as theoretical limits to efficiencies in extracting, transporting or processing fossil fuels, or intertemporal flows and accounting. While such studies have validity, the CERI study would confine itself to the actual direct and indirect energy flows, examined as a static condition.

9. The team would make no value judgements about society's demand for various types of fuels. It would assume that fuels of various qualities are needed by society. "Quality" as used here is a loose term covering such factors as usability, utility, timing, transportability, location, form of energy, and other non-quantitative descriptors. Quality has a thermodynamic meaning, also: the ability of energy to do work.

C. Study Boundaries

The CERI purpose is to determine data and facts for any possible direct use in the near future. Therefore, boundaries for this study were eventually drawn to include discrete systems for which valid data can be analyzed. If the purpose were to understand large, complex systems involving money, energy and materials (along with other social and natural variables), the boundaries would be larger. There is unquestionably a need for research on the broader systems, but there is also a need for research on hard data in discrete subsystems.

The boundaries of this study include:

- Fossil fuel Industrial System;
- American fossil fuels, with western emphasis;
- Technology available in mid-1980's;
- From resource to point of end use;
- Life-time of processes (approximately 20 to 35 years);
- Static, not dynamic (i.e. not including long-term trends, except as discernable from comparison of various static trajectories or intertemporal flows);
- General geographic rather than site-specific geographic scope;
- Energy and the energy-equivalents of materials, as inputs;
- Actual, not theoretically-feasible, energy flows;
- By-products of energy processing.

Environmental assumptions which relate to boundary conditions of the energy system and its outputs were based on the principle that the technologies will be "environmentally acceptable." While that may mean different things to different people, in the context of this study it means such things as:

- Mining will be done where rehabilitation is feasible, outside of river bottoms and unsuitable physiography, without disruption to aquifers, rare and endangered habitats, etc.;
- Waste disposal will be handled to minimize impacts; this includes waste heat;
- Pollutants will be controlled to meet current air and water quality standards; synfuel processes will produce fuels which can be used within environmental standards;
- Massive cummulative changes can be avoided or controlled perhaps by limiting the magnitude of development in any given area consistent with any "carrying capacity" which can be defined.

While these criteria do not mean "no impacts," they assume that impacts and changes are acceptable or else society will prevent the development, through the mechanisms of clean air and water legislation, NEPA, land use controls, politics and other mechanisms. For pragmatic reasons, ecological flows were not included in the boundary.

International movements of energy were not studied, due to data problems. End uses were not included because of the complexity of issues, data and systems pertaining to end uses (considering various forecasted needs, changes in end use technologies and the interrelatedness of end use politics, economics, technologies, life styles and impacts).

Non-fossil fuels were excluded because of time and budget limits and technological uncertainties.

Some energy and non-energy parameters relating to site-specific conditions were excluded. If they had been included, the number of factors and trajectories would multipy beyond a manageable level. The time and costs of obtaining site-specific data are prohibitive for a study of this type. An example would be the energy costs of all alternatives for obtaining cooling water.

Human energy and research energy were not included within the boundary. The reasons are found in the discussion in Section III.

D. Methodology

1. General

Energy-producing systems generally can be divided into steps. For our analysis eight steps were chosen. As shown in Figure 3, they are:

- Extraction loss
- Extraction (including exploration and development)
- Transport I
- Process
- Transport II
- Conversion I
- Conversion II
- Distribution

To clarify each step, consider a particular example; Suppose the energy-producing system is strip-mined coal converted to a liquid boiler fuel for electric power plant use. The system contains the following steps:

- A 5% extraction loss
- Strip mining with short distance (less than 10 miles) truck haulage, and crushing
- Railroad haulage (600 miles)
- Coal Liquefaction
- Liquid Pipeline
- Electrical generation
- Electrical transmission (150 miles)

(This example is in fact one of the systems studied herein.)

Energy-producing systems not only have similar steps; they also often contain the same processes. For example, raw coal which is gasified and raw coal which is liquefied both may be extracted from a surface mine. Also, it is difficult to separate natural gas extraction from petroleum extraction, since both products may be produced from a single well, and since gas and oil exploration and development are indistinguishable. These kinds of redundancies occur many times among energy-producing systems.

The commonalities of energy-producing systems naturally lend themselves to division by process. For this reason we have chosen to analyze energy-producing systems as series, or trajectories, of process modules. We have called this technique "linear-modular analysis."

A module trajectory is a combination of each process step normalized to form an integrated energy producing system. By normalized it is meant that the inputs and outputs of modules in a trajectory are adjusted so as to correspond to proceeding modules. Figure 3 is a display of some of the possible module trajectories of fossil-resource, energy-producing systems.

The chief advantage of using module trajectories to describe energy-producing systems is flexibility. If one wants to alter some part of a system, he changes only the appropriate modules, subject, of course, to technological feasibility. Substitution of one process for another, variation of transportation or distribution distances, and revision of input or output data can all be performed without necessarily affecting the basic structure of the module trajectory. For example, if for a site-specific case, the energy requirements of one petroleum refinery were different from those of an average refinery, the specifically appropriate data can be substituted without changing data for any other module in the petroleum system. (However, other modules would have to be normalized relative to the new refinery outputs.) The flexibility of linear-modular analysis allows easy application to a wide range of energy systems.

Each module of an energy-producing system was analyzed separately. A generalized module is shown in Figure 2. Modules were later combined to form trajectories typical of projected energy-producing systems in the western U.S. Other trajectories can be constructed using data gathered in this study.

A module is characterized by its energy inputs and its energy outputs. Inputs are of two basic types: (1) Principal Energy, which is energy to be processed by the module, and

(2) Energy Loss, which is the sum of losses from Principal Energy and from External Energy during the module process. Losses include degraded energy, physically lost and other unused energy.

The characteristics of Principal Energy affect its processing by the module. For example, heat content per weight of fossil fuel determines energy units of Btu/ton mile. Sulfur content may affect energy requirements for petroleum refining, for coal liquefaction, for coal gasification, and for electric power plant uses. Moisture content of natural gas determines its processing in a gas liquids plant. These effects interact to produce variations in Energy Product and in Energy Loss.

Direct External Energy is a sum of energy (electricity, petroleum fuels, natural gas, and coal) and of energy-equivalent of materials (the direct energy required to manufacture materials used directly by the module process). In fact, energy-equivalent of materials is a second-order energy input, as is the energy necessary directly to support first-order energy input (see Figure 4). Second order analysis includes: (1) direct energy to Module "A", (2) energy equivalents of materials used in the process (both directly used to support the process), and (3) energy required to produce energy. However, second-order analysis fails to consider all important energy inputs, as previously discussed.

There are several ways to organize energy analysis for orders above second order. Four of these possibilities are: (1) an iterative technique which uses data for each fuel source, for electrical generation, and for materials; (2) alternate means of determining energy conversions such as use of input-output matrix equivalents, construction of a small energy input-output matrix, or employment of sensitivity analysis to yield an estimated error range; (3) estimates of materials energy and estimates of multiplying factors for fuel and electricity; (4) a continuation to third, fourth, etc. orders combined with an analysis of total effect in an effort to establish a cutoff level.

A combination of (1) and (2) was selected for this analysis. Since all the common fossil fuels are included in our study, external fuels and electricity inputs were analyzed by iteration. Accuracy of results was as good as or better than the more involved technique of (4), because each fuel result was determined by the team member specifically assigned to that fuel, rather than requiring all members of the team to investigate all the common fossil fuel chains. Thus both efficiency of effort and accuracy of results were improved.

Direct fuel and electricity inputs were iterated using data from our final sample trajectories. There are five common fossil-fuels derived energy inputs -- coal, petroleum products, natural gas, electricity, and materials. The number of inputs which must be determined at order "n" (where n = 1,2,3,...) is 5^n. Consequently, direct computation quickly becomes unmanageable, and therefore we used approximations for orders above order 2.

Indirect energy supporting direct material inputs was calculated using conversion factors reported by Herendeen and Bullard (1). Their Btu-to-dollar equivalents appear to be as accurate as any other method for determining a wide variety of material energy-equivalents. However, their data, obtained by substitutions into the national economic input-output matrix, and by subsequent matrix algebra, were not considered to be reliable enough for first-order inputs for the following reasons:

- I-O data contains inaccuracies due to lack of information, proprietary restrictions, and data collection inconsistencies of time and of methods;
- Information relates to producers rather than products. Thus different products from the same company are summed up as production of the company's primary product;
- Capital goods, which can be significant energy consumers, are not included in the interactive section of the I-O matrix. Thus the energy attributable to plant buildings and equipment is not calculated directly from input-output analysis;
- Aggregation of data by industrial sectors leads to imperfect conversions to physical terms. For example, two items may vary considerably in price due to design features, although the energy required for each item is approximately the same. Conversion using an average Btu/$ factor distorts the energy requirement for each item. Also, different technologies which produce similar products are averaged, despite large possible differences in energy use;
- The interactive coefficients in an I-O model are assumed to remain constant with time. In fact, these coefficients change, sometimes significantly. Large errors can arise from changing coefficients, and this problem is likely to be particularly acute in the direct energy sectors due to rapidly changing fuel prices, to fuel substitutions, to pollution control requirements, and to energy conservation;
- Physical losses in manufactured products are not always accounted in economic data. Thus, the coal lost during coal processing may or may not be recognized in the input-output interaction, although considerable energy may be involved;
- A new technology sector is difficult to add to an extensive I-O table. A new addition requires development of the entire set of interactive coefficients. (The addition of one sector to the 357-sector national I-O table would require an additional 715 coefficients). The alternative -- adding new technology to an existing economic sector -- presents the difficulty discussed above in point 4. Furthermore, the output from new technology is so small as generally to be insignificant in aggregate with an established activity.

In addition to these seven qualifications there seems to be substantial differences in results for the base years 1963 and 1967 used in the Herendeen and Bullard study. Reproduced in Table 4 are results for the sectors most used in our study.

Differences between 1963 and 1967 data generally vary over an acceptable range of 10%-20%, but the large (30%) differences for three of the five energy sectors indicate serious reliability problems with the I-O technique, at least for energy sectors in direct energy.

Although our confidence level in the I-O conversion factors was not as high as we wished, the I-O factors are the best current method for determining energy equivalents of material products. An energy-content handbook constructed from specific investigations of the most important industrial sectors would be a very valuable tool in energy analyses. We suggest that a handbook should be made using linear-modular analysis or a similar technique.

All energy inputs -- Principal Energy and External Energy (including direct fuels and electricity and indirect energy for fuels, electricity, and materials) are divided among

Table 4

	Sector	1963 Primary Fuel	1967 Primary Fuel	Difference %
700	Coal Mining	1.0142	1.0068	-52
800	Crude Petroleum & Gas	1.0403	1.0568	+41
3101	Petroleum Refining Products	1.2010	1.2082	+ 4
6801	Electric Utilities	3.8887	3.7963	- 3
6802	Gas Utilities	1.1606	1.1005	-37
1102	New Const. Non-Residential	76294	67206	-12
1103	New Const. Public Utilities	86929	79610	- 8
1202	Maintenance Const. Other	80046	57108	-29
2701	Inorgans-Organic Chem.	347918	281962	-19
2704	Misc. Chem. Products	315968	183464	-42
3201	Tires	114102	99053	-13
3701	Steel Products	313193	267425	-15
3703	Iron, Steel Forging	199336	170894	-14
3902	Metal Barrels	159216	141180	-11
4006	Fabricated Plate Work	135647	105163	-22
4208	Pipe	85945	74272	-14
4302	Internal Comb. Engines	67519	61751	-11
4501	Construction Machinery	84700	68040	-20
4502	Mining Machinery	73560	71376	- 3
4503	Oil Field Machinery	84661	72338	-15
4604	Industrial Trucks	74113	59190	-20
4901	Pumps, Compressors	66853	55256	-17
4907	General Industrial Mach.	72225	64383	-11
6103	Locomotive	65879	54421	-17
6104	Railroad Heat Covs	131163	109725	-16

Energy Use By Sectors, 1963 and 1967

the energy outputs -- Energy Product and Energy Loss. That is, $E_{in}=E_{out}$. This fundamental requirement, that there be a balance of energy, avoids confusion as to how to account for internally derived energy. Referring to Figure 11, one can see that internally consumed energy must be counted as part of Energy Loss in order that outputs equal inputs.

Energy Product is comprised of a primary energy form (that became Principal Energy for the next module in a module trajectory) and of the energy equivalent of byproducts produced by the module process. There are two kinds of energy byproducts -- secondary fuels and byproduct materials. For example, a coal liquefaction facility may produce both pipeline-quality gas and sulfur as well as hydrocarbon liquids. Byproduct energy equivalents are considered outputs of the module and are credited the same as the primary energy product.

Energy Loss has three parts. It consists of External Loss, the sum of losses from External Energy inputs; of Physical Loss, leakage, spillage, or disposal of Principal Energy (e.g., venting or flaring of natural gas, oil pipeline spillage, disposal of incompletely retorted oil shale); and of Internal Consumption, the use of Principal Energy for power or for other chemical reaction in the module process (e.g., powering an oil refinery with part of the product slate). Often the difference between Physical Loss and Internal Consumption is indistinguishable in practice. For example, incomplete combustion of a fuel results in some physical loss as unburned hydrocarbons are emitted in the stack gas, but the fuel is used for internal power, and so the total may be counted as internal consumption.

Many processes can be run either by external energy or by internal consumption. Oil refineries can operate on part of the product slate or on natural gas, or on coal, for example. In those modules where technical options are currently available, the assumed option is noted (in Section VI.)

Data were gathered in raw form and then reduced to a standardized Principal Energy of 10^9 Btu. An analysis form was used to report data, for each module. (This is summarized in Section VI.) The left column of the analysis form was completed; conversion factors were applied to obtain all inputs and outputs in Btu's. Our conversion factors for fuels and electricity were as shown in Table 5.

Table 5

Form	Standard Units	Btu Equivalent
Electricity	KwH	3,413
Natural Gas	Scf	1,032
Coal	Ton	20,000,000
Crude Oil	bbl.	5,800,000
Gasoline	gal.	125,000
Diesel	gal.	139,000
Fuel Oil	gal.	139,000
Residual	gal.	150,000

Conversion Factors

Energy equivalents for materials were computed by first deflating to 1967 dollars and then employing the conversion factors derived by Herendeen and Bullard as discussed previsouly. When materials or supplies were not specified by kind, a standard conversion factor of 70,000 Btu/1967$ was used. This factor is an approximate median for the Herendeen and Bullard data. Conversion factors for physical loss and for internal consumption were the estimated heat values.

2. Computation of Indirect Energy

Because we were studying the principal fossil-energy-producing systems, we could rely on our selected trajectories to provide data; thus, we were able to compute second order energy directly. However, since the number of data rises as 5n, where n is the order, we elected to use an approximation to include all orders above second order. This approximation was derived in the following manner.

First, using data from our sample trajectories, we developed Table 6.

Table 6

Energy Form	External Energy Only	External Energy Process Losses	External, Process and Extraction Losses
Electricity	0.15	2.70	4.20
Petroleum	0.10	0.21	2.40
Gas	0.04	0.20	0.20
Coal	0.02	0.02	0.08

Direct Energy Requirements to Support Energy Producing Systems

(These numbers are relative to trajectory output of one unit.)

Electricity is a weighted average, assuming: (1) coal-electric 55%; (2) petroleum-electric 19%, and (3) gas-electric 26%.

The national energy use is given in Table 7.

Table 7

Electricity	9%
Petroleum	53%
Gas	30%
Coal	8%

National Energy Use Percentages

Combining Tables 6 and 7, we have the weighted averages shown in Table 8.

Table 8

Energy Form	External Energy Only	External Energy Process Losses	External, Process and Extraction Losses
Electricity	0.01	0.24	0.38
Petroleum	0.05	0.11	1.27
Gas	0.01	0.06	0.06
Coal	0.00	0.00	0.01
Total	0.07	0.41	1.72

Weighted Averages of Direct Energy Requirements for U.S. Energy System
(Numbers relative to one unit of output of trajectories)

The totals of Table 8 represent the average direct energy requirements to support energy-producing systems. The results are that on the average one unit of energy produced by fossil fuel systems require 0.07 units from other systems, lose 0.41 units of energy during processing, and suffer an additional loss of 1.31 units (1.72 - 0.41 units) of energy during extraction. In order to find the sum of all energy requirements we must iterate. We solve the following series:

- First, $0.07 + (0.07)^2 + (0.07)^3 + \ldots = \frac{0.07}{1-(0.07)} = 0.0752$ which is rounded to 0.08.
- Next, $0.41 = 0.07 + 0.34$. Only the 0.07 representing energy from other systems is iterated, since other process losses suffer no additional losses. Then $=$ $0.34 + 0.07 + 0.07\,(0.41) + (0.07)^2(0.41) + (0.07)^3(0.41) + \ldots = 0.34 + 0.07 + 0.41\,\frac{(0.07)}{(1-0.07)} = 0.44$,
- $1.72 = 1.31 + 0.45 + 0.07$. Again only the 0.07 need be iterated. $= 1.31 + 0.34 + 0.07 + 0.07(1.72) = (0.07)^2(1.72) + (0.07)^3(1.72) + \ldots = 1.72 + 1.72\,\frac{(0.07)}{(1-0.07)} = 1.85$.

We constructed Table 9 which lists the additional indirect energy, beyond direct energy inputs, required to support energy-producing systems.

Table 9

Energy Form	External Energy Only	External Energy Process Losses	External, Process and Extraction Losses
Electricity	0.01	0.07	0.28
Petroleum	0.01	0.04	0.18
Gas	0.00	0.02	0.07
Coal	0.00	0.01	0.04

Average Indirect Energy Requirements (Fraction) To Support Energy-Producing Systems

Then, we developed Table 10, which includes both direct and indirect energy required to support energy-producing systems.

Table 10

Energy Form	External Energy Only	External Energy Process Losses	External, Process and Extraction Losses
Electricity	0.16	2.77	4.50
Petroleum	0.11	0.25	2.58
Gas	0.04	0.22	0.27
Coal	0.02	0.03	0.12

Average Direct & Indirect Energy Requirements (Fraction) To Support Energy-Producing Systems

Energy multiplying factors are determined merely by adding the energy produced (1.00) to each number in Table 10. To check our numbers derived by this method we compare the multiplying factors including both External and Process Losses with those (which correspond) derived by Herendeen and Bullard using I-O data, as in Table 11.

Table 11

Energy Form	CERI	Herendeen and Bullard 1963	Herendeen and Bullard 1967
Electricity	3.77	3.8887	3.7963
Petroleum	1.29	1.2413 (1)	1.2650 (1)
Gas	1.22	1.1606	1.1005
Coal	1.03	1.0142	1.0068

(1) Obtained by adding Crude Petroleum to Petroleum Refinery Products.

Comparative Data: Energy Requirements Multipliers

The agreement for electricity, coal and petroleum is very good. Agreement for gas is not good, but neither is it between data of the two base years 1963 and 1967 of Herendeen and Bullard. Overall there seems to be reason for good confidence in the results derived here.

References and Footnotes - Section IV

1 Herendeen and Bullard, op.cit.

V. POTENTIAL NET ENERGY ANALYSIS APPLICATIONS

A. General Types of Decisions

"It seems that there is almost no energy policy problem to which energy analysis and net energy analysis cannot be applied," reported one subgroup at the NSF-Stanford Workshop. Since net energy analysis is not locked into a single rigid boundary and accounting system, this sanguine statement may be valid. The discussion in Section III of this Report explored issues and problems to which net energy analysis relates.

There are various types of decisions in which net energy analysis might be used. These are as follows:

1. Federal Government
   - Research, development and demonstration projects, as stated in Public Law 93-577;
   - Programs and projects involving direct Federal funding and action, such as water resource projects or transportation facilities; net energy analysis is applicable only if the product of the action is to be energy (hydropower, thermal electric power, etc.) but energy analysis may be useful in general;
   - Control and regulation, such as permits by the Federal Power Commission or leasing programs of the Bureau of Land Management; the "Energy Minerals Activity Recommendations System" (ERMARS) might be a prime candidate for the use of net energy analysis;
   - Planning: overall national energy and resource planning; regional energy studies such as the Northern Great Plains Resources Program; importation policies for energy; "energy park" planning; and
   - Fiscal actions: taxation, price controls, and "subsidy" programs such as the synthetic fuels commercialization program.
2. State Government
   - State actions: these are few in comparison with the Federal public works programs, but both general energy analysis and net energy analysis could be applied;
   - Control and regulation: permits and licenses for gas and oil production; facilities siting; utility expansion or change of service area;
   - Research, development and demonstration: although this is also limited in comparison with the Federal Government, there may be greater State involvment in the future. The State participation may be in issuing bonds for facilities to be built by private industry. Ohio's legislation could be an example of potential application to ensure that bonding capacity is wisely used;
   - Planning: State energy policy planning; State participation in Federal planning, should this become meaningful and properly organized; and
   - Fiscal actions, especially taxation, which can be a powerful tool at State level.
3. Industry
   - Multi-industry research and development through industry organizations such as the Electric Power Research Institute, the American Petroleum Institute, the American Gas Association, or the Institute for Gas Technology;

- Individual industry: siting; energy mix decisions by utilities, base load vs. peak load alternatives; new process or process expansion (such as a refinery) to identify factors not revealed by purely economic analysis; conservation and efficiency engineering; energy supply variables pertinent to industries which produce energy intensive products (for example, should Detroit build cars to use shale oil products, methanol, diesel oil, electricity, etc.)(1) and
- Multi-industry development such as electrical transmission grids, power plants, energy parks.

The <u>mechanisms</u> by which net energy analysis might be applied to these types of decisions could include: siting studies; environmental impact studies; technology assessments; energy models such as the Reference Energy System, and general policy and supply-demand analysis.

The <u>techniques</u> for applying net energy analysis are varied. Some examples which we suggest for further exploration are as follows:

B. Net Energy Analysis as a Policy Tool

We now realize that some energy resources are in short supply and that the current market prices of energy resources probably do not reflect their true social value. Accounting prices must therefore be assigned to elements of projects related to energy production and use to take into consideration this divergence between market and social value.

This is the point at which net energy analysis may be of some help. Our interest here is in explaining how net energy studies might be of use in public policy. It is clearly a political decision as to whether they should be and will be used. We have chosen four major areas in which net energy analysis may be of use in policy decisions. These are in the general areas of:

- <u>Cost-Benefit Analysis</u>
- <u>Taxation</u>
- <u>Evaluations of Technical Change</u>
- <u>Models of Resource Exploitation</u>

Others may soon become obvious as this kind of work continues. The examples and discussion which follow are, at this time, theoretical. CERI has not, in this study, actually applied the following concepts, and therefore suggests that they may be valuable as tools for use in decision-making after further exploration of these concepts.

1. Cost-Benefit Analysis

Let us use an example of a public decision to support or deny support to energy-producing projects. Assume that there are more potential projects than can be supported and therefore cost-benefit analysis is being used (this is standard practice) to help choose those projects which are most deserving of public support (if any are at all). Suppose that there are two projects which have the same economic rate of return when proper accounting prices are used on all inputs and outputs, but where no adjustment has been made for energy balance. Assume further that Project A has been shown to have an energy input-output ratio of 0.5 while Project B has one of 0.25 (using any ratio discussed in this Report). If the projects are otherwise equal, Project B should clearly be chosen because it economizes best in the use of energy resources. Standard cost-benefit analysis would leave public officials indifferent between the two projects, but if we assign a higher weight (i.e. raise the accounting price) to the output of Project B, as we apparently should in this case, then Project B would be clearly superior. Here any extra weight assigned to Project B's output would show it preferable.

But most project choices are not like the one illustrated here. Rarely are both projects equal in all respects other than in their energy balance. The trick is to come up with specific weights which bear a relationship to the energy balance and which are used to adjust the accounting prices of the projects' outputs.

Suppose, for example only, we chose to weight the net output of each project by the inverse of their energy input-output ratio. Thus, the net output of A would be multiplied by 2 and that of B by 4, so that the output of the most energy-efficient project receives extra weight. Now, even in some cases where the net benefits of B, calculated in the traditional way, are less than those of A, B will be shown to be superior when output is adjusted by the energy balance weighting system. Some projects which would not have received public support before considering energy input-output weights may be shown superior after such weights are attached.

Exactly what weights are to be used? We are not prepared to say. To some extent such choices will be arbitrary and could be established by legislation. Economic research into the true social value of energy should probably be done to serve as a guide. This again is standard procedure. For example, the Bureau of Outdoor Recreation (BOR) has established accounting prices to be used in the assignment of value to various types of outdoor recreation: hiking, fishing, boating, etc.,(2,3) and thus, no market prices are available at all. The BOR was guided in the determination of the values used by research done by economists and sociologists. There is no reason to think that assigning weights to different energy intensities is in principle any different from the assignment of weights by the BOR and many other Federal and State agencies, to benefits for which no market determined prices exist.

One could argue that there is in fact no need to change the way in which cost-benefit analysis is normally done and that it would indeed be best left as is. One could still incorporate the information gained in energy balance studies but in a more revealing way from that suggested above. The main concern lies with the fact that all Btu's are not of equal value. Society simply does different things with different fuels and each has its corresponding value. This point is often missed by persons advocating the wide use of energy balance studies in public policy decisions. Slesser,(4) for example, considers it a "difficulty" that "energy sells at widely varying prices." Difficulty or not, it is a fact that prices differ for different forms of energy because all energy is not alike. Higher quality (i.e., an ability to do the work demanded by consumers in the manner preferred by them) forms of energy carry higher prices than those of lower quality. Any abstraction which ignores the basic qualitative differences among energy sources severely distorts an analysis of what is ultimately human values, which are in part dependent upon thermodynamic realities.

Thus, one should collect and account for all energy input and output in an energy production system but, as previously discussed, energy from different sources (measured in say Btu's), if added together, has the qualitative differences concealed. These energies are each essentially different in value. In cost-benefit analysis the economist would know at what point a specific energy input or output occurred and the form in which the energy entered or left the system. He could then assign an accounting price to them, add them in with other inputs and outputs and then calculate the net present value of the project. In this way all inputs can be considered simultaneously and all can be valued in conformity with social preferences. No problem of discounting occurs since all would be expressed in money terms and spread over time in such a way that discounting can proceed as usual.

Using the method suggested above avoids creating dual criteria by which projects must be evaluated. Rather, we use a tried and accepted method which very easily handles our concern with energy scarcity. The energy analysis is integrated into cost-benefit analysis; if a project passes the cost-benefit test then the project is worthy of public support. If cost-benefit and energy balance studies were conducted separately there are no clear-cut criteria for project selection. A project might look acceptable from a cost-benefit point of view but unacceptable from the energy balance side. The question then must center upon priorities. Which criterion becomes overriding? If the two criteria conflict is there a tradeoff, what is it and who determines what it is? The maintenance of two (or more) separate criteria for project evaluation is clumsy and, in our mind, unnecessary since energy considerations can be integrated easily with normal cost-benefit calculations.

This example involves time flows, or intertemporal flows of money and energy.

The question of discounting has arisen. We do not believe that it is necessary to discount energy flows in net energy analysis. Energy values (Btu's) are simple, physical facts, which hold across time. A Btu now will be physically identical to one ten years from now. What will be different is the social value of a Btu ten years from now. But the social value is derived from more than physical data. As we have discussed elsewhere, the social value, reflected in prices, is derived from a combination of physical relationships (technology) and society's tastes and preferences. Since both technology and tastes and preferences change over time, the social value of things (e.g. energy) change over time. It is this social value which must be discounted, not physical Btu's.

One economic tool which might be useful is the concept of "internal rate of return," which is similar to discounting. The internal rate of return is that discount rate which, if applied to net costs and benefits, would make the present value of the project exactly zero.

Assume Project A has the following characteristics:

	Period 1	2	......	10
Energy input	1,000	100	......	100
Energy output	0	265	......	265
Net	-1,000	165		165

Project A
(10^9 Btu)

Assume the present cost of a project is "C". Assume that in each year of the project there are net benefits of "B_j" where "j" indicates the year and "j" = 1...n. The present value (V) of a unit amount which occurs in "m" years when the discount rate is "i", can be shown to be:

$$v = \frac{1}{(1 + i)^m}$$

Thus we can find the present value of each B_j (i.e. V_j). Then make the subtraction by choosing an appropriate "i". These calculations are available in tabular form in most books of standard mathematical tables.

The project requires one year to put in operation with an energy cost of 1,000 x 10^9 Btu after which an operating input of 100 x 10^9 Btu results in an output of 265 x 10^9 Btu per year for 9 years. The internal rate of return on this project is (roughly) 7 percent. Its energy balance is 1900 x 10^9 Btu compared to 2385 x 10^9 out. (Ratio of output to input is 1.25). This could then be compared to Project B which is strung out over a different time period:

	Period 1	2	3	......	20
Energy in	1,000	1,000	50	......	20
Energy out	0	0	252	......	252
Net	-1,000	-1,000	202		202

Project B
(10^9 Btu)

Project B has an energy balance of 2900 x 10^9 Btu in and 4536 x 10^9 Btu out. The out/in ratio is 1.56, which on the surface would make it look better than Project A. Its internal rate of return, however, is only about 6 percent.

Philosophically, the internal rate of return concept is slightly different from discounting. The latter relates to present value of some future amount. Internal rate of return is the return on an investment - in this case, an energy investment. It tells us the rate at which energy is returned to us relative to the original investment, if we invest a certain amount of energy and we get energy in return.

2. Taxation

One potential application of the methods developed by CERI is in the area of taxation to achieve greater economy in fuel consumption. Hudson and Jorgenson have proposed that a Btu tax be instituted to secure energy independence in the U.S.(5,6) The tax recommended by them is a uniform rate of tax levied on the energy content of all fuels used outside the energy production sectors. Such a tax was proposed in The Energy Revenue and Development Act of 1973 and has since been under consideration by The Senate Finance Committee. While their tax is assumed to be levied on fuels as they leave the fuel sectors, there is no reason why the taxation of energy inputs into energy production could not be given the same tax treatment. The tax is translated into an increase in the selling price of fuels and these markups vary for the fuels considered since the Btu content of each dollar of fuel output is different for each fuel. Thus, the tax would be lower per dollar's worth of electricity than per dollar's worth of natural gas since the latter contains a greater Btu value.

Clearly implementation of the proposed Btu tax requires considerable information about the energy inputs into production in order to determine the overall impact of the tax. It would not be necessary to tax each user of fuels separately since taxation could be done at the source. Presumably the tax would be used to meet certain specified objectives such as found in "Project Independence," etc., and meeting these objectives could not possibly be analysed without knowledge of the way in which energy was used in each production sector and the impact that the tax-induced price rise would have upon energy consumption. Price rises do affect economy in energy use: see Hudson and Jorgenson(7), Griffin(8), Davidson et al.(9), and Erickson et al(10).

The Hudson-Jorgenson model uses only nine productive sectors to represent the U.S. economy. Their results can therefore be considered only approximations until more disaggregative procedures are used. Nevertheless, they estimate that a tax of \$.50 per million Btu's would cut energy inputs in the U.S. by about 7.8 percent by 1980, with the largest cut being made in personal consumption (9.5%) and in the service sector (7.1%). Smallest cuts are in the electrical generation industry (2.1%) which is much more closely confined by technological considerations than are the other sectors used in their model.

As mentioned above the Btu tax would raise the prices of the different fuels by different amounts depending upon the energy content per dollar's worth of each fuel. The percentage rise in prices from the base price (1973) for two different tax rates: \$.30 and \$.50 per million Btu, for four fuels are as follows:

	Tax Rate	
	\$.30	\$.50
Coal	16.9	28.3
Refined Petroleum	13.7	22.8
Electricity	4.0	6.6
Natural Gas	14.6	23.4

Changes in price from 1973 base (%)

Whether or not the rates suggested by Hudson and Jorgenson are appropriate can easily be questioned. (This is not to criticize their method since their objective is to economize on fuel use and not to differentiate among the fuels.)

Coal prices rise more than any of the others (though its absolute price remains lowest) despite its relative abundance in the U.S. Thus, if an additional objective were added to the tax measure, that of economizing most on those fuels which were most scarce, we would want to tax coal proportionately less than the other fuels. Secondly, the tax rates used here do not reflect the energy input into the production of the fuel sources listed. Clearly the energy input into electrical generation, relative to the fuel value of the electrical output, is most unfavorable. Yet the price of electricity is raised least by the proposed tax. Hudson and Jorgenson simply do not have the information to make this adjustment but it is this information which is generated in this study. Thirdly, the breakdown into only four fuel types is inadequate since there are several ways to produce each of the fuels listed and each technology implies different energy intensities to deliver each dollar's worth of fuel to the final consumer.

Net energy analysis is particularly well suited to contributing to solutions of the second two criticisms listed. Assume that the tax rates should in some way represent the energy input into fuel production. We could rank the various fuels by the energy intensity of their production. Using this information, tax rates per Btu could be devised which penalize those energy forms which are most energy intensive in their production.

3. Assessment of Technological Change

One straight-forward application of energy balance studies is in its ability to aid in the evaluation of technological change as it affects energy use. Traditionally, economists have considered technological change as a process which allows a given output to be produced at a lower cost.(11) "Cost" however refers to total cost and does not distinguish among the various components of "cost", i.e., between energy cost and all other costs. Hordhaus' (1974) work shows that in the 1900-1970 period the cost of energy (as well as other minerals) declined relative to the cost of labor.(12) It is a basic tenet of economic theory (and substantiated by empirical evidence) that as the price of one input into a production process rises relative to other inputs, there occurs a substitution of the now relatively cheaper input for the relatively dear one. Thus, as energy becomes relatively cheap by comparison with labor we would expect energy to be substituted for labor so as to accomplish a given amount of output.(13) This substitution can lower total costs (and in fact will not be done unless it does) and thus "efficiency" goes up. But this is by the conventional definition of efficiency and does not speak to the fact that energy efficiency has declined. Indeed economic "efficiency" relates costs to output and an improvement in efficiency is defined as decreasing cost for a given output.

Clearly over the past seventy years "efficiency" in terms of total cost per given unit of output has increased. But due to the probable substitution of energy for other inputs, labor being only one of them, energy efficienty may have declined. Now that we have realized the important role of energy in our society and have become painfully aware of the limited supplies of it, concern is shifting in order to distinguish between overall efficiency and energy efficiency. The methods being developed by CERI are particularly well suited to evaluations of the latter. A monitoring system which periodically recorded the energy balance for a given production process would allow us to see how energy efficiency is faring over time. These data have not been collected in the past and thus estimates of energy efficiency in the past can be made only by inference. In the future, however, we can begin to rely upon energy balance studies to evaluate technological changes as they occur.

4. Models of Resource Exploitation

One of the major problems in economic models which analyze the optimal rates for resource exploitation is that they do not take into account the finite resources with which the world is endowed. Most of these models deal only on the micro level, such as that of the firm engaged in resource exploitation. These models deal only with such variables as price, capital costs, costs of exploration, technical progress (as conventionally defined above) and others, which are of relevance to the firm.(14,15,16,17) It has been clearly pointed out, however, that on the macro-level greater attention must be paid to the finiteness of our natural resource, and particularly energy endowment.(18)

Georgescue-Rogen clearly points out that "available" energy (available to do work) comes from two sources: (1) the stock of energy locked up in the earth's minerals and (2) the flow of energy from the sun. Modernization throughout the world has shifted man's source of energy from the sun (infinite energy) to the finite sources of the earth's crust. The "modernization" of agriculture is probably the most vivid example of this trend. As we "use up" the finite stock of energy in the earth (raise its entropy) we approach the point where the sun will constitute the only source. Simply, if the stock is "S" and the rate of degradation (maximization of entropy) is "r", the stock will last for S/r years.

More rapid economic growth implies that "r" rises and thus the shorter S/r; i.e., the life-style of the human species as we know it.

Some economists have been comfortable in the short run belief that somehow the technological change that we have experienced in the past will bail us out again as resource scarcity increases.(19) Macro-level analysis can produce fairly accurate projections of energy demands. For example, the Paley Commission, created in 1952 by the Truman administration to project resource demands for the 1970's, estimated a 97 percent increase in energy demand by the mid-1970's. The actual demand increase was 112 percent. This small error occurred because the Commission was rather pessimistic in its expectations for economic growth.(20) Nevertheless, none of these analyses consider the finite resources with which we are working.(21) What is worse, none of these models can take this into account in any empirical sense since calculations of this sort would require: (1) knowledge of resource availability which we do not now have, and (2) knowledge of future technological change (which we do not have either).(22) The energy balance analytical methods of this study cannot provide for these missing ingredients. However, these methods can help us evaluate technical progress while it is occurring and perhaps help foresee progress which will occur in "new" energy areas such as oil shale exploitation, coal gasification, etc. While we still may not know total resources available worldwide, we know that they are finite and that reducing their rate of degradation will prolong human society as we know it. The energy balance calculations speak directly to this rate.

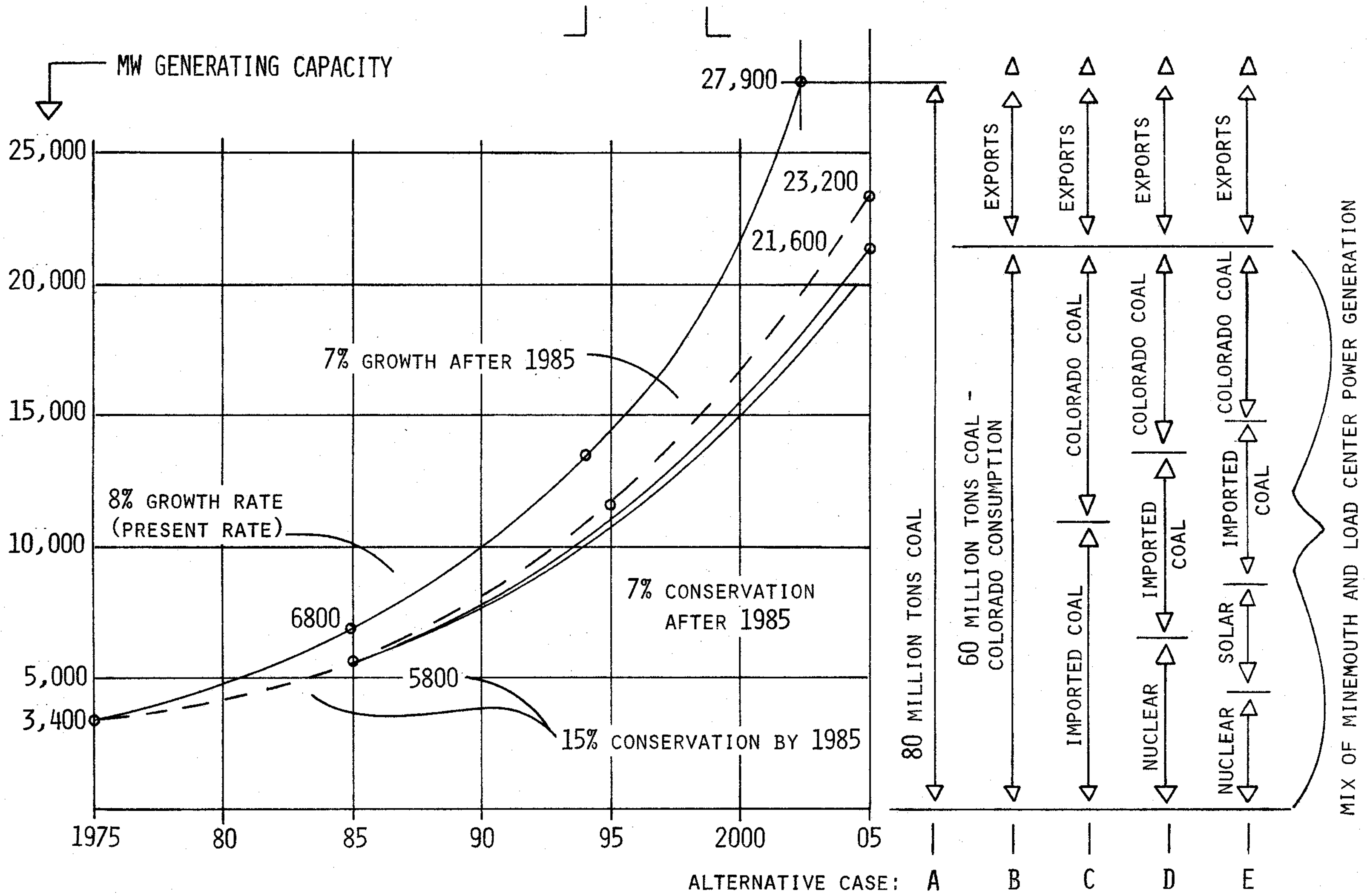
The application of this point could come about through modification of models used by ERDA, FEA and others, or through the development of entirely new models.

As an example, in a recent study by CERI, results made it possible to envision a very plausible scenario for growth of electricity production. This scenario would be based on high population growth, shifts to electricity in end uses, and more rapid development of energy-intensive industries. Various mixes of electricity generation and of Colorado coal production and exports can be considered. If 40 million tons of coal were being produced in Colorado by about the year 2000, then the present reserves of surface coal could be exhausted by perhaps year 2010. Figure 17 illustrates this potential growth and alternatives. However, if coal syngas were to meet the inherent demand for energy and shifts to coal-electric did not occur due to constrained gas supplies, the coal reserve depletion would be reduced. Figure 18 illustrates the concept, which needs more exploration. The policies of FPC and Congress would affect the decisions; the State government could play a role.

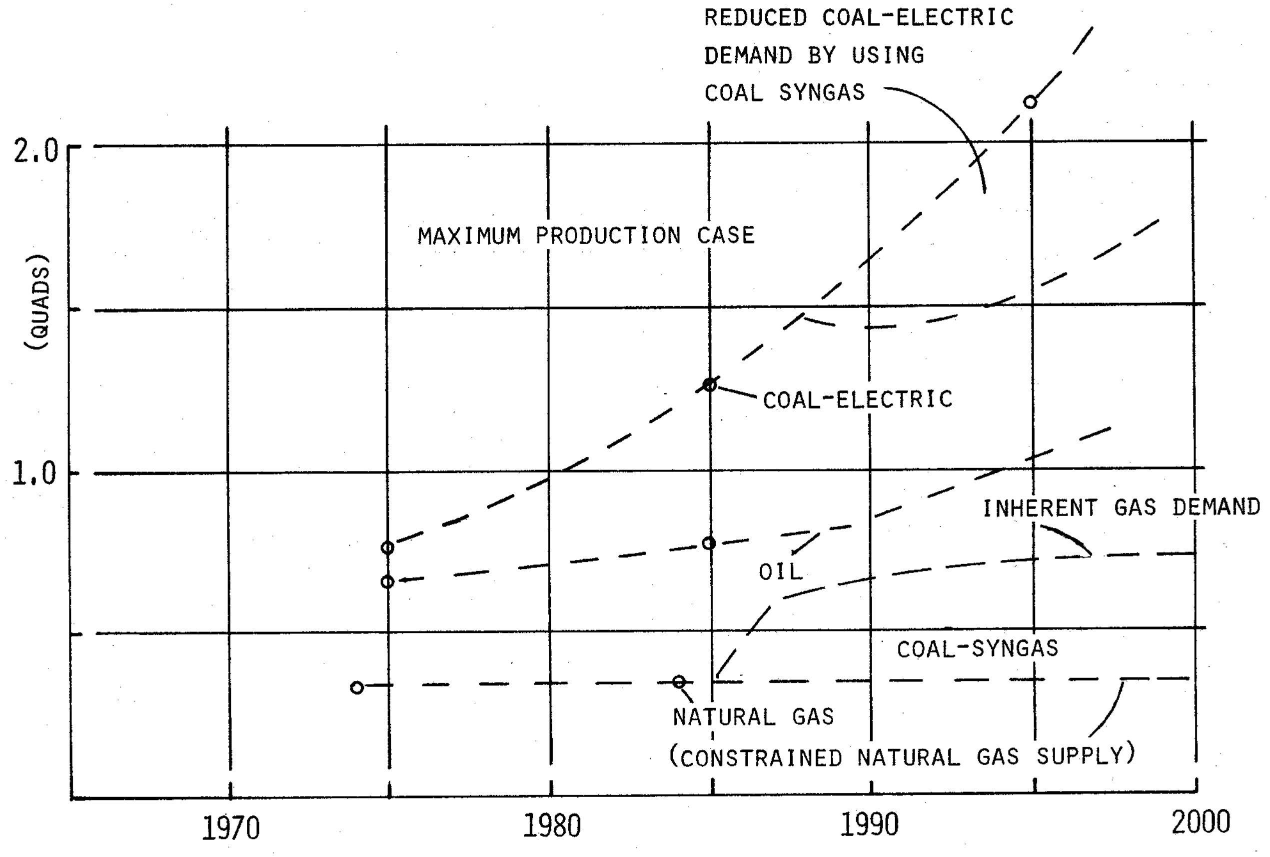
C. Problems and Caveats

In discussing the potential applications of net energy analysis, we have thought about a number of reservations and caveats which should be mentioned whether one is talking about public policy or energy company use of net energy analysis.

Energy balance studies are not easy to conduct at this time. They will become easier because of this study and perhaps others, so that ground rules, methodologies and data are readily established. Then, a single company could, in general, do an energy balance study fairly easily. There would be some cases where an energy balance study would be difficult, but a company would have the data at hand and would not have to dig it out as the CERI team has done.



COLORADO ELECTRICAL GROWTH: POTENTIAL
FIGURE 17



ALTERNATIVE SCENARIOS CONCEPT
COLORADO TOTAL ENERGY CONSUMPTION FORECAST
FIGURE 18

If companies do such studies, they will have to decide whether to do them on complete trajectories, or only on the portion of the trajectories over which they have control. It might be impossible for them to analyze a complete trajectory, as they may lack information on the behavior of the trajectory before or after the energy enters their part of the trajectory.

Legislation may be difficult to enforce or monitor. At the State level, this might not be too difficult or costly if the State has some existing mechanism, such as Montana's Energy Facilities Siting Act or California's Energy Conservation and Development Commission and its staff. If a special body had to be created simply to handle the monitoring of energy balance studies, the wisdom of such a use of State financial and personnel resources is questionable. The mechanisms and reports needed for monitoring would probably be a burden.

At the Federal level, the monitoring could be done for programs or projects. At the project level, no single agency has control authority over all types of energy development, so project net energy review would reside with various agencies. This means, that even if there were a common codified set of ground rules, interpretation and utilization would vary from agency to agency. Again, at the project level, ground rules would be needed to decide if the analysis were confined to the facility in question or on a while trajectory or trajectories.

At the Federal program level, a single agency could have comprehensive energy systems review authority for net energy, or different agencies could deal with the various aspects of energy in different programs. If only monitoring/review/non-regulatory roles were envisioned for Federal programs, then ERDA might well assume all responsibilities. It could utilize net energy analysis to seek technological improvements through R&D. Taxation and benefit-cost analysis, as discussed, could be done by various branches of government.

Enforcement at State or Federal level is another problem, if it is to be considered. There would have to (a) established net energy balance procedures, or (b) minimum acceptable ratios of net yields.

The rapidity of technological change militates against the establishment of minimum threshholds. These would have to be established for every type of energy needed for end uses. They would vary from type to type, and could change every year or two as technological improvements occur. It could actually be counter-productive to lock in any standards, as these might become the maximum for which a company would aim. The entire mechanism for legal adoption and enforcement could be cumbersome and unwieldy, given requirements of due process of law.

One possible use of net energy analysis in the regulation or control context would be in a permit process. A company could be required to show that it had used "best practicable means" to minimize input of energy, minimize or utilize waste energy, etc. This could be similar to the air and water quality control laws. Again, questions of the responsible agency, how to enforce, and other matters are relevant.

Legislation on net energy analysis may not be the best way to achieve the objectives underlying such analysis. Administration of such legislation would require money and people, as noted. This could be counter-productive as noted in "(3)" above and might direct attention from larger objectives and solutions. It could burden a company with reports, permits, controls, etc., few of which might add to national productivity. There is, however, a strong potential case that company overhead devoted to improvement of energy balances would increase national productivity. If companies (and government) were forced to take a look at the inputs and outputs of energy and energy equivalents of materials, it may well be that significant improvements in productivity could result.

It might be a better use of personnel and money to directly attack issues of waste heat, end use efficiency, "energy parks," life style, etc., without burden of massive net energy legislation and monitoring. Legislation could perhaps be oriented towards other goals than doing net energy analysis, for instance, towards stimulating renewable energy sources through tax incentives or assisting in creating new industries to provide the incentives to create them. It could stimulate technological changes such as "bottoming cycles," perhaps with economic incentives such as fast tax write-offs for the equipment. These may be more productive than rigorous governmental requirements for energy balance studies, considering the use of personnel and money. Net energy analysis could be used as a tool, but not necessarily in a legislative or regulatory manner.

A critical question legislators or regulators would have to face is in selecting the issues they wish to address, in order to decide on system boundaries and accounting methods. There is no reason why several boundaries/accounting systems could not be included. To do so, however, would increase the complexity of the legislation/regulation and would create more debate in operating the legislation or regulation.

Another important question regarding legislation on project-level net energy analysis is: would decision-making be altered? Aspects of this have been discussed above. Other aspects are:

- Would companies be forced to alter decisions in a manner contrary to the economics which must be the most influential aspect of their decisions? This might vary with the type of company (regulated utility, partially-regulated oil and gas firm, coal mine, etc.). Some could pass costs on to consumers if they were forced to spend money to improve energy balances. Others could not.
- Would companies go through the motions of a study without actually using the study to improve energy balances? Would they do this if there were no economic incentive to improve energy balances?

"Program-level" (such as mineral leasing programs) net energy analyses would usually be governmental. If used to compare alternative types of energy production, it must be decided how the comparisons should be weighted between energy balance, economic impact, end use needs, environmental impact, foreign policies and economics, capital needs, materials needs, manpower needs, resource depletion and other factors.

Program-level analysis could become more political than technological if a study of comparative net energy analysis showed one alternative as "more favorable" but this alternative would result in economic or environmental implications to one state or region. The study itself could be misused and challenged, and would end as a political football.

The comparison of actual vs. theoretical efficiencies, as used by the Federal Power Commission in one decision and American Physical Society, is one approach. Should it be utilized in preference to net energy analysis?

A decision involving the Federal Power Commission illustrates the complexity of issues. The FPC decision involved an application for use of off-shore gas as refinery fuel in southern Louisiana. The application was denied; the decision variables included the efficient use of fuels and the input-output factors of the refineries. "Science" stated that this is "perhaps the first example of government order" incorporating the input-output question.

The FPC case in Opinion No. 727, "Tennessee Gas Pipeline Company, a Division of Tenneco, Inc., et al.," Docket No. CP72-6 et al, dated April 17, 1975. The basic issue was approval or denial of a request to transport 77,000 Mcf/day of natural gas from off-shore Louisiana to refineries. The refineries, existing and in planned expansions, desired to use natural gas, along with by-produce gas, as fuel in steam cracking furnaces, gas turbines and engines, feedstock, process furnaces, steam and electrical generation, and other similar uses. The companies provided estimates of their costs to convert to oil, which would cost from $3.0 million to $33.5 million and would result in lost production time and revenues. Also, increased air pollution and decreased thermal efficiency would result.

The producers stressed their ownership of the natural gas, the costs of conversion of facilities to use alternate fuels, the efficiency of refinery use of natural gas, the increased operating expenses that would be incurred in using alternate fuels, and the adverse impact that the use of alternate fuels would have upon the environment. Opponents contended that all offshore gas should be reserved for the interstate pipelines, with the refineries and chemical plants securing such gas from a pipeline subject to Commission priority and curtailment policies. Also, it was contended that to grant the current applications would permit these individuals to obtain firm gas, and avoid Commission curtailment priorities. The FPC contended this major use of natural gas for expanding industrial use is improper in time of shortage, and oil should be used instead. FPC noted that, if pipeline supplies are curtailed, pieplines cannot operate at the highest load factors and efficiency and this will cause higher rates to their customers. Factors which were considered were the use to which the gas is put, the need of the user, prospective alternative uses, whether alternate fuels were available and at what cost, the efficiency of the proposed use of the gas, the effect upon the public of devoting or not devoting the gas to the proposed use, as well as any other factors which bear upon the desirability of gas going to one user rather than another. It was argued that refinery use of gas is so great that it would reduce interstate reserves; this argument was unconvincing to FPC. Refineries, unlike most industries, convert fuel to useable forms as well as consume it, thus somewhat offsetting the reduction in gas reserves. FPC found that the use of gas by the producers in their own refineries in the present case did not amount to unlawful discrimination against independent refiners or producers and there was no unlawful discrimination or violations of anti-trust laws. It was contended that environmental considerations dictate that the certificates be granted, and that they be denied. There was evidence to support either action.

Two types of efficiency were discussed. Witnesses testified that the furnace or "stack" efficiency in the refineries was 79 to 85 percent, and the industry, in general, had an "efficiency" rating of about 84 percent, measured by the ratio of total energy input, including feedstock, to the energy contained in the product output of the refinery. Neither of those measures of "efficiency" of fuel use provides a reliable basis for comparing efficiency of the refining industry with the fuel use efficiency of other industrial processes. FPC said that a more meaningful basis for comparison can be drawn if the theoretical new energy required to effectuate the chemical process in the feedstock is related to the actual process energy that is used. This approach employs the concept of efficiency based upon the theoretical minimum energy required to perform the chemical reactions of the refining or other process. This did not suggest to FPC that the theoretical minimum can be attained in practice. However, it defines a fundamental expression of efficiency that is independent of the use that is made of the fuel, and hence, direct comparison of this efficiency for any fuel consuming process can be more meaningfully made, according to FPC. By defining efficiency as the ratio of minimum energy to the actual energy used, the various industries can be more meaningfully compared in regard to utilization of energy. One refinery uses approximately 563,000 Btu's to refine a barrel of crude oil, which compares favorably with the United States average of 637,000 to 682,000 Btu's per barrel of crude. However, the theoretical minimum energy necessary to accomplish the refining process which is no more than approximately 60,000 Btu's per barrel.(24) Thus measuring actual fuel "efficiency" against that standard indicates that efficiency is only slightly in excess of 10 percent. The equivalent efficiency for selected industries is as follows:

Product	Energy Efficiency
Petroleum	9%
Steel	21%
Aluminum	13%
Cement	10%
Paper	0.3%

Thus, petroleum refiners in general do not outpace other industries in the overall efficiency of energy use.

The FPC further stated that boiler fuel use of natural gas in refineries or chemical plants cannot be justified to a different extent than boiler fuel use in other contexts. The United States is confronted with an apparently continuing diminution in the supply of natural gas which will require progressively greater conversion of facilities to use alternate fuels. While the burning of natural gas in boilers may be a more efficient use of natural gas in absolute terms than some other non-boiler uses, alternate fuels can be more readily substituted and the facilities can be more readily converted in the boiler context than with respect to other industrial uses.

Several factors stand out. First, a broad range of issues were considered. It would appear at present that the energy efficiency issues did not have a high priority in the decision. Second, energy efficiencies for alternative end uses of the fuel ("the desirability of the gas going to one user rather than another") bear on the problem. To address this, one would have to know the end users, and their efficiencies, to make comparisons. This could be exceedingly difficult in cases such as pipeline gas. Third, site-specific aspects of the environmental impacts of alternatives must be evaluated before comparisons can be made. Fourth, the FPC compared real vs ideal efficiencies for various industries. The implication seems to be that fuels should be denied to industries which are farthest below their theoretically ideal efficiency. If that were the case, then the steel industry should have allocated to it all the fuel that it needs, and the refineries should be cut off because of their low rating. This ignores fuel or energy quality, or in this case, materials and energy quality. It appears that a balance must be struck between efficiency for the sake of efficiency and the need for diverse types of energy and materials. Indeed, FPC recognized this in stating that "refineries convert fuels to useable forms as well as consuming it."

Apparently, FPC did not consider some oil-related impacts in using oil as a refinery fuel, such as dollar outflow to OPEC countries, fuel oil shortfalls, and other matters.

FPC did not use net energy analysis, but did use the "second law efficiency" analysis advanced by the American Physics Society. It could have conducted a net energy analysis. Specifically, it would have found out which option actually yielded what amount of various fuels. This case is discussed in detail as one example of the potential application of net energy analysis.

D. Summary

In summary, it is evident that net energy analysis has potential applications in many types of decisions, through many mechanisms, and by various techniques. It also has limitations and problems.(25,26) We close this discussion, however, with an emphatic statement that other factors must influence responsible decisions. These include: (1) economics, (2) environment, (3) national security and safety, (4) energy mixes and substitutability of energy of various qualities desired by society, (5) lead times in development, (6) institutional restraints and regulations such as fair trade, discrimination, etc., (7) availability of materials, water, transportation, labor, capital and other components of energy production, (8) local attitudes and growth, (9) potentials for effectiveness of energy conservation, (10) the need for sufficient energy of various qualities at a reasonable price, and (11) depletion rates of various resources.

References and Footnotes - Section V

1 Steele, op.cit.

2 Capel and Pandey, op.cit.

3 Pope, R.M.; "Evaluations of Recreational Benefits Accruing to Recreators on Federal Water Projects: A Review Article," American Economist, Vol.16, No. 2, 1973.

4 Slesser, op.cit.

5 Hudson, E.A., and Jorgenson, D.W.; "U.S. Energy Policy and Economic Growth, 1975-2000," The Bell Journal of Economics and Management Science, Vol. 5, No. 2, 1974, pp. 461-514.

6 Brannon, G.M.; "U.S. Taxes on Energy Resources," American Economic Review, Vol. 65, No. 2, May 1975, pp. 397-406, contains a discussion of how other taxes affect oil.

7 Judson and Jorgenson, op.cit.

8 Griffin, J.M., "The effects of Higher Prices on Electricity Consumption," The Bell Journal of Economics and Management Science, Vol. 5, No. 2, 1974, pp. 515-539.

9 Davidson, P., et.al.; "Oil: Its Time Allocation and Project Independence," Brookings Papers on Economic Activity, The Brookings Institute, Washington, D.C., 1974, pp. 411-448.

10 Erickson, E.W.; "Oil Supply and Tax Incentives," Brookings Papers on Economic Activity, The Brookings Institute, Washington, D.C., 1974, pp. 449-493.

11 Salter, W.E.G.; "Productivity and Technical Change," Cambridge University Press, Cambridge, England, 1966.

12 Nordhaus, op.cit.

13 That the substitution of labor for energy and vice versa due to relative price changes is observable empirically, see Hudson & Jorgenson (1974). We can only infer changes in energy efficiency since direct studies are inadequate for past time periods. The fact that energy has become cheap relative to other inputs, that substitution of cheap for dear inputs occurs regularly and that energy has substituted for labor make this inference a rather comfortable one.

14 Kulber, R.G., and Cummings, R.G.; "An Economic Model of Production and Investment for Petroleum Reservoirs," American Economic Review, Vol. 65, No. 1, March 1974, pp. 66-79.

15 Cummings, et.al.; "Energy Commodities and Natural Resource Exploitation," Southern Economic Journal, Vol. 41, No. 3, January 1975, pp. 411-448.

16 Rausser, G.C.; "Technological Change, Production, and Investment in Natural Resource Industries," American Economic Review, Vol.64, No.6, December 1974, pp. 1049-59.

17 Bradley, P.G.; "Increasing Scarcity: The Case of Energy Resources," American Economic Review, Vol. 63, No. 2, May 1973, pp. 119-25.

18 Georgescue-Rogen, N.; "Energy and Economic Myths," Southern Economic Journal, Vol. 41, No. 3, January 1975, pp. 347-381; also, "The Entropy Law and The Economic Problem," Distinguished Lecture Series No. 1, University of Alabama, December 3, 1970.

19 Beckerman, W.; "Economists, Scientists and Environmental Catastrophe," Oxford Economic Papers, Vol. 24, No. 3, November 1972, pp. 327-344.

20 Cooper, R.N.; "Resource Needs Revisited," Brookings Papers on Economic Activity, The Brookings Institute, Washington, D.C., 1975, pp. 238-45.

21 Committee on Mineral Resources and the Environment, op.cit.

22 Bradley, op.cit.

23 "Energy Conservation: Better Living Through Thermodynamics," Science, Vol. 188, May 23, 1975, pp. 820-821.

24 "The Potential for Effective Use of Fuel in Industry," Thermo-Electron Corporation Report TE 5357-71-74, April, 1974.

25 Leach, Gerald; "Net Energy Analysis -- Is It Any Use?" Energy Policy, London, England, December 1975, pp. 332-344.

26 Huettner, David A.; "Net Energy Analysis" An Economic Assessment," Science, Vol. 192, April 9, 1976, pp. 101-104.

ADDITIONAL REFERENCES

27 Klass, D.W., and Chambers, W.C., "A Comparison of the Net Energy Production Ratios of Integrated Systems Supplying Natural Gas, and SNG from Coal," Institute of Gas Technology, Chicago, Illinois, April, 1976.

28 Melcher,Albert G.; "Wanted: A Better Approach to Energy Planning," Rocky Mountain Center on Environment, Denver, Colorado, 1972; efficiencies of resource yields by alternative technologies was raised as a planning issue.

29 Northern Great Plains Resources Program Report, U.S. Department of the Interior, 1975.

30 Aalund, Leo; "U.S. Refiners on Btu Hunt," Oil and Gas Journal, April 2, 1973; this article describes refinery process energy analysis to reduce losses and inputs.