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METHODS OF NET ENERGY ANALYSIS AND ITS APPLICATION TO ENERGY PRODUCING SYSTEMS FOR COMPARISON OF ALTERNATIVE ENERGY RESOURCES

By

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ABSTRACT

METHODS OF NET ENERGY ANALYSIS AND ITS APPLICATION TO ENERGY PRODUCING SYSTEMS FOR COMPARISON OF ALTERNATIVE ENERGY RESOURCES

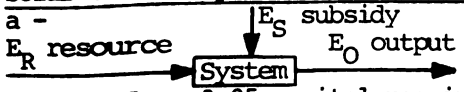
By

Richard Neal Chapman

A methodology for the energy analysis of energy supply systems based on a combination of process and input-output analysis was developed and applied to a coal gasification complex, central receiver power stations, solar derived process heat, crop production and the production of alcohol from corn. Acceptable analyses of fossil fuel based energy supply systems, conventional nuclear power stations, etc., were found in the literature. Results of the analyses of implementable alternatives and conventional systems are tabulated below:

Summary of Analyses Results

System	Overall Process Efficiency[a] (%)	Resource Utilization Factor[a]	Maximum Expansion Rate (%/year)
gasoline from crude oil[1]	82.6	1.11	63[b]
gasoline from coal[1]	61.0	1.49	60[b]
gasoline from oil shale[1]	57.8	1.58	60[b]
alcohol from corn[2]	110.0	0.00	40[b]
electricity from crude oil[1]	27.9	3.48	63[b]
electricity from coal[1]	28.8	3.37	63[b]
nuclear power station[3]	34.1(790.0)[c]	2.74(0.00)[c]	84
central receiver power station[4]	220.0	0.00	8[b]
natural gas[1]	82.9	1.21	67[b]
pipeline gas from coal[1]	60.0	1.63	67[b]
solar derived process heat[5]	310.0	0.00	18

a - 

Overall Process Efficiency = $E_O/(E_R+E_S)$
Resource Utilization Factor = E_R/E_O

b - based on 0.05 capital requirement factor, 30 year system lifetime

c - assumes the energy content of uranium to be freely available

The energy flows into an energy supply system are measured in units of primary energy (i.e., units of fossil fuel equivalents). The overall process efficiency is a measure of the total primary energy embodied in the energy produced and the resource utilization factor is a measure of the quantity of resource (that is converted into a useful energy product) utilized per unit energy produced over the lifetime of an energy supply system. The total energy subsidy required by an energy supply system is comprised of an initial capital energy investment followed by a continuous operational energy input over the lifetime of the system. The expansion of an energy supply system (i.e., the increase in the energy production by a specific technology) requires a re-investment of the energy produced as the capital investment for the construction of more facilities. Assuming a total re-investment of the annual energy produced, the maximum expansion rate measures the maximum annual increase in energy production a specific technology is capable of achieving. In a growth oriented industrial society, alternative technologies producing high quality energy (i.e., electricity and fuels) must have expansion capabilities similar to their fossil fuel based counterparts if they are to operate as independent energy supply systems.

Liquefaction technologies utilizing coal and oil shale require 34 and 42 per cent greater resource depletion respectively compared to crude oil for the production of the same quantity of gasoline due to less efficient conversions of

resources to products. Alcohol from corn does not require the utilization of a non-renewable resource, but production is realistically limited to the annual domestic corn surplus which amounts to about 2 per cent of the annual gasoline consumption by surface vehicles in the United States[6]. The lack of attractive alternatives for the production of liquid fuels suggests consideration of an electric mass-transit system. For example, an electric mass-transit system subsidized by conventional nuclear power plants could conserve 94 per cent of the crude oil resources or 96 per cent of the coal resources required for the provision of the same transportation service (assuming conversion efficiencies of 0.5 and 0.9 for the conversion of liquid fuels and electricity respectively to transportation work)

The obvious alternative for the production of electricity from crude oil and natural gas is the increased production of electrcity from coal. Increased production of electricity from conventional nuclear power plants is limited by natural U^{235} resources. It is estimated that the domestic U^{235} resources will be depleted in 40 years at the present rate of utilization for fabrication of light water nuclear fuel rods. Central receiver power stations could conserve 87 per cent of the crude oil resource required for the production of the same quantity of electricity, but are severely expansion rate limited compared to fossil fueled power plants (i.e., a difference of an order of magnitude in the respective

maximum expansion rates). Therefore, central receiver power stations are unacceptable as independent energy supply systems in the context of a growth oriented industrial society. This suggests the use of the central receiver concept in the repowering of existing fossil fueled power plants in which a portion of the heat load of the turbogenerator is solar derived. Unfortunately, the central receiver concept is restricted to the southwest and western portions of the United States.

In 1979, 56 per cent and 20 per cent of the energy consumed by the industrial and residential/commercial/non-energy sectors respectively of the United States was natural gas comsumed primarily in the production of process or domestic heat. The energy supply system which produces the process heat consumed in the manufacture of investment products such as concrete and steel (as opposed to end-use products) must have an acceptable expansion capability in order to allow the growth of the industrial sector. However, the expansion capabilities of systems producing low grade process or domestic heat are not important characteristics. In such applications, solar derived process heat can conserve 73 per cent of the natural gas resource required to produce the same quantity of heat. However, solar derived process heat applications are location limited. Pipeline gas can be synthesized from coal, but an increase of 35 per cent in the resource utilization compared to natural gas for the production of the same

quantity of gas is required.

It is clear that the total replacement of the domestic crude oil and natural gas utilization can be accomplished only through the extensive utilization of coal resources. However, the replacement of domestic crude oil and natural gas utilization by the year 2010 with coal derived products could deplete domestic coal reserves by about 2030. It is also clear that fossil fuel resources can be conserved through the implementation of solar derived liquid fuels, electricity and process heat and nuclear derived electricity. The transition of energy supply from a fossil fuel based network of energy supply systems to a network of long-term technologies capable of replacing the utilization of fossil fuels will require the availability of sufficient quantities of the energy products necessary to construct the long-term network of energy supply systems. The coal reserves are the only domestic energy resources capable of supplying such quantities of energy products. The extensive utilization of domestic coal reserves to replace the domestic utilization of crude oil and natural gas will not allow sufficient time to develop, construct and implement the technologies capable of replacing fossil fuels. Conservation of fossil fuel resources must be maximized to provide the greatest possible amount of time for the development, construction and implementation of fossil fuel replacement technologies. It is recommended that the consequences of proposed energy policies be quantitatively

assessed through the dynamic energy supply modeling of the transition era in order to select the policy which maximizes the conservation of fossil fuels.

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[1]Chapman, R.N., "Methods of Net Energy Analysis and Its Application to Energy Producing Systems for Comparison of Alternative Energy Resources," M.S. Thesis, Department of Chemical Engineering, Michigan State University, East Lansing, MI, Feb. 1981, p. 174.

[2]Ibid., p. 110, 500 mile coal delivery, 500 mile alcohol delivery.

[3]Ibid., p. 129, Rotty, system 2.

[4]Ibid., p. 96, design report 1, 500 mile prototype component delivery, 30 year system lifetime.

[5]Ibid., p. 100, system II, 5 per cent utility requirement.

[6]Chambers, R.S., Herendeen, R.A., Joyce, J.J. and Penner, P.S., "Gasohol: Does It or Doesn't It Produce Positive Net Energy," Science, Vol. 206, Nov. 1979, pp. 789-795.

To Barb and Bryan.

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CHAPTER 1

CONCEPTS, DEFINITIONS AND USES OF ENERGY ANALYSIS AND THE OBJECTIVE OF STUDY

Introduction

Industrial Revolution - the change in social and economic organization resulting from the replacement of hand tools by power tools and machines and the development of large scale industrial production (Webster).

The energy crisis now facing the United States, and the western industrialized world, exists because of the transition from a society dependent upon human and animal energy to a society dependent upon thermal and electrical energy currently produced primarily from fossil fuels. In reality, society has changed from a self-sufficient system (i.e., society consumed only what it could produce) to a non-self-sufficient system. Initially, the fossil fuel resources seemed to be infinite. However, the energy supply was all too easily tapped and the industrial society grew as quickly as man could extract the energy from the earth. As the industrial society grew out of control, the eventual depletion of its fuel became evident as was foreseen in 1912 by the Nobel prize-winning physicist Frederick Soddy (1).

> Civilization as it is at present, even on the purely physical side, is not a continuous self-supporting movement. It becomes possible only after an age-long accumulation of energy, by the supplementing of income out of capital. Its appetite increases by what it feeds on. It reaps what it has not sown and exhausts, so far, without replenishing. Its raw material is energy and its product is knowledge. The only knowledge which will justify its existence and postpone the day of reckoning is the knowledge that will replenish rather than diminish its limited resources.

Sixty-eight years later, society is beginning to realize the problem it faces. Society has grown into a giant energy sink, increasingly consuming energy at a rate of 3.5% per year (2) from a finite well of fossil fuels while producing no energy itself. This growth rate is further aggravated by the fact that each new Btu of energy extracted from the earth requires the investment of more energy than the previous Btu (3) and that a Btu from coal, the energy resource which is supposed to replace petroleum resources in the short-term future, requires more energy to extract and process than a Btu from petroleum to produce the liquid fuels that society is dependent upon (4). Thus, the energy supply projections are overestimated, possibly seriously overestimated.

Energy Analysis and the Energy Crisis

The "energy crisis" which now confronts the United States can be stated as follows:

The exhaustion of fossil fuel based energy, which is presently the backbone of society, grows near and a policy for the implementation of alternative energy

technologies is yet to be developed. The remaining supply of fossil fuels must be used for the following purposes:

1. To develop and implement an alternative energy supply system to eventually replace fossil fuels.

2. To sustain society at an acceptable standard of living until the alternative energy supply systems can replace fossil fuel based energy.

Currently, economic evaluations of alternative energy supply systems serve as the basis for energy policy formulation. Economics assumes the existence of an infinite dollar supply and, thus, an infinite energy supply. Traditional economics cannot deal with the depletion of investment resources. Furthermore, an economic analysis is not a purely physical evaluation due to the distortion of the value allotted to products based on human values, governmental price regulation and tax incentives, etc. Thus, economics cannot be relied upon as the basis for an energy policy that will allow the transition of society from fossil fuel dependence to a renewable energy resource without destroying the industrial nature and the high standard of living of the present society. Energy analysis can aid in the developing of a competent energy policy. The following paragraphs discuss the uses of energy analysis in the context of the energy crisis facing the United States.

The immediate energy supply crisis is the depletion of crude oil resources. It is not clear that this country

can implement a policy to enable an orderly transition from a liquid fuel dependence to an alternative energy supply system without a significant decrease in the standard of living. The probability that an orderly and comfortable transition from liquid fuels is unlikely rests with the lack of a viable alternative energy resource for the production of liquid fuels. This statement is based on energy parameters, which result from energy analyses, of alternative energy systems that produce liquid fuels. The energy parameters allow a comprehensive comparison of energy supply systems that are being considered for a specific end use, which is one of the tools necessary for policy decision that energy analysis can provide.

The depletion of petroleum is only the immediate phase of the overall energy crisis. Furthermore, evidence exists which suggests that this short-term crisis can only be resolved through the use of the United States' vast coal resources, the immediate implementation of light water nuclear power stations and solar energy when applicable. However, these energy supply systems are only interim solutions to the energy crisis. The long-term solution will necessarily be based on a renewable energy resource such as solar, or on resources which by definition may not be renewable, but offer a supply of energy from an unlimited resource, such as the nuclear breeder concept and fusion. The construction and implementation of any energy supply system

capable of sustaining society requires an enormous investment of energy. Thus, the transition to a renewable energy supply system places a tremendous load on the interim energy supply system. The development of a long-term energy transition policy must begin now to insure that sufficient energy is available to construct the long-term energy supply system. Energy analysis can be used to predict the feasibility of a transition energy supply policy through a dynamic energy supply and demand model. Using the energy parameters obtained from energy analysis and a proposed energy supply scenario, the dynamic model will predict the energy available for consumption given an annual energy supply system growth rate, or, in the opposite sense, the model will predict the energy available for investment given an end-use consumption requirement. Both modes of operation of the dynamic supply and demand model predict the transition behavior of an interim energy supply system. Thus, the model will predict whether or not the interim energy supply system is capable of both sustaining society and constructing the long-term energy supply system.

Objective of Study

The ultimate objective of this study is to provide information and insight essential to the development of a competent present and future energy policy. These inputs to energy policy formulation are the interpretations and implications of the results of energy analyses applied to

proposed alternative energy supply systems. The study is three-phased in nature. First, it is necessary to define a methodological approach for the energy analysis of producing systems which can be applied consistently to all systems analyzed. Secondly, the methodology is to be applied to alternative energy supply systems, or to search out analyses already performed that are acceptable under the definition of the approach outlined. The energy supply systems that are believed to be possible candidates as energy alternatives are listed below:

1. Coal
    a. for the production of electricity
    b. gasified to produce high Btu pipeline gas
    c. liquefied to produce a synthetic crude oil
2. Solar
    a. collection of radiation as heat for either direct use or for the production of electricity
    b. conversion of radiation directly to electricity (photovoltaics)
    c. conversion of wind directly to electricity
    d. conversion of solar radiation to stored chemical energy as biomass via photosynthesis and the subsequent harvesting, collection and processing of the biomass for the production of solid or liquid fuels
    e. conversion of ocean thermal energy directly into electricity
3. Nuclear
    a. breeder reactors
    b. fusion

Several of these alternatives are not analyzed due to lack of data (i.e., breeder and fusion). The methodology must

also be applied to the present energy supply systems for comparison purposes. The present energy supply systems considered are listed below.

1. Petroleum
    a. production of liquid fuels
    b. production of electricity
2. Natural Gas
    a. high Btu pipeline gas
    b. production of electricity
3. Coal
    a. production of electricity
4. Nuclear
    a. light water reactors

The third phase of the study is to understand the implications of the results of energy analysis and to use the results as the basis for energy policy recommendations. This final objective of the study implies the development of a dynamic energy supply model which can predict the implications of proposed energy policies and the dynamic behavior of proposed energy supply scenarios.

Definitions and Basis of Energy Analysis (4, 6, 7, 8, 9)

Energy analysis is the quantitative assignment of an energy equivalence to all actions (which would not have occurred if the system were not in existence), and materials required to construct, maintain and operate all processes within the system, and to all products of the system, over

the useful lifetime of the system. Immediately, three questions arise which ultimately serve as the basis for the analysis. The questions are:

1. How are the energy inputs and outputs of a process determined?

2. How is an energy equivalence assigned to an input or output of a process?

3. What is the unit energy of an energy equivalence? The definition of the unit energy establishes a hierarchy of the various energy forms by adopting a specific form and amount of energy as the unit equivalence and defining the relationship of other energy forms to this unit equivalency.

The establishment of the inputs and outputs of a process is a matter of convention. The convention suggested is based on the concepts of trajectories and levels of energy analysis. An energy analysis is applicable to any system which involves inputs and outputs of some form of energy. Inputs are usually in the form of energy embodied in materials and equipment, an indirect input of energy, or as a direct use of energy, such as heat or electricity. The outputs can be in the form of embodied energy, direct energy or in the form of energy conservation (the energy saved becomes the energy output).

The energy analysis of a system is in reality the energy analysis of many systems whose outputs are combined and eventually result in the system which is under

consideration. This interaction of multiple systems defines the trajectories of a specific system. The boundaries of the entire system are set by the definition of energy analysis. However, the boundaries of the many subsystems comprising the entire system are arbitrary (i.e., processes may be combined or isolated resulting in different subsystems of the entire system). This concept is discussed further in the methodology and application chapters.

The analysis is begun by establishing some initial boundaries of the system under consideration (usually concerning a specific operation such as conversion of processed and delivered coal into electricity). This boundary defines the first level of energy analysis illustrated by the dotted boundary in Figure 1.1. Next, the systems responsible for the manufacture and delivery of the inputs required by the system under consideration must be identified and their boundaries specified, thus defining the inputs to those systems. This is the second level of analysis illustrated by the solid boundary in Figure 1.1. (Note: Often the system and the delivery of the system's products are considered as separate systems. However, the system producing the product and the delivery of the product are included in a level of energy analysis.) The expansion of this network of systems results in horizontal (following the feed path) and vertical (following the paths of direct energy usage, raw materials and capital of each system) trajectories that trace the system under consideration back to inputs

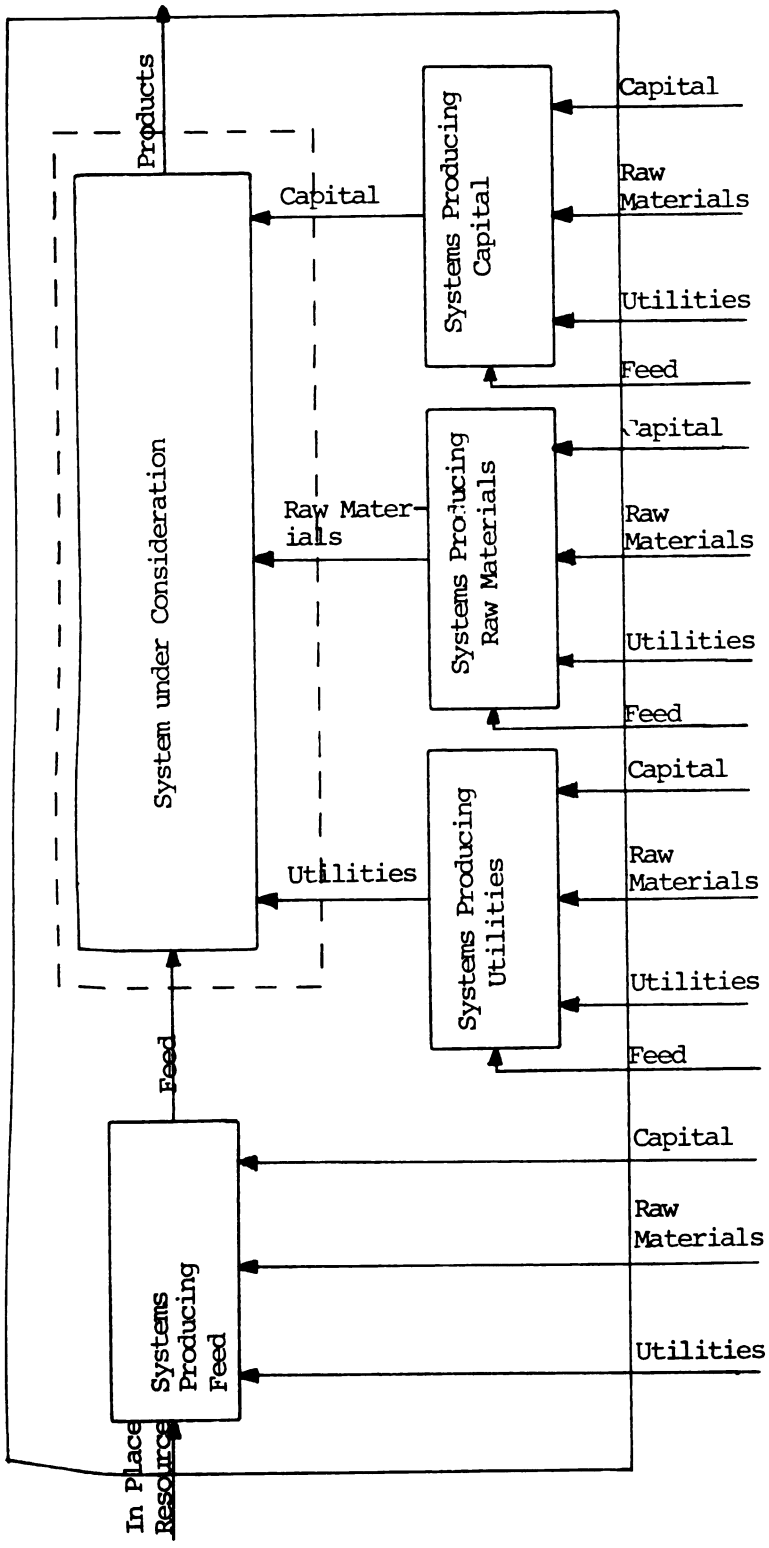


Figure 1.1. First and second levels of energy analysis
(- - - first level, —— second level)

of raw materials and energy extracted from the earth, and human labor (a free energy resource). This approach to energy analysis is known as process analysis. However, the rigorous use of this analysis becomes extremely complicated immediately after the first level and impractical after the second level.

The enormous task of developing the required trajectories to complete the analysis via the process analysis approach can be replaced by an economic correlation of the energy flows between sectors of the United States' economy and the energies embodied in the output of each sector. The method is referred to as input-output analysis and is based on the economic input-output structure of the United States. The economy is grouped into 357 producing sectors and the dollar transactions between sectors as well as each sector's output are calculated for a specific year based on data obtained from the national census (5). The economic structure is calculated at five-year intervals with the data for the year 1972 being the most recent published. Using this data, energy intensity coefficients for each of the 357 producing sectors are calculated in the form of a unit embodied energy per unit measure of product (see Chapter 2 for description of the calculation). The most recent available set of energy intensity coefficients are based on the input-output data for the year 1967. The coefficients for the year 1972 are presently being generated and are

anticipated to be available in the summer of 1980 (10). The use of these coefficients incorporates a certain level of uncertainty in the results of the analysis (discussed in Chapter 2) but allows the completion of an analysis not feasible with process analysis alone.

The basic strategy for an energy analysis is outlined as follows:

1. Determine the inputs and outputs of the system under consideration by the use of process analysis to define the first level of the energy analysis.

2. Assign energy equivalences to the inputs of the system by the use of the energy intensity coefficients from input-output theory. The energy output of the system is the energy content of the system's products (discussed in Chapter 3).

The unit energy of an energy equivalence is a matter of convention. However, the unit energy of an energy equivalence must be well defined and used consistently throughout the analysis. The definition of a unit of primary energy is adopted for this work (defined in Chapter 2) in order to be consistent with and allow the use of data from other sources such as the United States Bureau of Mines.

Summary

The energy crisis facing the United States is two-phased and must be solved in two steps as follows:

1. Transition from a petroleum dependence to a coal, nuclear (light water) and solar (where applicable) dependence.

2. Transition from an interim energy supply system to a long-term energy supply system.

The first transition cannot occur without significant conservation and a decrease in the United States' standard of living. However, it is possible to implement an orderly and comfortable transition to the long-term energy supply system with the proper energy policy. Planning for the second transition must begin now.

It is clear that economics alone cannot give the information necessary to develop either the short-term or long-term energy policies. Energy analysis can aid in the development of an energy policy through end-use comparison and the prediction of dynamic behavior of alternative energy supply systems.

Energy analysis is the quantitative assignment of an energy equivalence to the inputs and outputs of a system. The unit energy of an energy equivalence is defined to be a unit of primary energy. The identification of the inputs and outputs of a system is accomplished through the process analysis of the first level of energy analysis. The energy equivalence is assigned to the inputs of the system through input-output analysis and the energy output of the system is the energy content of the system's products.

CHAPTER 2

DEVELOPMENT OF METHODOLOGIES

Introduction

The methods used to perform an energy analysis vary widely from author to author usually without justification or documentation of the method used. Thus, by choosing the methodology cleverly, the results of an analysis can be made to yield the conclusion desired by the author. This use of energy analysis denies credibility to the results or conclusions that may be reached. For this reason, the science by and large has not been considered seriously as a tool in energy policy development. By precisely defining the methodologies used and documenting the analyses performed, the results and conclusions of this study can provide valid information for policy development as well as providing an understanding of the implications of specific energy policy options.

There presently exists two basic approaches to energy analysis that are generally considered viable and acceptable. These are process analysis, the preferred and most accurate method, and input-output analysis. An energy analysis usually incorporates both methodologies

depending upon the characteristics of the system, and the amount and type of data available. The characteristics of the system will determine the extent of process analysis required, while the available data determine the extent possible for the use of process analysis. An article by P. F. Chapman (1) offers an excellent introduction to energy analysis methods.

Process Analysis

Although this method of energy analysis appears frequently in the literature (1, 2, 3), it is not clear where the approach originated nor is it clear as to how the approach developed. An introductory description of process analysis is contained in the Energy Analysis Handbook by Bullard, Penner and Pilati (3).

The name adopted for this method of energy analysis is perhaps more appropriate than often realized. That is, the analysis yields results applicable to a specific process only and not to its products. At first, the point made may seem trivial. It is, however, a very important basis of this analysis which is realized when attempts are made to compare "energetics" of a product produced by several different processes, or when attempts are made to determine the energy embodied in a product of a process having many products (such as an oil refinery). Since process analysis is totally dependent upon the details of the specific process, the analysis can only be as complete

as the process description itself. Thus, great care must be taken when selecting a process description for analysis.

The first step in the analysis is the selection of an appropriate process description. Next, it is necessary to draw a boundary around the process to define the inputs and outputs of the system allowing the development of the trajectories of the system. Consider, for example, the production of electricity from coal (see Figure 2.1). As shown in the trajectory drawn, the boundary is drawn such that the inputs are in-place coal, direct energy use, and energy embodied in materials and capital, and the output is distributed electricity. Notice, as shown by the dotted lines, that the boundary is arbitrary. The in-place coal input can be replaced by a delivered coal, processed coal or extracted coal input depending on whether the energy embodied in the different types of coal inputs are known. In other words, the boundary must be enlarged until the energies embodied in the inputs are known. Also, note that vertical as well as the horizontal trajectories may be necessary so that the energies embodied in the inputs are known.

The smallest boundary of Figure 2.1 includes the electric plant and the distribution of electricity and represents the first level of analysis. To develop the second level of analysis, not only would it be necessary to include the two previous horizontal steps, transportation and processing, all applicable vertical steps would need to

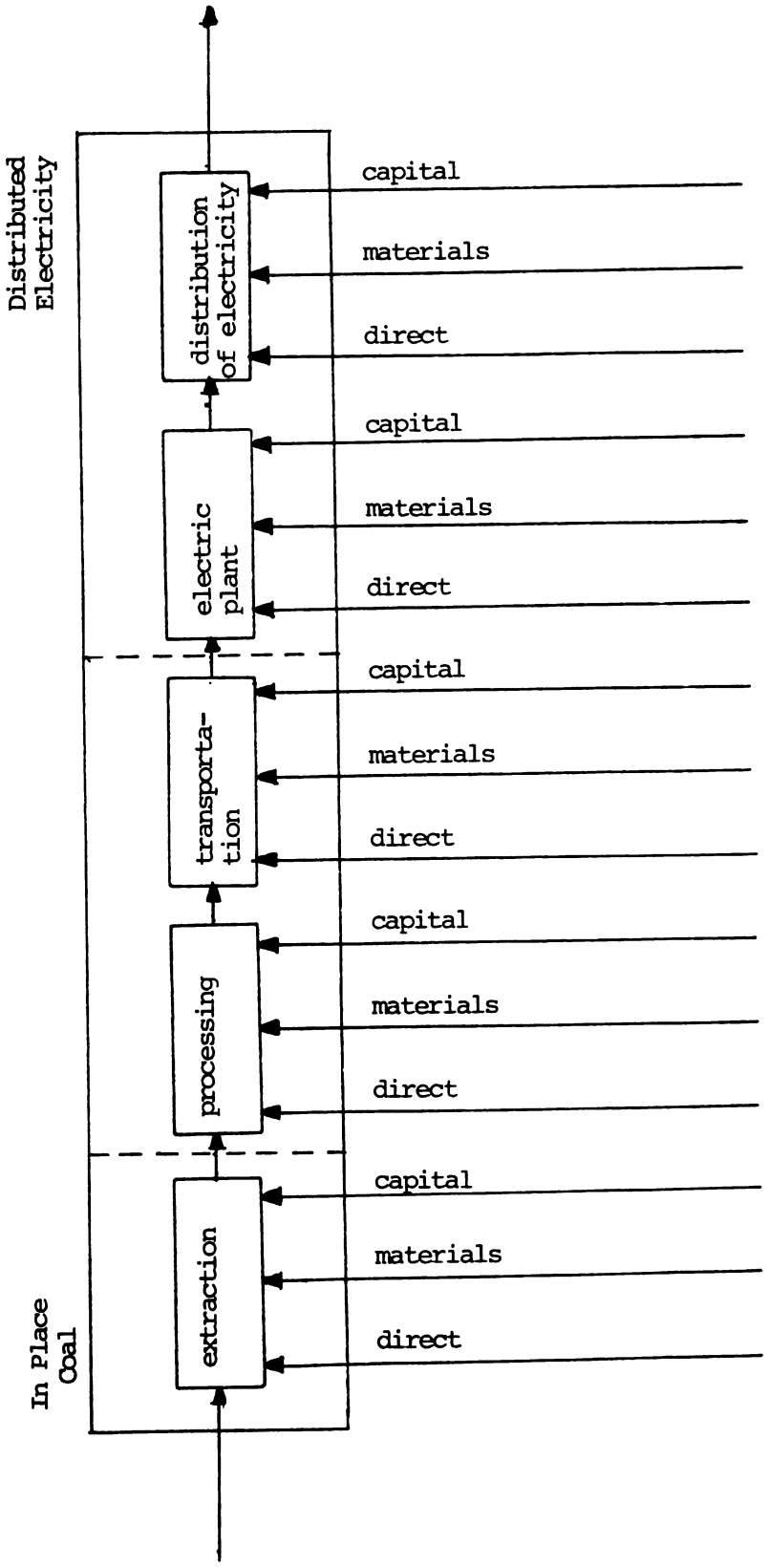


Figure 2.1. Trajectory of electricity produced from coal

be included (i.e., the production and transportation of direct energy used, materials and capital for the electric plant and distribution of electricity systems).

The complexity of extending process analysis to higher levels of energy analysis should now be apparent. Thus, as noted in Chapter 1, process analysis of the higher levels of energy analysis is usually approximated by the use of energy intensity coefficients from input-output theory. However, the energy intensity coefficients are often inadequate especially when dealing with inputs from new technologies (i.e., heliostats for electricity from solar thermal derived heat) which may not be included in one of the industrial sectors. Also, the input-output method gives average energy intensities representing all production processes of a product which may not be suitable in some instances. Thus, process analysis is extended to as many of the higher levels as permitted by available data. This usually results in an extension of process analysis along the horizontal trajectory.

While the specific definition of the unit energy of the energy equivalence does not directly influence the use of process analysis, it does establish the basis for energy accounting. The basis for energy accounting defines a hierarchy among various energy forms as well as which energy forms are considered as countable energy inputs. A unit energy of primary energy used by the Bureau of

Mines is chosen as the energy equivalence for this study and is defined as follows:

$$E_p = E_{coal} + E_{crude} + \alpha E_{electric}$$

where E_p ≡ Primary energy

E_{coal} ≡ Btu's of coal (based on the higher heating value for coal)

E_{crude} ≡ Btu's of crude oil and natural gas from the well head (also based on the higher heating values of crude oil and natural gas)

$E_{electric}$ ≡ The Btu equivalent for kwh of electricity

α ≡ The product of the percentage of electricity not produced from fossil fuels (i.e., from hydroelectric and nuclear fuels) and the combined heat rates of the hydroelectric and nuclear systems if replaced by the fossil equivalents. The Bureau of Mines uses the value of 0.6165 for α (5).

Notice that this definition of an energy equivalence places a zero value on energy from human labor. At first, this may seem to be erroneous. Energy analysis is the accounting of the energy required to perform all acts for a particular process which would not normally be done if the process were not in existence. The argument is made that human consumption of energy would not change whether the process were in existence or not. This statement is

clearly correct if we consider the role of humans in society. All industrial processes are ultimately in existence for human consumption either directly (such as foods) or indirectly to raise the standard of living for humans (such as housing, transportation or even environmental controls or wildlife preservation). Viewed in this light, any feedback of human energy to society is indeed a "free" energy form.

Input-Output Analysis

The first application of input-output theory to the United States' economic structure used the 1963 data and the energy intensity coefficients were determined by Wright (4). The method was then applied to data of the years 1963 and 1967 by Bullard and Herendeen (11) including several modifications of the data (to be discussed shortly). Presently, the energy intensity coefficients generated by Bullard and Herendeen at the Center for Advanced Computation, University of Illinois, for the year 1967 are those in use. The same group at the Center for Advanced Computation is now calculating the coefficients for the 1972 data, to be published in the summer of 1980.

An excellent review of input-output theory has been prepared by David Reister, Institute for Energy Analysis, Oak Ridge University (2). The method may be thought of as a process analysis of 357 separate sectors based on national average interactions. The trajectories of each

system are represented by a 357 x 357 matrix whose elements, X_{ij}, correspond to the amount of product from sector i required to produce the gross output of sector j. Thus, $\sum_{i=1}^{357} X_{ij}$ is the total requirement from all sectors required to produce the gross output of sector j. The producing sectors can be separated into energy and non-energy groups. The energy producing sectors are coal, crude oil and natural gas, petroleum products, electric utilities and gas utilities, and are designated as the first five sectors. The energy production sectors require energy extracted from the earth, designated as E_k (k = 1,2,....,5). An energy balance may now be defined which states that the energy embodied in the output of a sector is the energy embodied in inputs from other sectors, the energy extracted from the earth and the energy embodied in the value added to the output of that sector as shown schematically in Figure 2.2.

Where:

ε_{ki} represents the energy embodied in a unit output of the i^{th} sector of the k^{th} energy form. ε_{ki} is defined as the energy intensity coefficient.

X_j represents the gross output of sector j.

V_j represents the energy embodied in the value added to the output of the j^{th} sector.

The element V_j is included because the value added is not included in the interaction matrix X_{ij}, and

represents inputs such as land, labor, capital and employee compensation. Of the values added, capital is a valid energy input. The capital value added is reported in terms of purchases from the 357 sectors.

$$V_{cap,j} = \sum_{i=1}^{357} \varepsilon_{ki} X_{cap,ij}$$

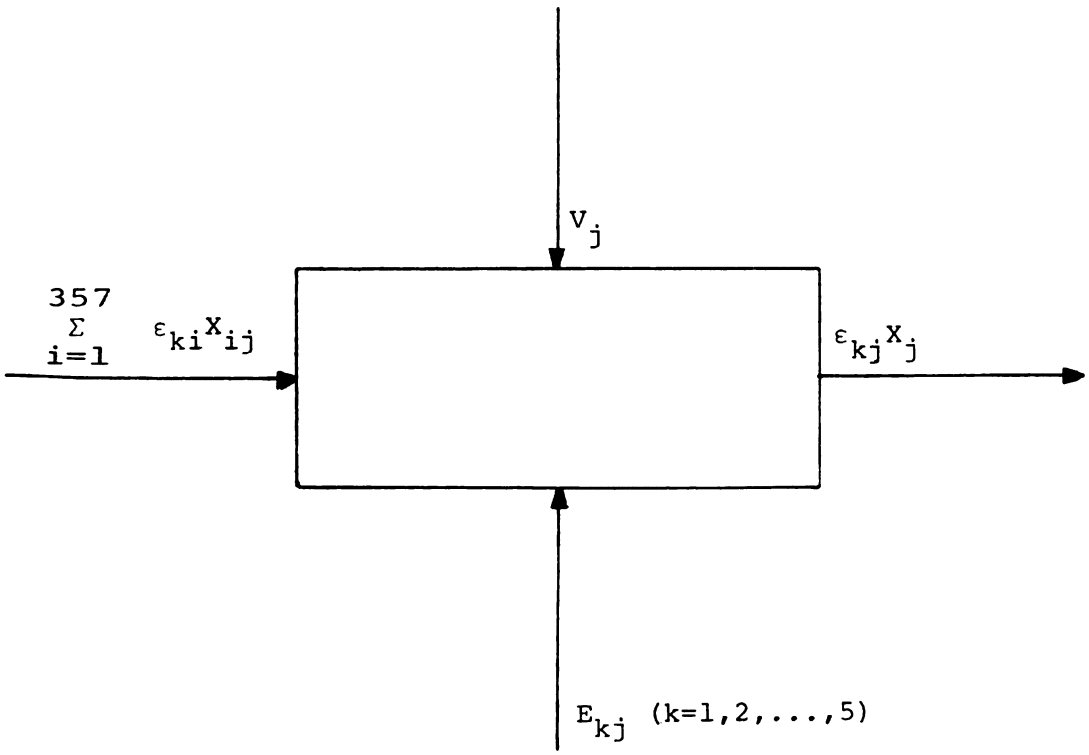


Figure 2.2. Definition of the energy balance used in input-output analysis

The capital investment can be incorporated in the interaction matrix by the appropriate modification of the interaction matrix elements.

$$X_{ij} = X_{ij} + X_{cap,ij}$$

In order to calculate the energy intensity coefficients ε_{ki}, the elements X_{ij} are assumed to be a function of X_j as follows:

$$X_{ij} = b_{ij} + a_{ij} X_j$$

where:

$b_{ij} \equiv$ fixed investment

$a_{ij} \equiv$ marginal investment

The current practice (as used in calculating the 1967 energy intensity coefficients) is to neglect the b_{ij}'s and assume the required input is directly proportional to the output. This is recognized as a poor assumption when dealing with industrial-type producing sectors and may introduce uncertainty in the results. The energy balance may now be written as:

$$\varepsilon_{kj} X_j = E_{kj} + \sum_{i=1}^{357} \varepsilon_{ki} a_{ij} X_j$$

Another modification of the data is required. The output of sector j includes the amount of the products of sector j that are imported (designated as P_j). Since no data are available regarding foreign economic structures, the imported output of sector j is ignored by subtracting

P_j from X_j. All imported products are assumed to have the same energy intensity as their domestic counterparts.

The energy balance may now be written as:

$$\varepsilon_{kj} (X_j - P_j) = E_{kj} + \sum_{i=1}^{357} \varepsilon_{ki} a_{ij} (X_j - P_j)$$

or in matrix notation for a specific energy form k:

$$\underline{\varepsilon} (\underline{\underline{X}} - \underline{\underline{P}}) = \underline{E} + \underline{\varepsilon}\ \underline{\underline{a}}\ (\underline{\underline{X}} - \underline{\underline{P}})$$

where:

$\underline{\underline{X}} - \underline{\underline{P}} \equiv$ a diagonal matrix whose elements are $X_{jj} - P_{jj}$

$\underline{E} \equiv$ a 357 x 1 row vector with one non-zero element in one of the first five columns corresponding to the energy form under consideration

$$\underline{E} = \underline{\varepsilon} \{(\underline{\underline{X}} - \underline{\underline{P}}) - \underline{\underline{a}}(\underline{\underline{X}} - \underline{\underline{P}})\}$$

$$\underline{E} = \underline{\varepsilon} \{(\underline{\underline{I}} - \underline{\underline{a}})\ (\underline{\underline{X}} - \underline{\underline{P}})\}$$

Noting that the k^{th} energy form extracted from the earth is the output of the k^{th} sector (i.e., $\underline{E} = \underline{e}\ (\underline{\underline{X}} - \underline{\underline{P}})$ where $\underline{e}$ is a 357 x 1 row vector with unity as the only non-zero element in the k^{th} position, k = 1, 2, 3, 4, 5) the energy balance may be written as:

$$\underline{e}\ (\underline{\underline{X}} - \underline{\underline{P}}) = \underline{\varepsilon} \{(\underline{\underline{I}} - \underline{\underline{a}})(\underline{\underline{X}} - \underline{\underline{P}})\}$$

$$\underline{e} = \underline{\varepsilon}\ (\underline{\underline{I}} - \underline{\underline{a}})$$

$$\underline{\varepsilon} = \underline{e}\ (\underline{\underline{I}} - \underline{\underline{a}})^{-1}$$

The energy intensity vector, $\underline{\varepsilon}$, is calculated for each energy sector resulting in a 357 x 5 matrix of energy intensity coefficients, ε_{ki}. The five coefficients for each sector are then summed into a single primary energy intensity coefficient.

$$\varepsilon_{primary} = \varepsilon_{coal} + \varepsilon_{crude} + \alpha\varepsilon_{electricity}$$

The definition of primary energy is the fossil fuel equivalency of the energy consumed by the United States. This definition does not differentiate between renewable and non-renewable energy resources. However, the contribution by renewable energy sources is not a significant fraction of the energy consumed. Thus, the use of primary energy as the energy equivalence is acceptable at this point in time. If alternative energy supply systems such as solar and nuclear energy do begin to contribute significantly to the supply of energy to the United States, the energy producing sectors will need to be expanded to include possibly solar energy and uranium (nuclear energy) energy supply sectors. Ideally, the categorization of the economy into producing sectors should be absolutely comprehensive in the energy supply area. In that situation, electricity consumed would not represent any energy consumption not included in the other energy sectors (since electricity is not an energy resource), and the need for the α term would be eliminated.

The data generated by the Department of Commerce is not in a form immediately useful for energy analysis purposes, as indicated by the modifications to account for capital and imported goods. Other potential limitations of the energy intensity coefficients obtained from input-output theory, which result from the conventions used in computing the data base, are as follows:

1. The data base is subject to inaccuracies from lack of complete coverage of an industry, restriction of data for proprietary reasons, and the use of data representing slightly different time periods in the interaction matrix for various sectors. Furthermore, errors in the interaction matrix $\underline{\underline{a}}$ may generate disproportional errors in $(\underline{\underline{I}}-\underline{\underline{a}})^{-1}$. In short, it is not known if the data accurately represent the interactions of the 357 producing sectors.

2. The use of dollar flows to describe physical material flows may not be acceptable. In economics, it is well known that there are human values and other intangibles that influence prices of items that in no way reflect the physical inputs to the production process. To assume that dollar flows accurately represent energy flows is not reasonable. There exist examples of similar items having widely varying energy intensities with no physical basis for the discrepancy. This has been dealt with for the five energy sectors by replacing dollar interactions with Btu interactions with data obtained from the census of Mineral Industries for 1967 (7).

3. A major problem with input-output methodology is the inability of the coefficients to change with time without continually generating a completely new set of coefficients from an up to date data base. As stated before, the data base is generated every five years (1963, 1967, 1972, etc.). However, it has typically taken the Department of Commerce six or seven years to publish the tables after the data base year. The coefficients presently used are

based on the 1967 census and are now thirteen years out of date. The coefficients based on the 1972 census will be available in 1980 and will immediately be eight years out of date. Typically, this problem is dealt with by employing price indices for the specific sector. Up to the year 1974, the recommended deflators are taken from a 1975 study published by the Bureau of Labor Statistics (8). Included in the study are detailed price indices for a 129 sector economy for the period 1958 to 1974. For 1975 and subsequent years an annual Bureau of Labor Statistics publication is used, Wholesale Prices and Price Indices, Supplement 1976, Data for 1975 (now titled Producers Prices and Price Indices for 1977 and following years) (9). Table 9 of this publication provides average price indices for SIC industries and Table 10 provides data for selected census product classes. From these two tables, price indices for either the exact industrial classification or a suitable similar classification can be found excluding transportation, trade, construction and business and professional services sectors. Price indices for services and structures are found in the Survey of Current Business, Table 21, for the appropriate year (10).

Aside from the use of price indices, there are two other methods suggested for "updating" the 1967 energy coefficients. The Bureau of Mines annually publishes energy consumption statistics for the United States. Included is the total amount of primary energy consumed in the United States during the year under consideration. The ratio of

the total primary energy consumed and the Gross National Product (GNP), which is the total output of all producing sectors or total sales to final demand, represents the national average of primary energy embodied per dollar spent for the year the data represent. If this ratio is known for both 1967 and the desired year, a correction can be uniformly applied to all sectors. This can also be thought of as applying a single price index based on current energy consumption. The final method suggested is to modify the 1967 interaction matrix and then generate a new set of coefficients for the desired year. It is reasoned that the sectors most likely to change rapidly are the energy sectors, coal, crude oil and natural gas, refined petroleum, electricity and gas utilities. Sufficient annual data can be obtained from the Bureau of Mines to update these five rows of the transaction matrix (as was originally done to change from dollar to Btu interactions) allowing the calculating of new energy coefficients.

The 1963 data were adjusted to the year 1967 according to the three methods suggested and the generated energy intensity coefficients were compared to the coefficients generated from the 1967 data (6). The use of the price indices (either separate indices for each sector or a single index) were shown to update the 1963 coefficients poorly. However, modifying the energy rows of the interaction matrix was shown to yield fairly accurate updated coefficients.

4. As mentioned previously, the energy intensity coefficients are based on producer's prices. However, most often cost data for industrial processes are based on purchaser's prices. Therefore, trade and transportation costs must be subtracted from the purchase price and transferred to the corresponding sector as a separate required purchase. In preparing the 1967 I-O tables, trade (wholesale, retail and insurance) and transportation (rail, motor, water, air and pipeline) margins were estimated for purchases by each sector from all 357 sectors plus ten types of final demand. Thus, each sector has 357 sets of trade and transportation margins for purchases from other sectors, and another ten sets of margins for sales to final demand. Clearly in energy analysis, purchased equipment and materials could be sold to other sectors (i.e., the construction sector) or to final demand, and judgement must be used in choosing the proper margins. (Note: The average margins for sales to final demand are published along with the coefficients and the detailed margins are available on tape from the BEA.) Since updating the margins could be quite difficult, it is recommended to first deflate or inflate the cost data, then correct for trade and transportation.

5. As indicated, imported products are assumed to have the same energy intensity as their domestic counterparts. Imports which have domestic counterparts are referred to as competitive imports. However, directly allocated imports

(those which have no domestic counterpart) are also ignored in the interaction matrix and, therefore, have no associated energy intensity coefficients. This presents no significant limitation to the methodology since the amount of directly allocated imports to the United States is small.

6. The method is not capable of accounting for secondary products of the producing sectors. The problem arises when an establishment produces, as a secondary product amounting to less than 50% of total sales, the primary product of another sector. Consider an establishment whose primary output is primary aluminum which also produces aluminum castings as a secondary product. In the interaction matrix, the aluminum castings are treated as a fictitious sale to the aluminum castings sector, thus accrediting the primary aluminum sector for the sale as part of its gross output. The sale is then transferred to the gross output of the aluminum castings sector without transferring any of the corresponding inputs. Two sectors have now been accredited for the output of the same volume of product without increasing the input requirements of the aluminum castings sector. The energy intensity coefficient for the aluminum castings sector will now be smaller than it should actually be. This cannot be corrected for since the inputs responsible for the secondary product production are not known. Furthermore, even if the correct inputs could be identified and transferred, they do not represent the

necessary input as required by the sector the inputs are to be transferred to, to produce the same volume of product.

7. The manner in which the economy is disaggregated into the 357 producing sectors is not optimum for energy analysis purposes. For example, the dairy industry has been delegated 22 producing sectors, where the inorganic chemical industry is delegated a single sector. The classification assumes all products of the inorganic chemical industry have the identical embodied energies.

Considering all the necessary modifications and inherent assumptions associated with the use of the economic input-output data to generate the energy intensity coefficients, the accuracy of the coefficients is suspect. In some instances, the lack of detail in the available data does not allow any meaningful use of the 357 sector level of disaggregation, denying exploitation of the method's greatest advantage. Thus, the need exists for another approach to analyzing the second and higher levels of energy analysis that could find use as a check on the input-output method as well as an option to input-output analysis when the data will not allow proper use of the level of disaggregation. An alternative approach is to treat the economy as a single sector, with a single total energy consumption and total dollar output for the specific year in question. The total primary energy consumed (12) divided by the gross national product of the United States (13) for various years is used as the single sector energy intensity coefficient. The single

sector energy coefficients for the years 1960-1978 are listed in Table 2.1.

Table 2.1. Total primary energy consumed per dollar spent for 1960-1978.

Year	E/GNP (Btu primary consumed / dollar spent)
1960	87,512
1961	85,983
1962	83,527
1963	82,303
1964	80,281
1965	77,369
1966	74,303
1967	72,906
1968	70,956
1969	69,343
1970	68,017
1971	64,228
1972	61,165
1973	57,102
1974	51,207
1975	46,252
1976	43,457
1977	40,517
1978	36,666

The use of this ratio has the advantages of representing the energy embodied per dollar purchaser's price for the specific year in question without any modification of the cost data.

Both approaches to estimating the second and higher levels of energy analysis will have appropriate applications not only as a function of the data available, but as a function of the characteristics of the system as well. For example, in systems in which the dominant inputs are associated with extraction and delivery of the feed, such as fossil fuel

based systems, the energy embodied in the capital of the system is probably best estimated from the single sector energy intensity coefficient. However, when dealing with systems in which the capital energy investment dominates, such as a central receiver solar thermal power station, the use of input-output analysis is more appropriate.

CHAPTER 3

APPLICATION

Energy Analysis Applied to Industrial Processes

Data Required

Data concerning the construction, operation and maintenance of an industrial process are required in order to estimate the energy embodied in the inputs and outputs of that process. The data usually originate from an engineering process design in the following forms:

1. Process flow diagram including material and energy (thermal and electric) flows
2. Economic evaluation of the process including:
    i. Capital investment for purchase and installation of materials and equipment, and construction of buildings and general facilities
    ii. Operation and maintenance costs
3. General and technical description of the process

The accuracy of the energy analysis is directly dependent on the accuracy of the design data. Thus, the selection of an accurate and competent process design is necessary in order to perform an accurate energy analysis.

The processing units included in the process design define the first level of energy analysis and the

data contained in the design quantitatively determine the inputs and outputs of the first level of energy analysis. In general, the inputs to the first level of energy analysis are categorized according to the producing sectors of the Standard Industrial Classification (1). This portion of the analysis is referred to as process analysis. The energies embodied in the inputs are determined by input-output analysis.

The application of input-output analysis requires the inputs of the first level of energy analysis to be represented in a specific form (i.e., the data describing the inputs must be of a specific nature). An input can be categorized as either an energy input or as a material input (referred to as a non-energy input). Energy inputs must be expressed as either the thermal energy content of one of the following energy fuels:

1. delivered coal
2. delivered crude oil or natural gas from the well head
3. delivered petroleum products (i.e., after refining)
4. natural gas distributed by a gas utility

or as electricity distributed by an electrical utility. Note that input-output analysis cannot be used to determine the energy embodied in a Btu of process heat. The energy inputs of the system are referred to as the utility requirement of the system.

The material inputs (referred to as the raw material and capital requirements of the system) must be expressed as a dollar cost defined at a specific point in time (for example, 1977). In general, dollar costs of a material can represent either a producer's price (defined as the cost for the non-distributed product) or a purchaser's price (defined as the cost for a distributed product which includes the cost of the product itself, trade services and transportation requirements). Input-output analysis allows the conversion of the producer's price, expressed in 1967 dollars, of a product that can be represented by a producing sector listed in the SIC code (1), into a quantity of a specific form of energy with the use of an energy intensity coefficient. If the material is represented by a purchaser's price, the cost is separated into the producer's cost, trade cost and transportation cost through the use of trade and transportation margins. (Refer to the sections on application of process analysis and input-output analysis for details of these operations.) Thus, the specific year that the cost represents must be known in order to select the appropriate price index to inflate or deflate the cost to 1967 dollars, and whether the cost is a producer's or purchaser's price must be known to allow the application of input-output analysis to non-energy inputs.

The data describing the energy inputs and outputs of a system refer to the energy inputs and outputs for the

lifetime of the system. However, it is common to express utility and raw material requirements in annual rates and to amortize the capital requirement over the lifetime of the process.

Definition of the Nameplate Processing System

In general, the nameplate processing system refers to a subset of processing units of the entire system which are responsible for the major products of the system. For example, the nameplate processing system of a coal gasification system would center around the processing units that convert processed and delivered coal into high Btu pipeline gas. However, the nameplate processing system is not confined to this subset of processing units and it is advisable to expand the nameplate processing system to include as many processing units of which the design details are known. A common example of an expansion of the nameplate processing system is the inclusion of on site utilities generation processes.

In order to expand the nameplate processing system, the system design must include facilities required for the transport of materials and energy between the processing units (i.e., pipelines, conveyor belts, small industrial motor vehicles, etc.). If the transportation system between the nameplate process system and the processing unit which is proposed to be included in the nameplate processing system unit is not specified in the design, the

expansion is not acceptable and the processing unit must be considered in the second level of the analysis.

Determination of the Energy Inputs and Outputs of the System

The general approach to the determination of the energy inputs and outputs of a system is outlined in Chapters 1 and 2. This section deals with the specifics of the application of process analysis, input-output analysis, and if required, the disaggregation of the energy intensity coefficients in the determination of the energy inputs and outputs of a system. The objective of this section is to provide a specific step by step procedure for an energy analysis which can be applied consistently to any system.

Application of process analysis

In the context of the approach to energy analysis presented in this study, process analysis is the quantitative determination of the raw materials, capital and energy flows into a system and the product flows out of a system. Process analysis requires the precise definition of system boundaries. Once the boundaries are set, the amounts and forms of the inputs and outputs of the systems are either taken directly from the system design or estimated through the use of the disaggregation of energy intensity coefficients. The material and energy flows of an industrial process are generalized as shown in Figure 3.1.

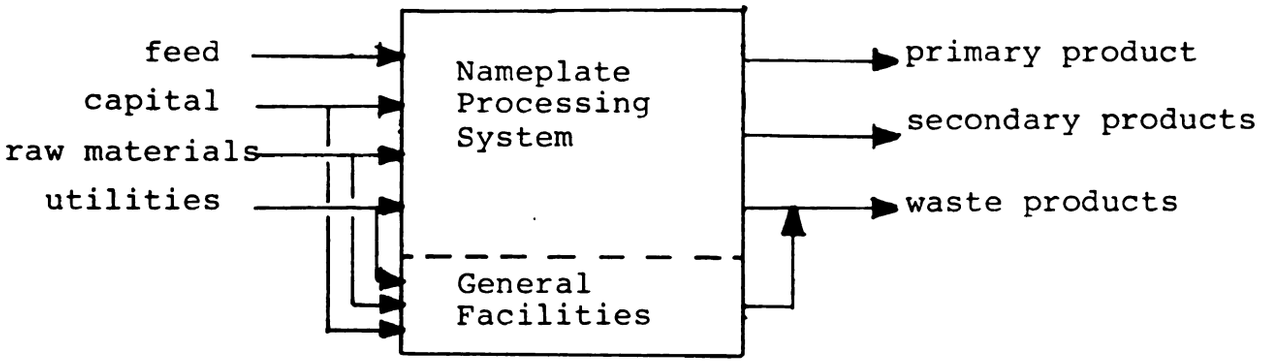


Figure 3.1. Generalized material and energy flows of an industrial process

Using Figure 3.1 as a model, a checklist of energy inputs for the first level of energy analysis of a generalized industrial process can be generated as listed in Table 3.1.

The inputs refer to the lifetime requirements of the system but it is acceptable to report the energy and raw material inputs per unit time (usually years) and amortize the capital energy inputs over the lifetime of the system. The term "required" energy represents all direct energy usage, energy embodied in materials used, and a portion of the energy embodied in equipment used based on the fraction of the equipment's useful lifetime depleted. Note that, even though the general facilities of the system do not produce any useful products, they are necessary for the operation of the system and are therefore valid energy inputs.

Table 3.1. List of energy inputs to the first level of energy analysis of a generalized industrial process

1.	Primary energy embodied in the nameplate process equipment and materials
2.	Primary energy required for the distribution (i.e., sales and delivery to nameplate process site) of the nameplate process equipment and materials
3.	Primary energy required for land preparation, required on site assembly and construction, and installation of nameplate process equipment and materials
4.	Primary energy embodied in feeds, raw materials and utilities
5.	Primary energy required for distribution (i.e., sales and delivery to nameplate process site) of feed, raw materials and utilities
6.	Primary energy required for distribution of primary and secondary products
7.	Primary energy required for disposal of waste products
8.	Primary energy embodied in the general facilities
9.	Primary energy required for the distribution of the general facilities
10.	Primary energy required for land preparation, required on site assembly and construction, and installation of general facilities
11.	Primary energy required for the maintenance of the nameplate process equipment and materials, and general facilities

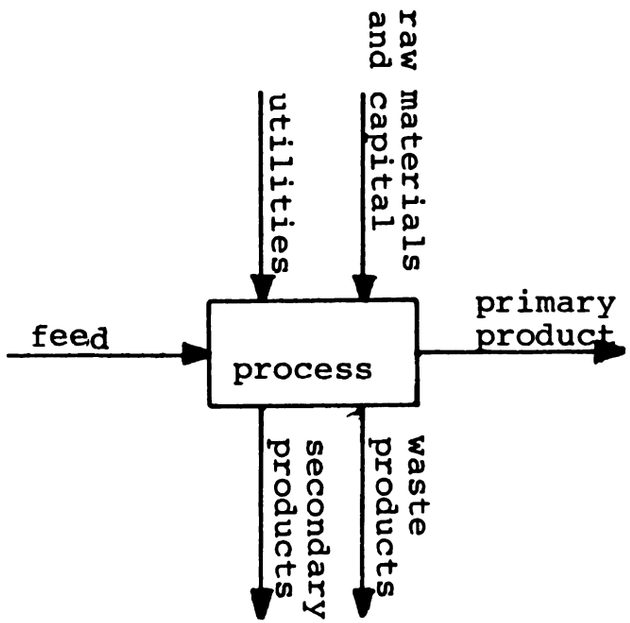
Note that energy inputs 1-3, 8-10 and 11 represent the capital energy investment.

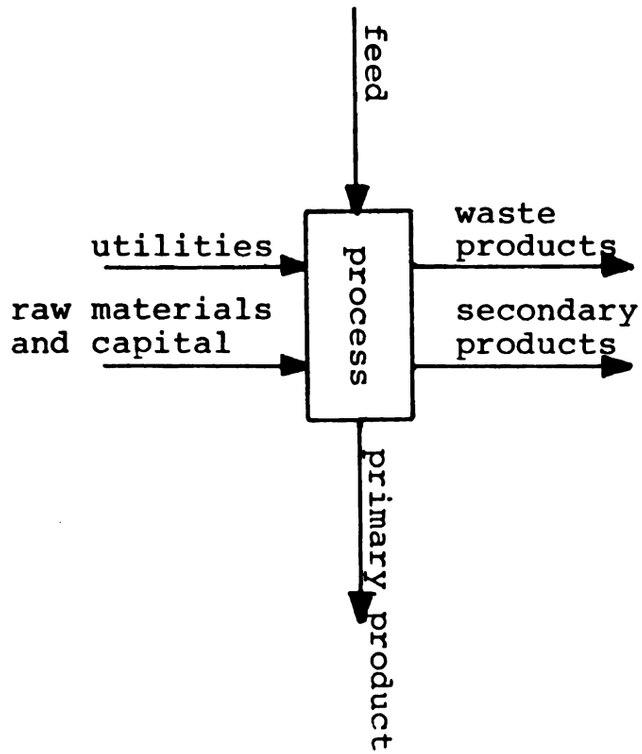
To complete the first level of energy analysis, the energy outputs of the nameplate processing system must be determined. However, there is not uniform agreement as to the definition of an energy product. The convention adopted for this study characterizes energy products according to the end use as a supply of useful energy to society. This definition includes all products that are either consumed in the production of work or produced directly as heat or other forms of energy. Examples of energy products are fuels, foods (human and animal) and electricity. If the product is considered to be an energy product, its energy content is taken as its higher heating value. Notice that this definition of embodied energy is fundamentally different than that of the inputs. This is consistent with the definition of the net energy of systems as the energy available for use by society after deducting all the energy required to construct, operate and maintain the energy supply system (not including the energy content of the energy resource utilized). Thus, a product may contain embodied energy by virtue of its manufacturing process, which must be considered if the product is used by a system, while it may not have any useful energy content. For example, petroleum products have an energy subsidy of 0.2157 Btu primary energy for every Btu of useful thermal energy content.

At this point of the analysis, it is useful to develop the horizontal trajectory of the nameplate

processing system. Recall that the horizontal trajectory of a process is a tracing back of all processing systems required to produce the delivered feed of the process from raw materials and energy resources extracted from the earth. It is advisable to extend process analysis along the horizontal trajectory from the delivered feed back to a point at which the remaining trajectory is well represented by national average production. Since the feed is the major material flow (excluding the possibility of capital) into the nameplate processing system, the transportation step (and perhaps the processing step) immediately preceding the nameplate processing system could represent major energy inputs. These process units are generally extremely site specific and often require extension of the process analysis. For example, consider the horizontal trajectory of coal gasification (Figure 3.2). As indicated by dotted line, the nameplate processing system begins with the processing of delivered raw coal. In general, national averages estimation of the transportation requirement (module B preceding module C on the horizontal trajectory) is not adequate requiring extension of process analysis.

Before the application of process analysis is complete, the raw materials, utilities and capital inputs to the nameplate processing system must be examined to determine if the specific inputs are the products of one of the 357 producing sectors for which energy intensity coefficients have been determined. If this is the case, the process





Key to Figure 3.2

A - coal mining
B - products handling and distribution
C - coal processing
D - coal gasification
E - utilities generation
F - secondary product handling and distribution
G - waste product handling
H - in place coal
I - high Btu pipeline gas
J - secondary products
K - waste products
L - electricity purchased to operate raw water pump
M - raw materials required by nameplate processing system

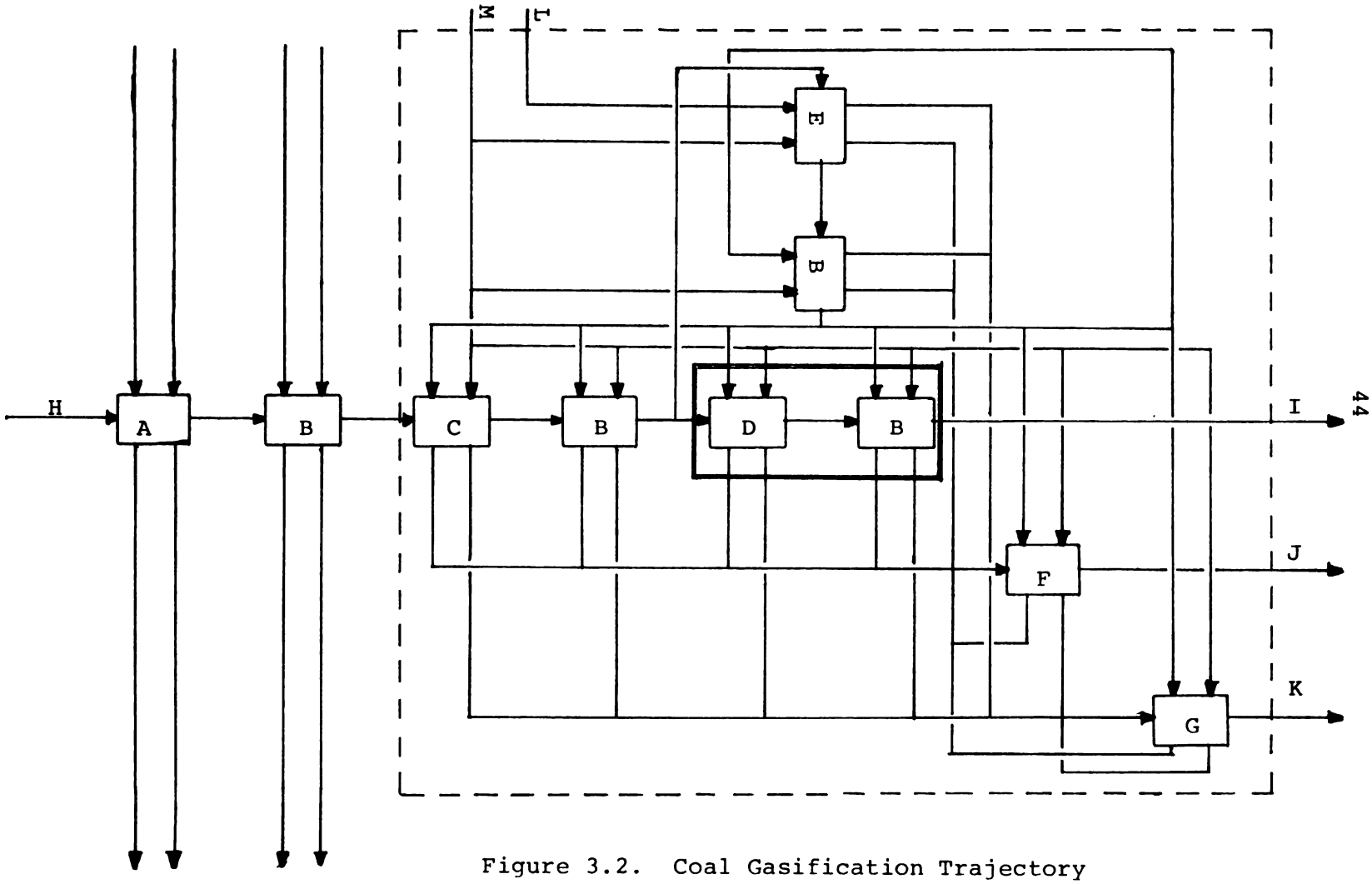


Figure 3.2. Coal Gasification Trajectory

analysis is complete and input-output analysis can be applied. If any of the inputs are not represented by one of the 357 producing sectors, process analysis must be extended along the vertical trajectory of each input not represented by one of the 357 producing sectors. Extension of process analysis back along vertical trajectories replaces the inputs that are not represented by a producing sector with additional inputs of raw materials, utilities and capital. The process analysis must be extended until the additional inputs are represented by producing sectors.

The extension of process analysis along either a horizontal or vertical trajectory is accomplished by identifying the system responsible for production of the inputs not represented by a producing sector and applying the same procedure outlined for the application of process analysis to the nameplate processing system. However, data describing the systems to which the process analysis is to be extended to is often not available. In these cases, the disaggregation of the energy intensity coefficients can be used to estimate energy inputs for which no information is available. (See use of the disaggregation of energy intensity coefficients.)

Application of input-output analysis

Comments

There are two modes of input-output application, the 357 sector disaggregation level and the single sector disaggregation level, as indicated in Chapter 2. The mode of application used is up to the discretion of the analyst and depends on the detail of the available data and the characteristics of the system (usually concerning the capital investment of the system). There are two independent points that influence the mode of input-output application chosen. These are:

1. When should the 357 sector disaggregation level be used?

The question is answered by the characteristics of the system with regard to the capital investment. If the energy input resulting from the capital investment is thought to be a significant portion of the total required energy input of the system, the 357 sector disaggregation level is appropriate because it offers more information about the capital energy inputs.

2. When can the 357 sector disaggregation level be used?

The available data determine the answer to this question. The data, usually the data describing the capital investment, should be of sufficient detail to allow significant use of the level of sector disaggregation in order for the use of the 357 level of disaggregation to be worthwhile.

Single sector disaggregation level application of input-output analysis

This application employs the direct use of the E/GNP coefficients given in Chapter 2. However, the required input data are of a different nature than that required by the 357 level application. The single sector coefficient represents the primary energy embodied per dollar spent (according to national averages) for a specific year. Thus, the input data should represent the entire dollar expenditure of the system (including labor). This is a sharp contrast to the nature of the data required for the 357 level of analysis which should include dollar expenditures for materials, energy forms and equipment (not labor) that must then be separated into producer's costs, trade costs and transportation costs.

357 sector disaggregation level application of input-output analysis

As indicated in the data required section, quantities of energy flows into the system must be in the form of the thermal energy content (or the thermal energy equivalence for electricity) of an energy product from one of the five energy sectors and the quantities of non-energy flows into the system must be in the form of dollar costs at a specific point in time. Furthermore, the type of energy inputs represented by the dollar costs must be known (i.e., do the costs represent producer's or purchaser's prices). Thus, the first step in the application of input-output analysis

is the organization and modification (if necessary) of the input quantities of the system that are required to assemble the data in the proper form.

Once the input data are assembled in the proper form, they must be assigned to the producing sectors that produce the specific products. Descriptions of the I-O sectors and a listing of their products are found in the Energy Analysis Handbook (2) and the Standard Industrial Classification (1). It is suggested that the analyst familiarize himself with the sector's descriptions and products before attempting an analysis. Table 3.2 lists common industrial equipment and the corresponding producing sectors.

It should be noted that the input-output code varies from the energy intensity coefficient sectors to the economic input-output sectors. The correlation between the codes is given in the Energy Analysis Handbook (2).

Recall that the present energy intensity coefficients apply to the year 1967. Thus, the inputs given in the form of dollar amounts must be either inflated or deflated to the year 1967. This is done using the price index of each specific sector. The sources of the suggested price indices are given in Chapter 2.

Next, trade and transportation requirements are estimated for the system inputs. As indicated in Chapter 2, the economic structure of the United States consists of interaction data between 357 divisions (sectors) of the economy.

Table 3.2. List of industrial sectors responsible for production of common industrial equipment (2)

Sector	Products
4006 - Boiler shop products	heat exchangers condensers boilers metal columns for distillation, absorption, etc. metal tanks and vessels (reactors)
4901 - pumps and compressors	pumps compressors
4903 - blowers and fans	industrial fans and blowers heat collectors, air washing and air purification equipment
4906 - industrial furnaces and ovens	electrical furnaces and ovens fuel fired furnaces and ovens high frequency induction and dielectric heating equipment
4907 - general industrial machinery	no subclassification
4806 - special industrial machinery	chemical manufacturing industries' machinery, equipment and parts
4208 - pipes and valves	pipes valves

Each sector acts as a producing sector (the sector produces products that are consumed by the consuming sectors or various types of final demand) and as a consuming sector (the sector purchases products from the producing sectors). Note that a sector may consume some of its own product. A portion of the interaction data are the dollars spent for trade (wholesale, retail and insurance) and transportation (rail, truck, pipeline, air and water) for the purchases of a consuming industry from the producing sectors. Since the dollar amount spent by the consuming industry for the purchase of a product (excluding the trade and transportation costs) from a producing sector is known, percentages of the total dollar transaction between consuming and producing sectors (either including or excluding trade and transportation costs) spent for trade and transportation can be generated. These percentages are referred to as trade and transportation margins. Thus, it is possible to generate 357 sets of trade and transportation margins (one for each producing sector) for each of the 357 consuming sectors. Furthermore, there are data of dollars spent for trade and transportation for the purchase of products by various types of final demand. Thus, trade and transportation margins for sales to final demand can be generated. The trade and transportation margins for sales other than to final demand were generated by the author for the 1967 input-output data and the margins for sale to final demand were generated at the Center for Advanced Computations, University of Illinois (2). The

use of trade and transportation margins are illustrated in the following examples:

Case I - Energy product inputs

The trade and transportation margins for sales of energy products to final demand have units of 1967 dollars per MM Btu energy content of the product. The trade and transportation margins for sales to final demand for the coal producing sector (sector 700) are listed in Table 3.3.

Table 3.3. Trade and transportation margins for sales to final demand of the coal producing sector (2)

I-O Sector	Trade Margins ($1967/MM Btu)			Transportation Margins ($1967/MM Btu)				
	6901	6902	7004	6501	6503	6504	6505	6506
700	0.0048	0.0277	0	0.0934	0.0186	0.01	0	0

The number labels given to the various trade and transportation margins are the input-output sectors that are responsible for trade and transportation. Table 3.4 lists the trade and transportation sectors.

Consider, for example, a system that requires an input of 1 MM Btu from coal per year. The trade and transportation requirements, given in terms of dollar cost, are listed in Table 3.5.

Table 3.4. List of trade and transportation sectors (2)

I-O Sector	Sector Descriptions
6901	wholesale trade
6902	retail trade
7004	insurance
6501	rail transportation
6503	truck transportation
6504	water transportation
6505	air transportation
6506	pipeline transportation

Table 3.5. Total requirement for delivery of coal input

I-O Sector	Required Input ($1967/year)
6901	0.0048
6902	0.0277
7004	--
6501	0.0934
6503	0.0186
6504	0.0100
6505	--
6506	--

For energy product sales to end uses other than final demand, the margins have units of percentage of dollar cost of product (either producer's or purchaser's price) and are applied as illustrated in Cases II and III.

Cases II and III are different applications of the same margins for non-energy products. Case II represents the use of margins on purchaser's prices and Case III represents the use of the margins on producer's prices. For example, consider the non-energy product of boiler shop work, sector 4006. Trade and transportation margins for sales to final demand for the purchases of products from sector 4006 are listed in Table 3.6.

Table 3.6. Trade and transportation margins for sales to final demand for sector 4006 (2)

I-O	Trade Margins (%)			Transportation Margins (%)					Totals
Sector	6901	6902	7004	6501	6503	6504	6505	6506	%
4006	4	0	0	1	1	0	0	0	6

Note: All non-energy product margins listed in this report are percentages of the purchaser's price.

Case II - Non-energy product input of 1,000,000 1967 dollars producer's price

Since the margins are percentages of the purchaser's price, the producer's price is modified to represent the purchaser's price then the trade and transportation costs are determined. The producer's price is 94% of the purchaser's price according to the total margin percentage in Table 3.6.

Thus, the purchaser's price is 1,063,830 1967 dollars. The calculated trade and transportation costs are listed in Table 3.7.

Case III - Non-energy product of 1,063,830 1967 dollars purchaser's price

If the inputs are expressed in terms of purchaser's prices, the application of the trade and transportation margins are straightforward. Given a purchaser's price of 1,063,830 1967 dollars, use of the margins in Table 3.6 yield a producer's price of 1,000,000 1967 dollars and the trade and transportation costs listed in Table 3.7.

Case IV - Inputs (energy or non-energy) reported as producer's costs and transportation requirements

The trade and transportation margins are intended for use in the absence of more site specific data. Specific data regarding the trade and transportation energy requirements of a product usually offer information dealing with the transportation of the product. Transportation data may appear in two forms. One form is referred to as a transportation requirement and consists of a weight to be transported over a distance and the specific form of transportation. Energy requirements per unit of transportation work (i.e., weight over a distance) have been determined for several forms of transportation (5). Thus, if the transportation requirement is known, the energy requirement for transportation can be determined. This approach to determining the transportation energy requirement is actually an extension of process

Table 3.7. Trade and transportation cost for a non-energy product input from sector 4006 of 1,000,000 $1967 producer's cost and 1,063,830 $1967 purchaser's cost

I-O Sector	Required Input ($1967/year)
6901	42,554
6902	--
7004	--
6501	10,638
6503	10,638
6504	--
6505	--
6506	--
Totals	63,830

Note that the total cost for trade and transportation is the difference in the purchaser's and producer's prices.

analysis to the delivery of the product, while the energy embodied in the non-delivered product is determined by input-output analysis requiring the cost data describing the non-delivered product to be the producer's price. Thus, this approach may require the use of trade and transportation margins to modify purchaser's prices. This approach is mainly utilized when the effect of transportation distances of inputs and/or outputs on the energy parameters of a system is to be evaluated.

The other form of transportation data is a dollar cost of a specific form of transportation. This form of transportation data is available from design reports that present cost data of materials in components of the material and shipping and handling. The cost data components are assumed to represent producer's prices of the non-delivered product and required transportation. This data form allows the direct application of energy intensity coefficients after deflation of the cost data.

In general, the energy requirement for trade is neglected when specific transportation data are available, primarily due to the lack of available specific trade data. This is not considered to result in an underestimation of the energy embodied in the delivered product because trade is less energy intensive than transportation (as indicated by the respective energy intensity coefficients) and transportation energy requirements determined from specific data

are usually significantly greater than trade energy requirements estimated from the margins.

The choice of the proper trade and transportation margins (i.e., sales to final demand or to a consuming sector) is usually the intuitive judgment of the analyst based on knowledge of the system being analyzed. In general, sales made directly to the nameplate processing system (representing direct inputs of the first level of energy analysis) are considered sales to final demand. Indirect sales to the nameplate process (such as materials sold to the construction industry used to construct the system, or sales that result from the extension of process analysis to the second level of energy analysis) are usually considered sales to the intermediate sector.

The energy intensity coefficients for converting dollar amounts (for non-energy products) and energy content amounts (for energy products) to primary energy amounts can now be applied to the input data. At this point, the data are in the form of energy content or 1967 dollars producer's costs of the input products, and 1967 dollars producer's costs for the estimated trade and transportation requirements or a transportation requirement (i.e., ton-miles) via a specific mode of transportation. The data are converted to energy inputs of primary energy by multiplying the data quantifying the input required from each sector by the energy intensity coefficient of that sector.

Use of the disaggregation of energy intensity coefficients

D. Reister has published a disaggregation of the energy intensity coefficients of a 90 sector economy (3) (i.e., the disaggregation is performed on energy intensity coefficients obtained from an interaction matrix based on a 90 sector grouping rather than a 357 sector grouping of the economy). The disaggregation is a listing of the contributions to the total energy intensity of a sector (represented as a percentage of the energy intensity coefficient) from the other producing sectors. The percentage contributions are grouped into two main categories, capital and non-capital contributions. The capital contributions list the percentages from the top twenty non-energy contributing sectors. The non-capital contributions list the percentages from the five energy sectors, and the percentages from the top twenty non-energy contributing sectors. Thus, the disaggregation of energy intensity coefficients represents a detailed energy analysis of the energy inputs per unit output of 90 systems (based on national average inputs and outputs). The utility of the disaggregation of energy intensity coefficients for the purpose of approximating energy inputs of systems through analogies is enormous.

For example, consider a system in which an energy input is not known due to the lack of data. By establishing an analogous system that is one of the 90 systems included

in the disaggregation of energy intensity coefficients (such as the gas utilities as an analogy to a coal gasification complex), an estimation, expressed as a percentage of the total energy input of the system, can be made for the unknown input. Also, estimations can be made of specific unknown portions of a given input by establishing an analogous system to the system that produces that input.

Energy Analysis Results

Reporting of results

As indicated previously, the complete documentation of the methodology and calculations of the analysis is essential to the credibility of the analysis. However, the usefulness of the analysis is determined by how the results of the analysis are documented. Table 3.8 lists the information required to allow complete use of the results of an energy analysis.

Energy parameters

Definition of energy parameters

As a relatively new and developing science, research in the field of energy analysis has been mainly devoted to methodological approaches and, as a result, the area which deals with interpretation of the analysis has been neglected. Scientists involved with energy analysis traditionally define some parameter, useful for their own purpose, that they claim to be the end result of the analysis, and ignore other

Table 3.8. Suggested format for reporting of energy analysis results

1. Process description - A brief description of the technology base of the process along with characteristics of the process and the state of the feed to the process.

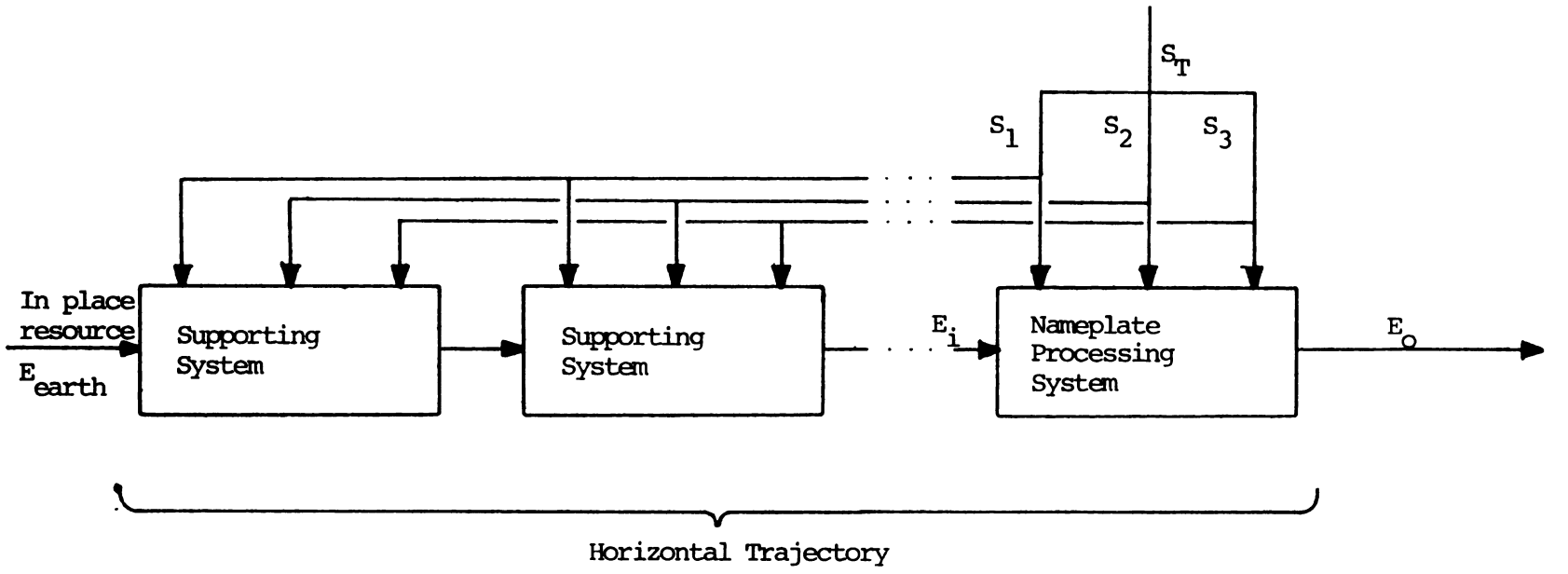
2. State of system outputs or products (waste, secondary and primary) - The word state is meant to indicate physical location and form as well as its quality. It is necessary to know where the products are, what form they are in and their energy content in order to draw comparisons with other processes producing similar products.

3. Breakdown of energy inputs - The inputs should be presented in groups as feed, utilities, raw materials and capital.

4. Breakdown of energy outputs - Each product that is considered an energy product should be reported separately with its energy value.

information that is essential in understanding the true energetic characteristics of the system under consideration. Thus, many conclusions can be drawn from a single analysis depending on how the analyst decides to manipulate the results of the analysis. Any conclusions drawn from an energy analysis should be based on a group of parameters. Certainly, for any comparisons to be made between systems on the basis of one parameter, the other parameters must be similar between the systems. Otherwise, the conclusions drawn from the comparison may be invalid. Therefore, the purpose of this section is to define a set of parameters that will provide a complete description of a system's energy characteristics.

First, the energy flows of a system (see Figure 3.3) must be defined. Notice that all energy flows are rates with units of Btu primary energy/unit of time. This does not, however, accurately represent the real situation. The process may be thought of as a semi-batch operation where one invests subsidy one, the capital energy subsidy, all at once and then adds the other subsidies at a continuous rate for the lifetime of the process. For computational convenience, the capital subsidy is amortized into an annual rate over the lifetime of the process and is accounted for the same as any other subsidy. This aspect of the analysis gives rise to dynamic as well as time independent interpretations of energy analysis results. The definition of the energy parameters useful in interpreting the results of an analysis are listed in Table 3.9.



Key

S_1 - Capital energy subsidy
S_2 - Raw materials energy subsidy
S_3 - Utilities energy subsidy
S_T - Total energy subsidy ($S_1 + S_2 + S_3$)
E_{earth} - Energy resource requirement which is converted to a useful energy form
E_i - Feed to nameplate processing system
E_o - Energy output of system

Figure 3.3. Energy flows of an energy supply system

Table 3.9. Definitions of energy analysis parameters

Total Energy Subsidy (S_T)	$S_1+S_2+S_3$
Net Energy	E_o-S_T
Energy Gain (G)	E_o/S_T
Overall Process Efficiency	$E_o/E_{earth}+S_T$
Resource Utilization Factor	E_{earth}/E_o
Capital Requirement Factor	S_1/E_o

One final parameter which is useful when comparing energy supply systems is the rated energy output. System designs are often influenced by the size of the energy supply systems and, as a result, the results of the energy analyses are influenced as well.

Discussion of energy parameters

Total Energy Subsidy - This value is the absolute energy cost of producing the energy output of a system. The total energy subsidy does not include the energy content of the energy resource that is converted to a useful energy form (E_{earth}).

Net Energy - This value is the amount of useful energy made available to society. Consider the following illustration:

An energy supply system is given an amount of crude energy (resource) to convert to a useful energy form. During the conversion, process losses are experienced, and the

resource is reduced to the energy output of the system E_o. Furthermore, the system requires an energy investment in order to operate (S_T). The remaining energy that can be consumed by society is the net energy ($E_o - S_T$).

Energy Gain - The energy gain is a measure of the energy cost to produce a unit output of energy (i.e., the relative cost of energy). The parameter is a useful comparison between energy supply systems in which the gross energy outputs and the resource utilization factors are similar. The comparison of energy supply systems on the basis of the energy gain alone can lead to inaccurate conclusions. The inadequacies of the energy gain parameter are illustrated in the following examples:

1. External supply vs. internal generation of utilities

Consider the following systems shown in Figure 3.4 and Figure 3.5.

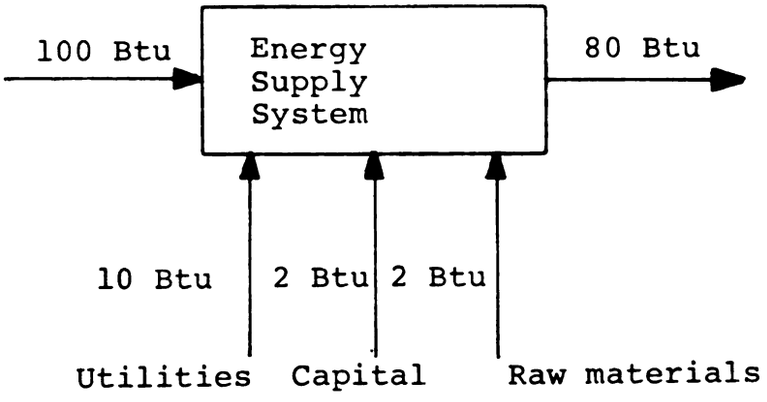


Figure 3.4. System with external supply of utilities

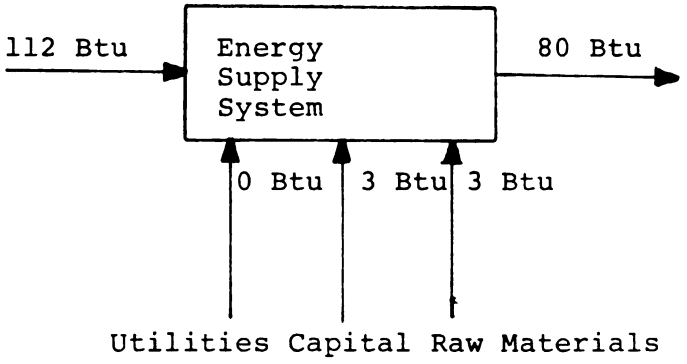


Figure 3.5. System with internal generation of utilities

Table 3.10 lists a comparison of the energy gains, resource utilization factors, gross energy outputs and the overall process efficiencies of the two systems.

Table 3.10. Comparison of energy parameters for systems with internal and external utilities supply

Utility Supply	Gross Energy Output (Btu)	Resource Utilization Factor (Btu)	Energy Gain	Overall Process Efficiency (%)
internal	80	1.40	13.3	67.80
external	80	1.25	5.7	70.18

A comparison of the energy gains alone would lead to the conclusion that the internal generation of utilities offers a significantly more efficient supply of energy. Upon examination of the overall process efficiencies, it is clear that this is an inaccurate conclusion.

2. Dominance of the total energy subsidy by a single module in an energy trajectory

This phenomenon is illustrated by two trajectories (shown in Figure 3.6 and Figure 3.7) leading to the same end-use product.

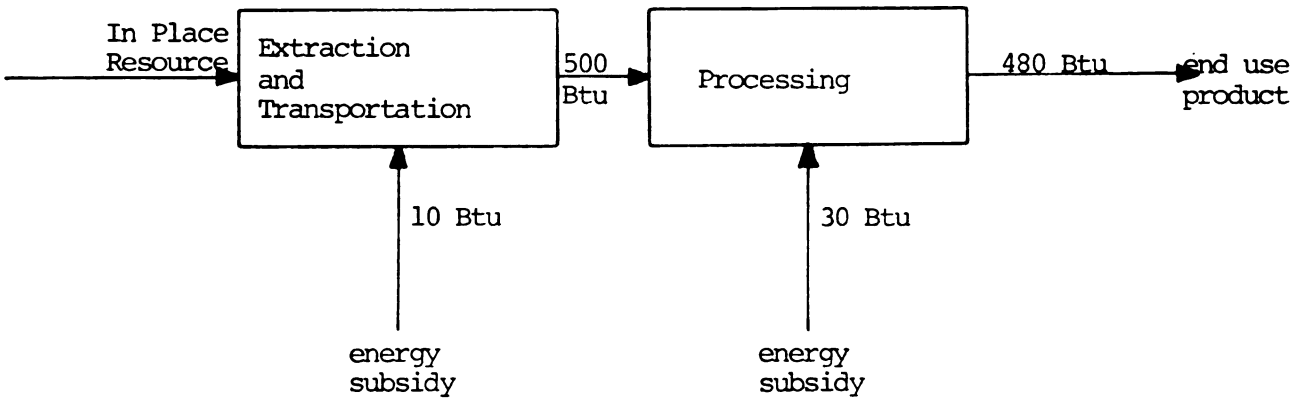


Figure 3.6. Trajectory I

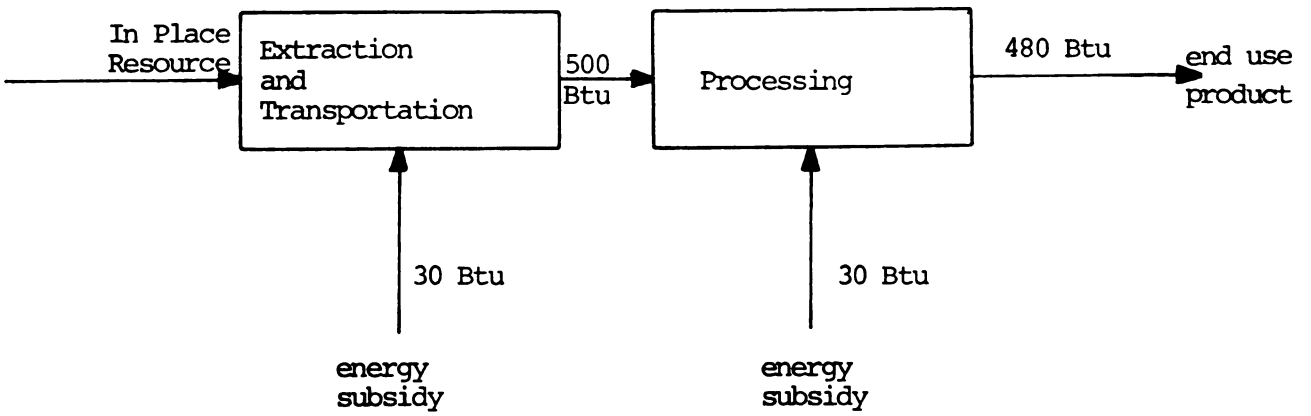


Figure 3.7. Trajectory II

Table 3.11 lists a comparison of the energy gain as a function of position for each trajectory.

Table 3.11. Comparison of energy gain and total energy subsidy as a function of position in the trajectory

	Extraction and Transportation		Processing	
Trajectory	Energy Gain	Energy Subsidy	Energy Gain	Energy Subsidy
I	50	10	12	40
II	16.7	30	8	60

It is observed that the energy characteristics of feeds with vastly different energy parameters can be washed out by processing systems that have energy subsidies much larger than all modules in the trajectory. Intuitively, it is difficult to accept similar energetics of products produced from feeds of vastly different energetics. In this case, however, the similar gains represent an accurate comparison of the systems.

3. Energetics of scale

The energy gain ratio contains no information regarding the size of a system. As in economics, the required energy inputs of a system are not proportional to the output of the system. This aspect of energy analysis must be considered when comparing systems which differ significantly in gross energy outputs.

Overall Process Efficiency - This value is similar to a thermodynamic process efficiency including the total

energy subsidy in the energy flow into the system. This value is useful in comparing energy supply systems based on non-renewable vs. renewable (i.e., free) energy resources.

Resource Utilization Factor - This value represents the quantity of resource (i.e., the resource that is being converted into a useful energy form) per unit of useful energy produced. Note that this value is not the total energy consumed per unit of energy produced. Also, note that this value is not necessarily the thermodynamic efficiency of the entire system since a portion of the energy subsidy may be generated from the energy resource as well as being converted into a useful energy form.

Capital Requirement Factor - This value represents the "capital" cost of energy per unit of energy produced. This value multiplied by the annual output and the lifetime of the system represents the total capital investment of the system that must be invested before the system can operate (excluding a small annual maintenance energy included in the capital energy subsidy). The capital energy requirement, the resource utilization factor and the energy gain are combined in a dynamic energy supply and demand model that can predict the dynamic behavior of energy supply systems.

Example of Energy Analysis Application
Energy Analysis of a Coal Gasification Complex

Comments

The organization of this energy analysis serves as the outline for the other analyses performed by the author presented in this study.

Summary of Energy Analysis

Description of Process

The system is based on the process design of the Burnham Coal Gasification Complex assembled by the Stearn-Rogers Corporation for the El Paso Natural Gas Company (4). The system is designed to produce 288 MMSCF per day of 954 Btu/SCF synthetic pipeline gas at an overall load factor of 91%. The gas will be produced from 9,383,000 tons/year of Navajo coal with a higher heating value of 8664 Btu/lb using the Lurgi coal gasification, purification and methanation technology. Included in the complex is a utility plant for production of compressed air, high purity oxygen, fuel gas, cooling water, steam and electricity and a coal processing unit for the crushing and cleaning of the raw coal. Electricity is purchased for operation of the raw water pump only. The secondary products of the complex are listed in Table 3.12.

The properties of the coal used as the feed to the system are listed in Table 3.13.

The complex is to be located local to the coal mining operation allowing a minimum coal transportation requirement.

Table 3.12. Secondary products of coal gasification process

Product	Quantity (4)	Higher Heating Value (Useful Energy Content)(7)
Tar	239,250 $\frac{gal}{day}$	$0.15 \times 10^6 \frac{Btu}{gal}$
Tar oil	157,370 $\frac{gal}{day}$	$0.15 \times 10^6 \frac{Btu}{gal}$
Naptha	74,900 $\frac{gal}{day}$	$5.248 \times 10^6 \frac{Btu}{bbl}$
Crude phenols	32,740 $\frac{gal}{day}$	----
Elemental Sulfur	167 $\frac{long\ ton}{day}$	----
Ammonia Soln. (20 wt %)	332,550 $\frac{gal}{day}$	----

Table 3.13. Properties of Navajo coal (4)

Proximate Analysis	Weight %
Dry and Ash-Free Coal	64.50
Ash	19.25
Moisture	16.25
Total	100.00
Component Analysis (D.A.F. Coal)	
Carbon	76.26
Hydrogen	5.58
Nitrogen	1.32
Sulfur	1.07
Oxygen	15.74
Trace Compounds	0.03
Total	100.00
Higher Heating Value	
8664 Btu/lb	
Ash Softening Data	
Softening Point	2282°F
Melting Point	2597°F
Flow Point	2723°F

State of system products

Primary products

The complex produces 288 MMSCF per day of a synthetic pipeline gas. The properties of the pipeline gas are listed in Table 3.14.

Table 3.14. Properties of the synthetic pipeline gas (4)

Component	Volume %
Hydrogen	4.16
Methane	92.93
Carbon Dioxide	1.81
Carbon Monoxide	0.01
Nitrogen and Argon	1.09
Total	100.00
Higher Heating Value - 8954 Btu/SCF	

The system design includes the transportation of the gas via pipeline for 7.3 miles, where it will join the El Paso Natural Gas Company's main line (already in existence).

Secondary products

The quantities and energy contents of the secondary products are listed in Table 3.12. The system design includes temporary tank storage of the secondary products and loading and unloading facilities for rail transportation.

Waste products

Liquid wastes are stored temporarily in tanks with facilities included for loading and unloading for rail transportation. Solid wastes (ash) from both air and oxygen

blown gasifiers along with refuse from coal fines cleaning are dewatered and transported to the mine area for disposal. Only facilities for transporting and handling of waste ash are included in the design. Actual disposal facilities are excluded. Water effluents from the complex are handled by either the general sewage system or by solar evaporation and settling ponds.

Energy inputs and outputs of the system

The breakdown of the energy inputs to the system are listed in Table 3.15 and the breakdown of the energy outputs of the system are listed in Table 3.16.

Energy parameters

The energy parameters of the coal gasification complex are listed in Table 3.17.

Basis of Analysis

General approach

The system generates all the required utilities (with the exception of purchased electricity for operation of the river water pump) local to the main processing units. Thus, the utility generating units will be included in the nameplate processing system.

The system is atypical in the sense that the nameplate processing system is local to the coal mining operation. In general, coal gasification complexes require transportation of mined coal to the process site. Therefore, a fictitious

Table 3.15. Energy inputs of the system

Input	Embodied Energy ($\times 10^9$ Btu Primary/Year)
feed (coal)	
energy content	162,589
energy subsidy	1,414
feed transportation requirement	
0 mile distance	0
50 mile distance	704
100 mile distance	1,409
500 mile distance	7,037
utilities	
purchased electricity	313
capital - amortized over a 30-year complex life	812
raw materials	
chemicals and catalyst	892

Table 3.16. Energy outputs of the system (4)

Product	Energy Content ($\times 10^9$ Btu/Year)
Pipeline gas	91,260
Tar	11,921
Tar Oil	7,841
Naptha	4,974
Total	115,996

Table 3.17. Energy parameters of coal gasification complex

Coal Transportation Distance (Mile)	Total Energy Subsidy ($\times 10^9$ Btu Primary)	Net Energy ($\times 10^9$ Btu Primary)	Energy Gain	Overall Process Efficiency %	Resource Utilization Factor	Capital Requirement Factor
0	3431	112,565	33.81	69.87	1.40	0.007
50	4135	111,861	28.05	69.57	1.40	0.007
100	4840	111,156	23.97	69.28	1.40	0.007
500	10468	105,528	11.08	67.03	1.40	0.007

transportation requirement is added to the system, with the distance of transportation variable. Thus, the analysis requires process analysis of the nameplate processing system with the extension of the process analysis along the horizontal trajectory to include the transportation of mined coal (refer to the coal gasification trajectory shown in Figure 3.2).

Description of data

The data used to perform the analysis are contained in the coal gasification complex design developed by the Stearn-Rogers Corporation for the El Paso Natural Gas Company (4). The energy flows into the system, coal and electricity, are expressed in terms of Btu/year and kwh/year, respectively. The raw material and capital flows are expressed in terms of $1973/year and $1973/processing unit, respectively. All dollar costs represent purchaser's prices of equipment and materials. Also, the detail of the data warrants the use of the 357 sector disaggregation level of input-output analysis.

Definition of the nameplate processing system

The nameplate processing system is defined to include the processing units, all interconnecting facilities and required general facilities of the processing units listed in Table 3.18.

Table 3.18. List of nameplate processing units (4)

1.	Gas Production
2.	Crude Gas Shift Conversion
3.	Gas Cooling
4.	Gas Purification
5.	Refrigeration
6.	Methane Synthesis
7.	Product Gas Compression and Dehydration
8.	Gas Liquor Separation
9.	Phenol Extraction
10.	Gas Liquor Stripping
11.	Lock Gas Storage and Compression
12.	Sulfur Recovery
13.	Fuel Gas Production
14.	Fuel Gas Cooling
15.	Fuel Gas Treating
16.	Air Compression
17.	Steam and Power Generation
18.	Oxygen Production
19.	Oxygen Compression
20.	Raw Water Treating
21.	Cooling Water System
22.	Miscellaneous Plant Utility System
23.	Ash Dewatering and Transfer
24.	River Water Pumping Plant
25.	Raw Water Pipeline
26.	Raw Water Storage and Pumping
27.	Mine Crushing and Screening
28.	Coal Storage Blending and Screening
29.	Coal Fines Cleaning
30.	Mine Ash Handling

Determination of Energy Inputs of the System

Application of process analysis

Quantities of inputs and identification of appropriate producing sectors

Data are extracted from the design report which represents the required energy inputs outlined in Table 3.1. The data are assigned to the appropriate producing sectors and presented according to the energy inputs they represent.

Energy Inputs 1 and 2

Table 3.19 lists the quantities and the appropriate input-output sectors for the purchase and delivery of the nameplate processing equipment and materials.

Energy Input 3

The energy required for land preparation, required assembly and construction at site, and installation of the nameplate processing equipment is estimated using the disaggregation of energy intensity coefficients.

Energy Inputs 4 and 5

Table 3.20 lists the appropriate input-output sectors and the required quantities of the utilities, feed, feed transportation requirement, and the dollar expenditure for the purchase and delivery of the raw materials.

Table 3.19. Quantities of energy inputs 1 and 2 (4)

Processing Unit	Quantity ($1973)	I-O Sector
Gas Production	37,510,000	4006
Crude Gas Shift Conversion	4,220,000	4006
Gas Cooling	4,440,000	4006
Gas Purification	17,060,000	4903
Refrigeration	5,270,000	4901
Methane Synthesis	11,710,000	4006
Product Gas Compression & Dehydration	3,300,000	4901
Gas Liquor Separation	3,270,000	4006
Phenol Extraction	3,790,000	4006
Gas Liquor Stripping	3,100,000	4006
Lock Gas Storage & Compression	1,110,000	4901
Sulfur Recovery	4,490,000	4006
Fuel Gas Production	12,540,000	4006
Fuel Gas Cooling	860,000	4006
Fuel Gas Treating	2,220,000	4903
Air Compression	13,310,000	4901
Steam & Power Generation	16,610,000	4301
Oxygen Production	14,550,000	4006
Oxygen Compression	4,250,000	4901
Raw Water Treating	3,700,000	4006
Cooling Water System	3,190,000	
Miscellaneous Plant Utility Systems	3,350,000	4907
Ash Dewatering & Transfer	3,480,000	4907
River Water Pumping Plant	1,770,000	6803
Raw Water Pipeline	5,710,000	4208
Raw Water Storage & Pumping	880,000	4901
Mine Crushing & Screening	1,610,000	4502
Coal Storage, Blending and Screening	6,460,000	4502
Coal Fines Cleaning	1,900,000	4502
Mine Ash Handling	270,000	4502
Materials Initial Catalyst and Chemicals	4,010,000	2701

Table 3.20. Energy inputs 4 and 5 (4)

Input		Quantity (Units/Year)	I-O Sector
Feed (Coal)		162,589 x 10^9 Btu	700
Transportation of Feed	0[a]	0 ton-mi	Process Analysis
	50[a]	469 x 10^6 ton-mi	
	100[a]	938 x 10^6 ton-mi	
	500[a]	4,692 x 10^6 ton-mi	
Utilities (Electricity)		80.5 x 10^9 Btu	6801
Raw Materials Catalyst and Chemicals		3,520,000 $1973	2701

a - transportation distance

Energy Inputs 6, 7, 8 and 9

Energy inputs for transportation of primary and secondary products to end use and the disposal of waste products are included in the general facilities. Table 3.21 lists the appropriate input-output sectors and quantities for the purchase and delivery of the general facilities.

Table 3.21. Energy inputs 6, 7, 8 and 9 (4)

Product	Quantity ($1973)	I-O Sector
Site Improvements	1,420,000	3611
General Plant Buildings	2,130,000	3610
Electrical Distribution	3,070,000	5308
Header Systems & Interconnecting Piping	4,540,000	4208
Evaporation & Settling Ponds	690,000	3611
Storage & Loading	1,420,000	4006
Product Gas Pipeline	280,000	4208

Energy Input 10

The energy input for land preparation, required assembly and construction at site, and installation of general facilities is estimated using the disaggregation of energy intensity coefficients.

Energy Input 11

The energy input for the maintenance of the nameplate processing equipment and the general facilities is estimated using the disaggregation of energy intensity coefficients.

Extension of process analysis

The analysis requires the extension of process analysis to the transportation of coal by rail. The analysis of rail transportation has already been performed and is reported to require 1,500 Btu primary/ton mi. (5). The energy requirements for the transportation of coal are listed in Table 3.22.

Table 3.22. Energy requirements for the transportation of coal

Transportation Requirement (ton-mi/year) (4)	Energy Input ($\times 10^9$ Btu primary/year)	Transportation Distance (mi)
0	0	0
469×10^6	704	50
938×10^6	1,407	100
$4{,}692 \times 10^6$	7,037	500

Application of input-output analysis

Comments

Note that separate accounts must be kept for energy inputs 1-2 and 6-9 (lifetime inputs) and the annual investments.

Deflation of cost data

The deflation of the cost data from 1973 dollars to 1967 dollars is listed in Table 3.23 (lifetime energy investments) and Table 3.24 (annual energy investments).

Table 3.23. Deflation of cost data (lifetime investments)

I-O Sector	Purchaser's Price (x 10^6 $1973)	$\frac{\$1973}{\$1967}$ (6)	Purchaser's Price (x 10^6 $1967)
2701	4.010	1.075	3.730
3610	2.130	1.304	1.633
3611	2.110	1.304	1.618
4006	105.090	1.261	83.339
4208	10.530	1.264	8.331
4301	16.610	1.271	13.068
4502	10.240	1.318	7.769
4806	3.700	1.303	2.840
4901	28.120	1.260	22.317
4903	19.280	1.260	15.302
4907	6.830	1.260	5.421
5308	3.070	1.147	2.677
6803	1.770	1.214	1.458

Table 3.24. Deflation of cost data (annual investments)

I-O Sector	Purchaser's Price (x 10^6 $1973/year)	$\frac{\$1973}{\$1967}$ (6)	Purchaser's Price (x 10^6 $1967/year)
2701	3.520	1.075	3.274

Modification of purchaser's prices into producer's prices of products, trade and transportation, and the conversion of producer's prices to primary energy

The inputs expressed in dollar quantities represent purchaser's prices. All inputs, except inputs from sectors 3610 and 3611, are considered as sales to final demand. Inputs from sectors 3610 and 3611 (concrete bricks and concrete products) are considered as sales to the new construction industry, sector 1103. Table 3.25 lists the appropriate trade and transportation margins.

Table 3.25. Trade and transportation margins

I-O	Transport (%)				Trade (%)			
Sector	6501	6503	6504	6505	6506	6901	6902	Total
			(sales to final demand) (2)					
2701	2	1	0	0	0	3	2	8
4006	1	1	0	0	0	4	0	6
4208	0	1	0	0	0	11	0	12
4301	0	0	0	0	0	1	0	1
4502	0	1	0	0	0	5	0	6
4806	0	1	0	0	0	4	0	5
4901	1	2	0	0	0	10	0	13
4903	0	1	0	0	0	7	0	8
4907	0	0	0	0	0	7	0	7
5308	0	0	0	0	0	3	0	3
6803	0	0	0	0	0	0	0	0
			(sales to sector 1103) (8)					
3610	0	1.43	0	0	0	17.86	1.43	20.72
3611	0	0	0	0	0	10.24	4.17	14.41

The modification of the purchaser's price into the producer's prices for the product, trade and transportation, and the conversion of the producer's cost into primary energy are listed in Table 3.26 (lifetime energy investments) and Table 3.27 (annual energy investments).

Table 3.26. Modification of purchaser's prices into producer's prices, and the conversion of the producer's prices into primary energy (lifetime energy investments)

I-O Sector	Producer's Price (x 10^6 $1967)	Btu Primary / $1967 (2)	Embodied Energy (x 10^9 Btu Primary)
2701	3.432	291,465	1,000
3610	1.295	148,220	192
3611	1.385	113,661	157
4006	78.339	111,172	8,709
4208	7.331	78,483	575
4301	12.937	74,377	962
4502	7.303	75,541	552
4806	2.698	63,177	170
4901	19.416	59,006	1,146
4903	14.078	66,579	937
4907	5.042	68,763	347
5308	2.597	63,182	164
6803	1.458	114,263	167
6501	1.131	92,917	105
6503	1.683	54,968	93
6901	9.215	37,501	346
6902	0.165	37,329	6

The energy embodied in non-delivered materials and equipment is 15078 x 10^9 Btu primary.

Table 3.27. Modification of purchaser's prices into producer's prices, and the conversion of producer's prices into primary energy (annual energy investments)

I-O Sector	Producer's Price ($\times 10^6$ \$1967/Year)	Btu Primary / \$1967 (2)	Embodied Energy ($\times 10^9$ Btu Primary/Year)
2701	3.012	291,465	878
6501	0.065	92,917	6
6502	0.033	54,968	2
6901	0.098	37,501	4
6902	0.065	37,329	2

The energy embodied in non-delivered materials is 878×10^9 Btu primary/year.

Estimation of trade and transportation costs for the energy product inputs and the conversion of the energy product inputs and the trade and transportation costs into primary energy

The only energy product input requiring estimation of the trade and transportation margins is the purchased electricity. Table 3.28 lists the trade and transportation margins for purchased electricity for sales to final demand.

Table 3.28. Trade and transportation margins (2)

I-O Sector	Trade (\$/MM Btu)			Transportation (\$/MM Btu)				
	6901	6902	7004	6501	6503	6504	6505	6506
6801	0	0	0	0	0	0	0	0

Since the trade and transportation margins are zero, no modification of the purchased electricity data is required. The energy flows into the system, mined coal and purchased electricity, are converted into primary energy as listed in Table 3.29.

Table 3.29. Conversion of energy flows into primary energy (annual energy investments)

I-O Sector	Quantity ($\times 10^9$ Btu/Year)	Btu Primary/ Btu (2)	Embodied Energy ($\times 10^9$ Btu Primary/ Year)
700	162,589	1.0087	164,003
6801	80.5	3.8951	313

Note that the primary energy embodied in the coal (i.e., feed) includes 162,589 Btu energy content and 1414 Btu primary energy subsidy. The total energy subsidy of the feed is the 1414 Btu primary plus the transportation energy requirements.

Use of the disaggregation of energy intensity coefficients

Estimation of energy inputs 3 and 10

The estimation of the energy required for the installation of the nameplate processing equipment and the general facilities is made by assuming an analogy between installation and the new construction industry, sector 1100. Table 3.30 lists the disaggregation of the energy intensity coefficient for sector 1100.

Table 3.30. Disaggregation of the energy intensity coefficients for sector 1100 (3)

Energy Usage	% of Total Energy Requirement
Direct	20.77
Capital	2.62
Materials	65.34
Transportation	2.31
Services	4.21
Trade	4.75

The estimation of the installation energy is made by assuming the energy embodied in the non-delivered materials and equipment of inputs 1-2 and 8-9 represent the material requirement of sector 1100. The installation energy is then assumed to be the remaining energy requirement. Table 3.31 lists energy inputs 3 and 10.

Table 3.31. Energy inputs 3 and 10

Energy Embodied in Non-delivered Materials and Equipment (Inputs 1-2, 8-9) ($\times 10^9$ Btu Primary)	Energy Inputs (1-3, 8-10) ($\times 10^9$ Btu Primary)	Energy Inputs 3 and 10 (Installation Energy) ($\times 10^9$ Btu Primary)
15,078	23,076	7998

Estimation of energy input 11

The energy required to maintain the nameplate processing equipment and the general facilities is estimated by assuming an analogy between the coal gasification complex and the natural gas utility sector. The disaggregation of the energy intensity coefficient for sector 6802 reports that 0.08% of the total energy requirement is for maintenance (3). It is assumed that the capital investment, which is 1.44% of the total energy requirement of the complex, requires the maintenance energy. Thus, the total capital energy requirement, including maintenance, is 1.52% of the total energy requirement of the complex (including the energy content of the feed) of which 5.26% represents the maintenance energy requirement. Table 3.32 lists the energy required for maintenance.

Table 3.32. Energy input 11

Capital Energy Investment (Not Including Maintenance) ($\times 10^9$ Btu Primary)	Total Capital Energy Investment ($\times 10^9$ Btu Primary)	Maintenance Energy Requirement ($\times 10^9$ Btu Primary)
23,076	24,358	1,282

Determination of Energy Outputs of the System

The outputs of the system are determined from the data in Table 3.12 and an energy content of 954 Btu/SCF for the synthetic gas (gas production is 288 MM SCF/day). Table 3.33 lists the energy outputs of the system.

Table 3.33. Energy outputs of the system

Product	Quantity	Energy Content	Energy Output ($\times 10^9$ Btu/Year)
Pipeline Gas	9.566×10^{10} $\frac{SCF}{year}$	954 $\frac{Btu}{SCF}$	91,260
Tar	7.947×10^{7} $\frac{Gal}{year}$	0.15×10^{6} $\frac{Btu}{gal}$	11,921
Tar Oil	5.227×10^{7} $\frac{Gal}{year}$	0.15×10^{6} $\frac{Btu}{gal}$	7,841
Naptha	2.488×10^{7} $\frac{Gal}{year}$	5.248×10^{6} $\frac{Btu}{gal}$	4,974
		Total energy output	115,996

Note that the system products of crude phenols, elemental sulfur and 20 wt. percent solution of ammonia are not considered as energy products. One might argue that crude phenols are an energy product. However, the crude phenols will most likely be sold as feedstock to the chemical industry, in which case the crude phenols' end use is not as an energy product. Thus, the crude phenols should not be considered as an energy output of the system.

CHAPTER 4

SUMMARY OF ENERGY ANALYSES

Introduction

This chapter summarizes the application of energy analysis to central receiver solar thermal power stations, systems supplying industrial process heat from solar radiation, crop producing systems and the production of alcohol from corn. Complete descriptions and documentation of the analyses summarized in this chapter are included in the appendices of this study.

Summary of Energy Analysis of Central Receiver Solar Thermal Power Stations

Description of System

High efficiency collector subsystem (system 1)

Energy analysis is applied to the system described in a design report prepared by Martin Marietta (1). The collector subsystem of the 150 MW(e) intermediate to peak load central receiver power station is comprised of fifteen collector modules. Each module consists of 1554 high efficiency heliostats focused on a single cavity-type receiver mounted on a 90m steel tower. The operational mode changes and the sun tracking motion of the heliostats are accomplished via an open loop control system utilizing preprogramed microprocessors. Superheated steam is produced in the fifteen receivers which is used directly to

drive a single turbogenerator. A three-hour thermal storage capacity (load factor of 0.5) is obtained through a combination of molten salt and oil storage. Waste heat from the electric plant is rejected using a wet cooling tower.

Lower efficiency collector subsystem (system 2)

Energy analysis is applied to the system described in a system evaluation prepared by the Mitre Corporation (2). The system is based primarily on ERDA contractor's generic design of a 100 MW(e) intermediate to peak load central receiver power station. The proposed collector subsystem is made up of three collector modules. Each module contains 7500 lower efficiency heliostats focused on a single cavity-type receiver mounted on a 198m concrete tower. The operational mode changes and the sun tracking motion of the heliostats are accomplished via a closed loop control system utilizing sun-sensors. Superheated steam is produced in the three receivers which is used directly to drive a single turbogenerator. A three-hour thermal storage capacity (load factor of 0.5) is obtained through a steel ingot storage system. Forced air cooling towers are proposed for rejection of waste heat from the electric plant.

State of System Outputs

Central receiver power stations produce non-stored electricity fed into a utility grid as its primary

product. The system does not produce secondary products, nor waste products that require handling or disposal facilities not included in the power station itself.

Energy Inputs and Outputs of System

Due to the capital intensive nature of central receiver power stations, the energetics of such a system are strongly influenced by the lifetime of the system. The actual lifetimes of proposed central receiver power stations are not known. Thus, Table 4.1 and Table 4.2 list the energy inputs of systems 1 and 2, respectively, as a function of the system lifetime. The energy outputs of systems 1 and 2 are 2153 x 10^9 Btu per year and 1435 x 10^9 Btu per year, respectively.

Table 4.1. Annual energy inputs required by system 1 (3)

Energy Input	Transportation Distance of Prototype Components (miles)	Embodied Energy (x 10^9 Btu primary/year) 20 yr[a]	25 yr[a]	30 yr[a]
Amortized Capital	100	1347	1093	924
	500	1355	1100	929
	1000	1366	1108	936
Raw Materials	---	69	55	46
Utilities	---	---	---	---
Totals	100	1416	1148	970
	500	1424	1155	975
	1000	1435	1163	982

a - System lifetime

Table 4.2. Annual energy input required by system 2 (3)

Energy Input	Transportation Distance of Prototype Components (miles)	Embodied Energy ($\times 10^9$ Btu primary/yr) 20 yr[a]	25 yr[a]	30 yr[a]
Ammortized Capital	100	609	501	430
	500	614	505	432
	1000	619	509	436
Raw Materials	---	---	---	---
Utilities	---	---	---	---
Totals	100	609	501	430
	500	614	505	432
	1000	619	509	436

a - System lifetime

Energy Parameters of System

Table 4.3 lists the energy parameters of systems 1 and 2.

Summary of Energy Analysis of Systems Supplying Industrial Process Heat from Solar Radiation

Description of System

Currently, solar industrial process heat systems are designed to be subsystems that are integrated into existing systems to operate in a fuel displacement mode. Thus, solar industrial process heat systems are utility supply systems, installed at the site of the existing system that will consume the process heat produced. Solar industrial process heat systems usually utilize low to moderate efficiency solar collectors such as flat plate collectors, evacuated tubular collectors, Winston concentrating collectors, Fresnel lens concentrating collectors and parabolic trough concentrating collectors. If possible, the collector field is mounted on the roof of existing structures to minimize the required capital investment. Depending on the demand load for the process heat, thermal storage may or may not be required.

Energy analysis is applied to the system designs of three solar industrial process heat systems described in system evaluations prepared by the Mitre Corporation (4). The energies embodied in the mentioned low to moderate efficiency solar collectors are estimated from

Table 4.3. Energy parameters of systems analyzed (3)

System	Transportation Distance of Prototype Components (miles)	System Lifetime (years)	Total Energy Subsidy ($\times 10^9$ Btu primary/yr)	Net Energy ($\times 10^9$ Btu primary/yr)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
1	100	20	1416	737	1.52	152	---	0.626
		25	1148	1005	1.88	188	---	0.508
		30	970	1183	2.22	222	---	0.429
	500	20	1424	729	1.51	151	---	0.629
		25	1155	998	1.86	186	---	0.511
		30	975	1178	2.21	221	---	0.431
	1000	20	1435	718	1.50	150	---	0.634
		25	1163	990	1.85	185	---	0.515
		30	982	1171	2.19	219	---	0.435
2	100	20	609	826	2.36	236	---	0.424
		25	501	934	2.86	286	---	0.349
		30	430	1005	3.34	334	---	0.300
	500	20	614	821	2.34	234	---	0.428
		25	505	930	2.84	284	---	0.352
		30	432	1003	3.32	332	---	0.301
	1000	20	619	816	2.32	232	---	0.431
		25	509	926	2.82	282	---	0.355
		30	436	999	3.29	329	---	0.304

data describing the collectors found in the Mitre reports (2, 4) (see TablesB.9 and B.1 for the embodied energies and energy outputs, respectively, of the mentioned solar collectors). Energy parameters are determined for the following solar industrial process heat systems:

System I. 60^{o}-80^{o}C Hot Water - Textile Process Water

The system is designed to supply 30% of the yearly hot water requirement at 60^{o}-80^{o}C from an available solar insolation of 550,000 Btu/ft^2/yr (South Carolina). About 2.5×10^5 ft^2 of evacuated tubular collectors operating at 50% efficiency over daylight hours are used to supply 180,000 gallons of water (at an average of 70^{o}C) per day. The system is estimated to collect 67850×10^6 Btu/yr with an estimated system lifetime of thirty years.

System II. 80^{o}-100^{o}C Hot Water - Can Washing

The system is designed to supply 40% of the yearly hot water requirement at 80^{o}-100^{o}C from an available solar insolation of 637,500 Btu/ft^2/yr (southern California). About 150,000 ft^2 of copper flat plate collectors operating at an average 40% efficiency are used to supply a maximum of 20,000 gallons/hr of hot water at an average temperature of 90^{o}C. The system is expected to collect $38,250 \times 10^6$ Btu/yr with an estimated system lifetime of 35 years.

System III. 100^{o}-150^{o}C Hot Air - Plastic Curing

The system is designed to supply 90% of the hot air requirement at a constant temperature of 149^{o}C. The system includes a recuperator heat exchanger to recover

exhaust air enthalpy and rock bed storage to provide thermal inertial for 48 hours at 150°C to 200°C. About 135,000 ft^2 of Winston concentrating collectors are used with an available solar insolation of 650,000 $Btu/ft^2/yr$ (California) operating at an average daily efficiency of 50%. The system is expected to collect $29,565 \times 10^6$ Btu/yr with an estimated system lifetime of 20 years.

State of System Outputs

The primary products of systems I, II and III are process heat in the form of 60°-80°C hot water, 80°-100°C hot water and 100-150°C hot air, respectively. The primary product of each system is consumed at its production site. There are no secondary or waste products reported for the systems analyzed.

Energy Inputs and Outputs of System

Table 4.4 and Table 4.5 list the annual energy inputs and outputs, respectively, of the systems analyzed.

Energy Parameters of System

Table 4.6 lists the energy parameters of the systems analyzed.

Table 4.4. Annual energy inputs of solar industrial process heat systems (5)

Input	Embodied Energy (x 10^9 Btu primary/yr) I[a]	II[a]	III[a]
Amortized Capital			
50 miles[b]	5.5	4.9	5.0
100 miles[b]	5.5	4.9	5.0
500 miles[b]	5.5	5.0	5.1
Raw Materials	---	---	---
Utilities			
5[c]	13.2	7.4	5.8
10[c]	26.4	14.9	11.5
20[c]	52.9	29.8	23.0

a - System
b - Transportation distance for collector delivery
c - Per cent of total thermal output required as electrical input

Table 4.5. Annual energy outputs of solar industrial process heat systems (5)

System	Energy Output (x 10^9 Btu/yr)
I	67.850
II	38.250
III	29.565

Table 4.6. Energy parameters of solar industrial process heat systems assuming a 100 mile transportation distance for collector delivery (5)

System	Per Cent of Annual Thermal Output Required as Utility Input	Total Energy Subsidy ($\times 10^9$ Btu primary/yr)	Net Energy ($\times 10^9$ Btu primary/yr)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
I	5	18.7	49.2	3.63	363	---	0.081
	10	31.9	36.0	2.13	213	---	0.081
	20	58.4	9.5	1.16	116	---	0.081
II	5	12.3	26.0	3.11	311	---	0.128
	10	19.8	18.5	1.93	193	---	0.128
	20	34.7	3.6	1.10	110	---	0.128
III	5	10.8	18.8	2.74	274	---	0.169
	10	16.5	13.1	1.79	179	---	0.169
	20	28.0	1.6	1.06	106	---	0.169

Summary of Energy Analysis of Crop Producing Systems

Description of System

From an energy supply point of view, crop production is the conversion of solar radiation into chemical energy stored in biomass. The process uses raw materials of seeds, fertilizers and chemicals, utilities of motor fuel and electricity and requires farm equipment (i.e., tractors, plows, discs, etc.) as capital. The feed to the process is freely available solar radiation.

The capital, raw materials and utilities required for the production of specified yields of various crops are reported by Keener and Roller (6) and represent intensive cultural practices (i.e., maximum use of equipment, commercial fertilizers and chemicals for maximum crop yield) for crop production without the use of irrigation. The crop producing system includes operations performed in the field and the utility requirement for operation of the farm shop. The system does not include any general facilities such as the farm house and farm shop.

State of System Outputs

The primary products of the crop producing systems analyzed are dried and chipped biomass ready for consumption as a solid fuel. The wet crops (as stored at the farmstead) are transported to the processing site where they are dried

and chipped. The biomass is assumed to be consumed at the processing site. There are no secondary or waste products reported for the crop producing systems.

Energy Inputs and Outputs of System

Table 4.7 and Table 4.8 list the energy inputs and outputs, respectively, of the crop producing systems analyzed.

Energy Parameters of System

Table 4.9 lists the energy parameters of the crop producing systems analyzed.

Summary of Energy Analysis of the Production of Alcohol from Corn

Description of System

Energy analysis is applied to the system design of a 50 MM gal per year (actual production) alcohol (199 proof ethanol) plant prepared by the Raphall Katzen Associates (8). The secondary products of the system are listed in Table 4.10. The system is designed to process 543,977 tons/yr of corn at a fifteen per cent moisture content. The corn is assumed to be delivered 500 miles from the farm to the alcohol plant via truck transportation. The process heat required by the system is supplied by 97899 tons/yr of #6 Illinois coal delivered via rail transportation. The delivery distance of the coal is

Table 4.7. Energy inputs of crop producing systems (7)

Crop	Transportation Distance for Delivery of Crops to Processing Site (miles)	Energy Inputs (MJ primary / hm^2 growth cycle) Capital	Raw Materials	Utilities	Delivery of Crops	Processing of Crops
Alfalfa	50	4352	39,973	15362	12450	31903
	100				24900	
	500				124500	
Corn	50	1495	25,166	4179	6600	16755
	100				13190	
	500				65960	
Kenaf	50	1495	22,678	4185	6660	16866
	100				13330	
	500				66640	
Napier Grass	50	4352	185,756	22393	51780	132491
	100				103550	
	500				517770	
Slash Pine	50	21467	182,502	70594	125830	537181
	100				251650	
	500				1258260	
Wheat	50	1425	14,067	3775	2480	5992
	100				4970	
	500				24830	

Table 4.8. Energy outputs of crop producing systems (7)

Crop	Energy Output (MJ/hm^2 Cycle)
Alfalfa	645,500
Corn	348,800
Kenaf	331,500
Napier Grass	2,587,600
Slash Pine	4,933,400
Wheat	128,600

Table 4.9. Energy parameters of crop producing systems (7)

Crop	Transportation Distance for Delivery of Crops to Processing Site (miles)	Total Energy Subsidy ($\times 10^3$ MJ primary / hm^2 growth cycle)	Net Energy ($\times 10^3$ MJ primary / hm^2 growth cycle)	Energy Gain	Overall Process Efficiency %	Resource Utilization Factor	Capital Requirement Factor
Alfalfa	50	104.0	541.5	6.20	620	---	0.007
	100	116.5	529.0	5.54	554	---	0.007
	500	216.1	429.4	2.99	299	---	0.007
Corn	50	54.2	294.6	6.44	644	---	0.004
	100	60.8	288.0	5.74	574	---	0.004
	500	113.6	235.2	3.07	307	---	0.004
Kenaf	50	51.9	279.6	6.39	639	---	0.005
	100	58.6	272.9	5.66	566	---	0.005
	500	111.9	219.6	2.96	296	---	0.005
Napier Grass	50	396.8	2190.8	6.52	652	---	0.002
	100	448.5	2139.1	5.77	577	---	0.002
	500	862.8	1724.8	3.00	300	---	0.002
Slash Pine	50	937.6	3995.8	5.26	526	---	0.004
	100	1063.4	3870.0	4.64	464	---	0.004
	500	2070.0	2863.4	2.38	238	---	0.004
Wheat	50	27.7	100.9	4.64	464	---	0.011
	100	30.2	98.4	4.25	425	---	0.011
	500	50.1	78.5	2.57	257	---	0.011

Table 4.10. Secondary products of the alcohol plant

Product	Quantity
Distillers Dark Grains	173,448 tons/yr
Fusel Oil	224,000 gal/yr
40 Weight % Aqueous Ammonia Sulfide Solution	26,058 tons/yr

varied from 500 to 1500 miles. The system operates at a load factor of 0.90 (330 days per year) and has an expected lifetime of twenty years.

State of System Outputs

Quantities of the system products are given in the description of system. The secondary products are delivered 500 miles to their end-use site via truck transportation. The alcohol is delivered to its end-use site via truck transportation and the distance of delivery is varied from 500 to 1500 miles.

Energy Inputs and Outputs of System

Tables 4.11 and 4.12 list the energy inputs and outputs, respectively, of the alcohol plant.

Energy Parameters of System

The actual energy resource of the production of alcohol is solar radiation. However, the conversion of the crop to the liquid fuel (alcohol) consumes a great deal of energy as process heat. It is proposed that the consumption of crude oil in the production of gasoline be displaced by the production of alcohol from corn, consuming coal for the supply of the required process heat. The obvious alternative to alcohol production is the production of liquid fuels directly from coal. The overall process efficiencies of alcohol production and coal liquefaction will indicate which process produces liquid fuels more efficiently

Table 4.11. Energy inputs of the alcohol plant (9)

Input	Embodied Energy ($\times 10^9$ Btu primary/yr)
Capital (amortized over plant life)	92
Raw Materials	1910
Utilities	920
Coal - energy content	2085
energy subsidy (non-delivered)	18
Delivery of Coal - 500 miles[a]	73
1000 miles[a]	147
1500 miles[a]	220
Delivery of Alcohol - 500 miles[a]	576
1000 miles[a]	1153
1500 miles[a]	1729
Delivery of Secondary Products - 500 miles[a]	701

a - Delivery distance

Table 4.12. Energy outputs of the alcohol plant (9)

Energy Product	Energy Content ($\times 10^9$ Btu/yr)
Alcohol	4203
Distillers Dark Grain	2834
Fusel Oil	34

(i.e., with the least energy embodied in the fuels produced). Furthermore, the resource utilization factor based on the assumption that coal is the energy resource of the alcohol producing system is 0.29 (9) compared to a resource utilization factor of 1.49 (10) for coal liquefaction. Table 4.13 lists the energy parameters of the production of alcohol based on the resource of solar radiation.

Table 4.13. Energy parameters of alcohol production based on an energy resource of solar radiation (9)

Transportation Distances (miles)		Total Energy Subsidy	Net Energy		Overall Process	Resource Utilization	Capital Requirement
Alcohol	Coal	(x 10^9 Btu primary/yr)	(x 10^9 Btu primary/yr)	Energy Gain	Efficiency (%)	Factor	Factor
500	500	6375	696	1.11	111	---	0.013
	1000	6449	622	1.10	110	---	0.013
	1500	6522	549	1.08	108	---	0.013
1000	500	6952	119	1.02	102	---	0.013
	1000	7026	45	1.01	101	---	0.013
	1500	7099	- 28	1.00	100	---	0.013
1500	500	7528	-457	0.94	94	---	0.013
	1000	7602	-531	0.93	93	---	0.013
	1500	7675	-604	0.92	92	---	0.013

CHAPTER 5

BACKGROUND AND HISTORY OF ENERGY ANALYSIS APPLICATIONS

Introduction

Interest in and the recognition of the need for the science of energy analysis dates back to the early 1900's. However, the development of the science was not initiated until the early 1970's as a result of the "Federal Non-Nuclear Energy Research and Development Act of 1974", public law 93-577 (1). This act of Congress was established to instigate a research and development program designed to make available to American consumers the large domestic energy reserves of the United States. Parts four and five of Section five-a of the act state the following:

Sec. 5(a) (4) Heavy emphasis shall be given to those technologies which utilize renewable or essentially inexhaustible energy sources.

Sec. 5(a) (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.

Thus, application of energy analysis is indeed an undeveloped science. However, a significant number of applications do appear in the literature. Since energy

analysis is not standardized as yet, applications vary greatly in methodology and content from complete, well-documented work to non-documented analyses. Thus, the need exists to evaluate all analyses before accepting their results. The literature has been surveyed for energy analysis applications. The applications found are evaluated and summarized in this section. Unlike the methodology or theory of energy analysis, which is a specific area of discipline, the application of energy analysis is a tool for system evaluation that may be applied to systems of many different disciplines. Due to the "diffuse" nature of published and unpublished energy analysis applications, this survey may be somewhat incomplete.

The summaries of the literature analyses are reported as either individual analyses (i.e., the analysis of a single energy supply system) or comprehensive analyses. The individual analyses are categorized according to the following energy resources:

1. Nuclear fuels
2. Solar energy
    i. Collection of solar energy as heat
        a) Solar thermal electric systems
        b) Supply of domestic hot water and space heating
    ii. Crop production

iii. Production of alcohol

iv. Direct conversion of solar energy to electricity

a) Wind energy

b) Ocean thermal energy

c) Photovoltaics

The comprehensive analyses summarized are as follows:

1. Energy supply systems based on fossil fuels (production of fuel and electricity from crude oil, natural gas, coal and oil shale)
2. Ocean thermal energy conversion, wind energy, in-situ oil shale processing, fluidized bed and conventional coal combustion and municipal wastes disposal
3. Nine electricity generating systems

Summaries of Individual Analyses

Nuclear Fuels

Comments

The question of whether nuclear power plants are net energy producers or consumers has spurred the application of energy analysis by several investigators (5, 7, 8, 23). The results of the various analyses show that nuclear power stations are indeed net energy producers. Apparently, the highly energy intensive fuel processing operations and power plant are offset by the high energy intensity of the fuel, uranium. The high energy subsidy intensity per volume throughput of fuel renders the energy parameters of the system sensitive to the type of uranium ore (i.e., natural uranium concentration), parameters of the U^{235} enrichment processes (such as the tails assays) and the recycle of "active" material left in spent fuel. The crucial result of these analyses is not that nuclear power is a net energy producer but, under certain design conditions, that electricity from nuclear power can compete energetically with electricity from fossil fuels. The reader is referred to an article by G. T. Mays (31) for a contrasting and comparison of analyses by various authors.

Description of systems

Many configurations of the conventional (i.e., non-breeder) nuclear power plant exist depending on the

variations of the reactor design and the nuclear fuel cycle. Energy analyses of light water reactors including pressure water reactors (PWR) and boiling water reactors (BWR), heavy water reactors (HWR) and high temperature gas cooled reactors (HTGR) with various fuel cycles are reported in the literature.

P. F. Chapman (5) reports an energy analysis of a 1000 MW(e) PWR, HWR and HTGR. The reactor design details are contained in capital investment cost breakdowns by the CEGB (6). Parameters of the fuel cycle of each reactor are listed in Table 5.1. The fuel cycles analyzed by P. F. Chapman (5) do not recycle spent fuel.

Table 5.1. Fuel cycle parameters of nuclear power plant designs analyzed by P. F. Chapman (5)

Reactor Design	Natural Uranium Required for Initial Core (tonnes)	Fuel Inventory for Initial Core (tonnes)	Enrichment (%)	Tails Assays (%)
HWR	182	182	natural	---
HTGR	308	22.7	6.5	0.25
PWR	862	130	3.3	0.25

The power plants have an expected lifetime of 25 years and a capacity factor of 0.62. The distribution of the electricity is reported to consume 7.5% of the system's output. 3.75% of the system's output is fedback to operate the plant. Chapman (5) reports the energy required for

refueling to be a feedback of the system's output. The PWR, HWR and the HTGR require 49.2, 3.2 and 42.6 MW(e), respectively, for refueling over the lifetime of the plant.

Rotty, Perry and Reister (7) report an energy analysis of a 1000 MW(e) PWR, BWR, HWR and HTGR for various fuel cycles. The reactor design details are obtained from Volumes 1 and 2 of "The Energy Supply Planning Model" prepared by the Bechtel Corporation (32). The power plants are estimated to have a lifetime of 30 years and a capacity factor of 0.75. Rotty, Perry and Reister (7) report the energy requirements for fuel cycles with tails assays of 0.20%, 0.25% and 0.30%, with or without recycle of uranium and plutonium from spent fuel rods and with either conventional ores or Chattanooga shales* as the uranium source. The fuel cycle requirements are reported as annual system inputs rather than as an initial core input and a feedback of the system's output for refueling as reported by Chapman (5).

Rombough and Koen (8) report an energy analysis of a 1000 MW(e) PWR and BWR. Uranium and plutonium are recovered from the spent fuel rods and 0.2% tails assays are specified for uranium enrichment. The power plant design details are contained in Volumes I (PWR) and II (BWR) of "1000 MW(e) Central Station Power Plants Investment Cost Study" (9). A

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*Chattanooga shale is a low grade uranium ore containing approximately 0.006% natural U^{238}. Conventional ores have an average U^{238} concentration of 0.176%. Unless noted otherwise, fuel cycles are based on conventional ores.

lifetime of 30 years and a 0.8 capacity factor are specified for the power plants.

Moraw, Schneeberger and Szeless (23) report an energy analysis of a 1000 MW(e) PWR with a 0.75 capacity factor and a plant lifetime of 30 years. The fuel cycle includes the recycle of spent fuel rods and assumes a 0.3 per cent tails assays for uranium enrichment. Power plant design details are found in reference (9). Moraw, et al., (23) update the design details of reference (9) to account for technical changes.

Description of analyses

The energy analyses of the various authors are similar in that some form of input-output analysis is applied to determine the energy embodied in the power plant itself and process analysis is extended both backwards and forwards along the horizontal feed trajectory (i.e., the fuel cycle) to determine the energy embodied in the delivered fuel rods and the energy required to either recycle or dispose of the spent fuel. The analysis by Rotty, et al., (7) is by far the most complete and best documented effort. Thus, the results from Rotty's analysis (7) will be used for comparison of nuclear to other energy supply technologies. All analyses reported define the unit energy equivalence as either a unit of delivered electrical energy or a unit of thermal energy and separate accounts are kept for each energy form {excluding Rombough and Koen (8)}.

Rotty (7) and Moraw (23) utilize the energy intensity coefficients for the year 1967 (10) to determine the energy embodied in the power plant. By using the energy intensity coefficients which correspond to the various energy producing sectors (i.e., coal, crude oil and natural gas, petroleum products, electrical utilities and gas utilities), separate accounts are kept for thermal and electrical energy requirements (i.e., coal and crude oil and natural gas coefficients are summed to give a thermal energy coefficient). However, this use of the energy intensity coefficients leads to a double counting of embodied energy since the majority of electricity is produced from coal, crude oil and natural gas. Rotty (7) corrects for the double counting by subtracting the coal and crude oil and natural gas consumed for production of the required electricity from the total coal and crude oil and natural gas requirement. The energy coefficients for electric utilities list the Btu's of coal and crude oil and natural gas consumed per Btu of electricity produced (10). The results of Rotty's analysis (7) report the energy requirements as the total electric energy requirement and the corrected thermal energy requirement. Moraw (23) corrects for the double counting in the same manner as followed in the definition of a unit of primary energy (i.e., the electrical energy input is reduced to the portion produced from hydroelectric and nuclear power). Moraw (23) presents his results in the uncorrected form allowing the calculation of energy

requirements as units of primary energy. Rotty (7) estimates the energy required to erect the power plant and install the equipment using the disaggregation of energy intensity coefficients, whereas Moraw (23) assumes these energy requirements to be included in the capital investment costs.

Rombough and Koen (8) use the single sector input-output approach to determine the energy embodied in the power plant from the total required capital investment. Thus, Rombough (8) reports the energy embodied in the power plant in terms of units of primary energy. However, only the electrical energy requirements are reported for the fuel cycle energy requirements. The methodology used by Chapman (5) to determine the energies embodied in the power plants is not documented.

The fuel cycles of nuclear power plants are comprised of the following unit operations: Mining of uranium ore, milling of uranium ore producing U_3O_8 (yellow cake), conversion of U_3O_8 to UF_6, enrichment of uranium, fuel rod fabrication, spent fuel reprocessing (optional), and waste disposal. Also, there are transportation requirements for delivery of material from one unit operation to the next and, ultimately, to the power plant. The analysis by Rotty, et al., (7) includes a thorough and complete extension of process analysis to determine the energy requirements of the fuel cycle unit operations. Moraw (23) uses Rotty's (7) analysis for fuel cycle energy requirements. Chapman (5) and Rombough (8) generate fuel cycle energy requirements

independently. The largest discrepancy in energy requirements for fuel cycles reported by the various authors deals with the enrichment energy requirement. Table 5.2 compares the various enrichment energy requirements reported.

Table 5.2. Enrichment energy requirements reported by the various authors

	Enrichment Energy Requirement	
Author	Thermal (x 10^6 Btu/SWU)	Electric (MWh/SWU)
Rotty (7)	0.798	2.8235
Chapman (5)	0.097	2.42
Rombough (8)	---[a]	2.582

a-value not reported

Energy inputs are required for operation of the power plant and distribution of the produced electricity. Chapman (5) assumes a 7.5% loss of the produced electricity for distribution and a 3.75% feedback for internal consumption. Rotty (7) includes the energy required for plant operation in the energy embodied in the plant, and Moraw (23) and Rombough (8) neglect the energy required for plant operation. Rotty (7), Moraw (23) and Rombough (8) neglect the energy required for distribution of the electricity.

State of systems outputs

The outputs of the systems analyzed by Chapman (5) are distributed electricity while the outputs of the systems

analyzed by Rotty (7), Moraw (23) and Rombough (8) are non-distributed electricity as it is produced at the power plant. The systems have no secondary products and facilities for the disposal of waste products are included in the fuel cycles.

Energy inputs and outputs of systems

Tables 5.3 and 5.4 list the lifetime energy inputs of nuclear power plants as reported by Chapman (5) and Rombough (8), respectively. The analysis by Rotty (7) allows the evaluation of 52 reactor configurations. The lifetime energy inputs of 6 reactor configurations are presented in Table 5.5 and the design parameters of the 6 reactor configurations are listed in Table 5.6. Recyle of uranium and plutonium from the spent fuel rods, 0.3% tails assays from conventional ores represent the base case fuel cycle. The lifetime energy inputs of the PWR, BWR, HWR and HTGR are presented for the base case fuel cycle (note that the HWR requires no enrichment of uranium). The lifetime energy inputs for the PWR with fuel cycle variations of 0.2% tails assays and no recycle of uranium or plutonium are presented for comparison purposes. The fuel cycle lifetime energy requirements listed for system 1 (i.e., PWR, 0.3% tails assays, recycle) of Table 5.5 and a capital lifetime energy requirement of 13,652,000 x 10^6 Btu thermal and 300,000 MWh(e) are the energy inputs reported for the system analyzed by Moraw (23).

Table 5.3. Lifetime energy inputs to systems analyzed by P. F. Chapman (5)

Unit Operation	Energy[a] Form	Lifetime Energy Requirement (Thermal - 10^6 Btu, Electric - MWh) PWR	HWR	HTGR
Mining and Milling*	th	813,771	171,670	291,174
	e	23,055	4,889	8,333
Enrichment*	th	191,587	---	85,361
	e	1,398,294	---	619,427
Fuel Fabrication*	th	14,227	19,917	2,845
	e	6,111	8,611	1,111
Capital	th	10,157,910	11,505,659	10,909,083
	e	270,270	306,103	290,270
Heavy* Water	th	---	14,340,579	---
	e	---	454,987	---
Refueling	th	---	---	---
	e	10,774,800	700,800	9,329,400
Heavy Water	th	---	---	---
	e	---	1,149,750	---

*initial core energy requirement

a - th ≡ thermal energy
e ≡ electrical energy

Table 5.4. Lifetime energy inputs to systems analyzed by Rombough (8)

Unit Operation	Energy[a] Form	Lifetime Energy Requirement (Electric - MWh) (Primary - x 10^6 Btu primary)	
		PWR	BWR
Mining	e	7,380	7,380
Milling	e	289,500	289,500
Enrichment	e	9,300,000	9,000,000
Fabrication	e	71,400	71,400
Reprocessing	e	14,010	14,010
Capital	p	15,000,000	15,000,000

a - e ≡ electrical energy
p ≡ primary energy

Table 5.5. Lifetime energy inputs to 1000 MW(e) nuclear power plants analyzed by Rotty, et al. (7)

Unit Operation	Energy Form[b]	Lifetime Energy Input (Thermal - 10^6 Btu, Electrical - MWh) 1[a]	2[a]	3[a]	4[a]	5[a]	6[a]
Mining	th	1,927,000	1,851,500	998,800	1,497,000	1,582,000	3,006,000
	e	70,560	67,800	36,570	54,800	57,920	110,100
Milling	th	1,913,000	1,837,800	991,200	1,485,000	1,520,000	2,983,000
	e	80,470	77,320	41,700	62,490	66,050	125,500
Conversion	th	4,922,000	4,728,500	---	3,822,000	4,039,000	7,676,000
	e	53,190	51,100	---	41,300	43,650	82,960
Enrichment	th	1,698,000	874,800	---	2,003,000	2,121,000	2,412,000
	e	6,006,000	3,094,600	---	7,084,000	7,502,000	8,533,000
Fuel Fabrication	th	2,472,000	2,915,600	5,818,800	1,152,000	2,472,000	2,109,000
	e	269,500	317,900	634,400	71,960	269,500	247,400
Power Plant	th	18,140,000	18,070,000	34,070,000	18,820,000	18,140,000	18,140,000
	e	461,500	456,200	1,190,000	452,000	461,500	461,500
Reprocessing	th	285,500	33,680	67,210	263,700	285,500*	292,600
	e	15,960	18,830	37,570	18,400	15,960*	16,360
Waste Storage	th	183,200	183,200	183,200	183,200	183,200	183,200
	e	5,010	5,010	5,101	5,010	5,010	5,010
Transportation	th	302,230	344,970	482,490	120,800	292,800	337,830
	e	2,199	2,510	3,510	879	2,130	2,458

a - Table 5.6 lists the parameters of the various systems.

* - Reprocessing is not required for fuel cycles without recycle. This energy represents energy required for spent fuel rod storage.

b - th ≡ thermal energy, e ≡ electrical energy

Table 5.6. Parameters of nuclear power plant systems analyzed by Rotty, et al. (7)

System	Tails Assays	Recycle of U and Pu	Reactor Type
1	0.3	yes	PWR
2	0.3	yes	BWR
3	---	yes	HWR
4	0.3	yes	HTGR
5	0.2	yes	PWR
6	0.3	no	PWR

The energy content of the energy resource (i.e., uranium) required by nuclear power plant systems is a useful quantity for comparing nuclear power to other energy supply systems. However, only Rotty (7) reports the total amount of natural uranium required over the lifetime of the system. Natural uranium has a U^{235} content of 0.71 (7) weight per cent and U^{235} has an enthalpy of 75.69 x 10^6 Btu/kg (11). Table 5.7 lists the amounts and energy contents of the natural uranium required by the systems analyzed by Rotty (7). Table 5.8 lists the lifetime energy outputs of the systems analyzed by the various authors.

Table 5.7. Lifetime quantity and energy content of natural uranium required by the systems analyzed by Rotty (7)

System Description[a]	Lifetime Uranium Requirement Quantity (MT)	Energy Content (x 10^6 Btu)
1	3643	1,963,180,000
2	3500	1,886,115,000
3	2829	1,524,520,000
4	1888	1,017,424,000
5	2990	1,611,281,000
6	5682	3,061,973,000

a-refers to system description listed in Table 5.6

Table 5.8. Lifetime energy outputs of nuclear power plant analyzed

Author	Lifetime Energy Output of Systems Analyzed by Specified Author (MWh)
P. F. Chapman (5)	115,029,750
Rotty (7)	197,100,000
Moraw (23)	197,100,000
Rombough (8)	210,240,000

Energy parameters of systems

From the energy inputs and outputs reported by the various authors, it is possible to generate energy parameters for each system analyzed. However, this requires the combination of the electrical and thermal energy inputs to form a single energy requirement. All electrical requirements {excluding the capital electrical requirement reported by Moraw (23)} are multiplied by the energy intensity coefficient, 13,293,976 Btu primary per MWh (10), to obtain the primary energy embodied in the electricity. The electrical requirement is then added to the thermal energy requirement to obtain a single energy input very similar to the definition of primary energy. The thermal and electrical capital energy requirements reported by Moraw (23) are combined according to the definition of primary energy (i.e., thermal energy + 0.6165 electrical energy). The capital energy requirement reported by Rombough (8) is already in the form of primary energy. Table 5.9 lists the energy parameters of all systems analyzed.

Solar Energy

Collection of solar radiation as heat

Comments

Collection of solar energy as heat for small scale supply of domestic hot water or space heating, for intermediate scale supply of industrial process heat and for large scale supply of steam to an electricity generating plant

Table 5.9. Energy parameters of nuclear power plant systems analyzed

Author	System Description	Total Energy Subsidy (x 10^{10} Btu)	Net Energy (x 10^{10} Btu)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
P. F. Chapman	PWR	17699	21,561	2.22	---	---	0.035
	HWR	6094	33,166	6.44	---	---	0.040
	HTGR	14753	24,507	2.66	---	---	0.038
Rombough	PWR	14372	57,383	4.99	---	---	0.021
	BWR	13973	57,782	5.14	---	---	0.021
Moraw	PWR	11444	60,311	6.27	34.5	2.74	0.020
Rotty	1[a]	12442	54,828	5.41	32.2	2.92	0.036
	2[a]	8523	58,747	7.89	34.1	2.80	0.036
	3[a]	6852	60,418	9.82	62.0	1.51	0.074
	4[a]	13292	53,978	5.06	40.6	2.27	0.037
	5[a]	14262	53,008	4.72	38.4	2.40	0.036
	6[a]	16455	50,815	4.09	20.85	4.55	0.036

a - refers to system descriptions listed in Table 5.6

represent the majority of the current feasible solar application technologies (wind energy and the production of biomass comprises the remainder of the feasible technologies). In this case the term "feasible" is meant to represent a combination of economic and technological conditions that allow solar energy technologies to compete with fossil fuel based energy supply. In other words, the mentioned technologies represent systems which could feasibly penetrate the fossil fuel market under certain economic conditions, such as tax incentives, etc. A good deal of federal research funding has been provided for the development of the mentioned solar technologies with an emphasis on engineering technically sound systems which are economically competitive with fossil fuels. President Carter has set a goal for the supply of 2 quads of energy per year from solar energy systems by the year 2000 (33). With a major research program directed towards solar energy, very little effort is being extended to determine beyond doubt whether solar energy technologies can be net energy producers. The analyses of solar thermal technologies that do appear in the literature are incomplete in determining the energy subsidies of the systems (2, 4, 23, 25, 26) and yet the results of these analyses indicate that solar thermal applications are marginal energy supply systems.

Not only can energy analysis indicate whether the solar energy supply system is a net energy producer or consumer, energy analysis can also identify the portions

of the system to which design research should be directed in order to improve the net energy producing capability of the system. Furthermore, energy analysis can determine the optimal role of solar energy supply systems in a national energy policy through the use of a dynamic energy supply and demand model. The energy producing capabilities of the highly capital energy intensive solar energy supply systems are extremely sensitive to system designs. Thus, any design research of solar energy supply systems should be closely monitored with energy analysis, as well as economic analysis. Without the information offered through energy analysis, it is difficult to develop an energy policy which optimally exploits the solar energy technologies available to the United States.

Solar thermal electric systems

Description of systems. The analysis reported by Baron (2) is based on the data obtained from an ERDA (3) environmental assessment of a 100 MW(e) solar thermal electric plant with 3 hours storage. The plant is estimated to require 26×10^6 ft^2 of land. A six inch concrete matt foundation for the collector field is added to the design to minimize dust formation on the collectors and to allow water to drain from the field. The material requirements reported by ERDA are increased by 50 per cent to account for losses, final design and replacements. The plant is estimated to operate at a capacity factor of 29.7% in the Southwestern United States for a lifetime of 30 years.

Moraw, Schneeberger and Szeless (23) report an energy analysis applied to the design of a 1000 MW(e) solar thermal electric power station published by the Aerospace Corporation (24). The plant is designed for base load operation (i.e., 12-hour storage) with a capacity factor of 79% over a lifetime of 30 years. The collector subsystem is made up of three modules, each with 15,400 heliostats focused on a receiver mounted on a 260m tower. The collector field requires 42 x 10^6 ft^2 of land to accomodate 16 x 10^6 ft^2 of collector surface area.

Meyers and Hildebrant report an energy analysis of the solar radiation collection subsystem of a 10 MW(e) solar thermal electric power station (25). The collector subsystem is comprised of 2,200 heliostats, a receiver and tower including the risers and downcomers. The heliostat is a McDonnel-Douglas concept with an octagonal reflective surface using eight glass segments. The sun tracking motion is controlled with a sun-sensor pole and is included in the material requirements of the collector subsystem.

Description of analyses. The major contributor to the total energy subsidy of systems producing electricity from solar radiation is the solar collector subsystem (i.e., including both collectors and receivers). Energy analyses of solar collectors and receivers commonly determine the materials required for fabrication and the energy embodied in the materials while neglecting direct energy usage and energy embodied in capital facilities required for collector

and receiver manufacture as well as the energy required to distribute the manufactured product. The analyses reported by Baron (2), Moraw (23), and Meyers (25) first determine the material requirements of the power station (or collector subsystem as reported by Meyers). Baron (2) and Meyers (25) determine the energy embodied in the materials using process analysis and Moraw (23) uses input-output analysis.

Baron (2) includes energy requirements for construction labor and machinery for construction of the power station. Moraw (23) accounts for the energy required for construction of the power station in the total cost for buildings that represents a contract fee paid to a subcontractor. However, neither analysis includes energy requirements for the transportation or installation of equipment and components.

The unit of the energy equivalence utilized in the analyses by Baron (2) and Meyers (25) is defined as a Btu of thermal energy. Baron (2) assumes 3.34 Btu's of thermal energy are embodied in a Btu of electricity. Meyers (25) assumes the amount of thermal energy consumed to produce the electricity to be embodied in the electricity (i.e., Meyers uses a thermal efficiency). Moraw (23) keeps separate accounts for thermal and electrical energy subsidies that are combined according to the definition of primary energy.

State of systems outputs. The primary products of the systems analyzed by Baron (2) and Moraw (23) are non-distributed electricity at the busbar. The system analyzed by Meyers (25) has no product (i.e., the purpose of the analysis is to determine the energy embodied in the collector subsystem of the power station). Baron (2) and Moraw (23) do not report secondary or waste products.

Energy inputs and outputs of systems. Table 5.10 lists the lifetime energy inputs and Table 5.11 lists the lifetime energy outputs of the systems analyzed.

Table 5.10. Lifetime energy inputs of solar thermal electric systems

Input	Energy Subsidy		
	Baron (2) ($\times 10^{11}$ Btu Thermal)	Moraw (23) ($\times 10^{11}$ Btu Primary)	Meyers (25) ($\times 10^{11}$ Btu Thermal)
Capital	120	707	1.58
Raw Materials	---	---	---
Utilities	---	---	---

Table 5.11. Lifetime energy outputs of solar thermal electric systems

Author	Lifetime Energy Output ($\times 10^{11}$ Btu)
Baron (2)	266
Moraw (23)	7086

Energy parameters of systems. Table 5.12 lists the energy parameters of the systems analyzed.

Supply of domestic hot water and space heating

Description of systems. Baron (2) reports an energy analysis of a solar heating system designed to supply 50 per cent of the hot water requirement of a two-story single family reference house (four occupants) with 1800 sq. ft. of roof area. The General Electric Company has surveyed several areas of the United States for the annual energy requirements for space heating and hot water supply of the reference house and for the annual collectable solar energy (27). An aluminum and copper solar collector with an acrylic cover (estimated lifetime of 20 years) is utilized in the system. The collector is assumed to convert diffuse solar radiation into heat at an efficiency of 30 per cent. The system includes a 650 gallon steel storage tank using ethylene glycol as the working fluid, a copper heat exchanger, copper plumbing and required pumps. The system is assumed to require 6.5% of the heating load as electricity for system operation.

H. J. Wagner (26) reports the energy analysis of several configurations of solar space heating and hot water supply systems for a single family reference house (four occupants) with 140 m^2 of housing space in the Federal Republic of Germany. Wagner (26) compares the primary energies consumed by the reference house for space and water heating supplied from central oil heating alone (at an efficiency of 60%)

Table 5.12. Energy parameters of solar thermal electric systems

Author	Total Energy Subsidy ($\times 10^{11}$ Btu)	Net Energy ($\times 10^{11}$ Btu)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
Baron	120	146	2.22	222	---	0.451
Moraw	707	6379	10.02	1002	---	0.100

and from a combination of central oil heating, electrical heating and solar heating. The reference house has an estimated annual heat load of 85.3×10^6 Btu thermal for space heating and 13.7×10^6 Btu thermal for hot water supply. For energy supply from oil alone, 165.0×10^6 Btu of light fuel oil is required. Wagner (26) assumes 1.1111 Btu of primary energy to be embodied in a Btu of the fuel oil. Thus, the reference house has a total fuel energy requirement of 183.3×10^6 Btu primary for space heating and hot water supply from central oil heating alone.

Wagner (26) considers the energy requirements for installation of the three solar energy supply systems listed in Table 5.13.

Table 5.13. Characteristics of solar energy supply systems analyzed by Wagner (26)

System	Portion of Energy Requirement Supplied[a] (%)	Hot Water Supply	Space Heating	Storage	Collector Area (M^2)
I	58	yes	no	no	8
II	42	yes	yes	yes	35
III	63	yes	yes	yes	65

a - System I supplies 58% of annual hot water requirement only. The solar heat load share is determined from optimization calculations.

The remainder of the energy requirement not supplied by solar energy is supplied by electricity and oil. Electricity supplies the hot water energy requirement during the summer months (i.e., 25 per cent of the total hot water energy requirement) at a boiler efficiency of 95 per cent. The remaining energy requirement is supplied by oil at an increased boiler efficiency of 65 per cent (due to not running during the summer months). Wagner (26) neglects the additional electricity requirement for operation of the solar energy supply systems.

Description of analyses. The shortcomings of the literature energy analyses applied to solar thermal electric systems, which are described in the description of analyses of solar thermal electric systems, exist in the literature applications of energy analysis to solar domestic energy supply systems (i.e., the incomplete assessment of energy embodied in solar collectors and receivers). Baron (2) uses process analysis to determine the energy embodied in the solar hot water supply systems and Wagner (26) does not describe the methodology used. Neither author documents the analysis. Baron (2) defines the unit of energy equivalence as a Btu of thermal energy and assumes 3.34 Btu of thermal energy to be embodied in a Btu of electrical energy. Wagner (26) defines the unit of energy equivalance as a Btu of primary energy and assumes 3.33 Btu of primary energy to be embodied in a Btu of electrical energy.

State of systems outputs. The only product of the system analyzed by Baron (2) is stored thermal energy. Wagner (26) reports products of stored and non-stored thermal energy, or of energy savings. All systems analyzed are installed at the end-use site of the product.

Energy inputs and outputs of systems. Tables 5.14 and 5.15 list the lifetime energy inputs and outputs, respectively, of the systems analyzed by Baron (2) as a function of location. Tables 5.16 and 5.17 list the annual energy inputs and outputs, respectively, of the systems analyzed by Wagner (26).

Table 5.14. Lifetime energy inputs to the systems analyzed by Baron (2)

	Embodied Energy ($\times 10^6$ Btu Thermal)			
Input	Wash., D.C.[a]	Boston[a]	Phoenix[a]	Charleston[a]
Capital	493	916	314	514
Raw Materials	---	---	---	---
Utilities	300	600	186	315

a-location of system

Table 5.15. Lifetime energy outputs of systems analyzed by Baron (2)

System Location	Lifetime Energy Output ($\times 10^6$ Btu Thermal)
Washington, D.C.	1380
Boston	1800
Phoenix	1160
Charleston	1260

Table 5.16. Annual energy inputs to systems analyzed by Wagner (26)

Input	Embodied Energy ($\times 10^3$ Btu Primary/Yr) I[a]	II[a]	III[a]
Amortized Capital	1,758	6,587	11,399
Raw Materials	---	---	---
Utilities	---	---	---

a - Description of system is listed in Table 5.13.

Table 5.17. Annual energy outputs and energy savings of systems analyzed by Wagner (26)

System[b]	Annual Energy Output ($\frac{\text{x } 10^3 \text{ Btu}}{\text{Yr}}$)	Annual Energy Savings (x 10^3 Btu Primary/Yr)
I	7,918[a]	26,713[a]
II	41,570	81,598
III	62,356	118,418

a-Based on 85 per cent supply of hot water during summer months and 49 per cent supply during winter months (i.e., 58 per cent yearly supply).

b-Description of system is listed in Table 5.13.

Energy parameters of systems. Table 5.18 lists the energy parameters of solar domestic energy supply systems analyzed.

Crop production (production of stored chemical energy via photosynthesis)

Comments

The growing dependence of the agricultural industry on fossil fuels (mainly crude oil and natural gas) has resulted in enormous improvements in crop yields and farming efficiency (20). However, the almost total dependence of western farming practices on fossil fuels has rendered the most essential American industry at the mercy of an increasingly unstable petroleum products market. Application of

Table 5.18. Energy parameters of solar domestic energy supply systems

Author	System Description	Total Energy Subsidy (x 10^6 Btu)	Net Energy (x 10^6 Btu)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
Baron (2)	Wash., D.C.	793	587	1.74	174	---	0.357
	Boston	1516	284	1.19	119	---	0.509
	Phoenix	500	660	2.32	232	---	0.271
	Charleston	829	431	1.52	152	---	0.408
Wagner (26)	I-a[c]	35	123	4.52	452	---	0.221
	I-b[c]	35	499	15.27	1527	---	0.066
	II-a[c]	132	699	6.30	630	---	0.159
	II-b[c]	132	1500	12.36	1236	---	0.081
	III-a[c]	228	1019	5.47	547	---	0.183
	III-b[c]	228	2140	10.39	1039	---	0.096

c - a refers to energy parameters based on thermal output of system, b refers to system parameters based on primary energy savings.

Description of the system is listed in Table 5.13. Wagner estimates the lifetime of the solar domestic energy supply systems to be 20 years.

energy analysis to crop production illustrates the increasing dependence of the industry on fossil fuels and the large amounts of energy embodied in the crops.

Description of systems

Keener and Roller report the energy requirements, expected average yields and energy outputs for the production of corn, alfalfa, napier grass, kenaf, slash pine and wheat (21). The data presented by Keener and Roller (21) serve as the basis for the energy analysis of crop production in this report with modifications to account for transportation and crop processing energy requirements. The results of the analyses do not differ significantly and a summary of Keener and Roller's analysis (21) is not necessary.

Pimentel, et al., report the energy analysis of corn production at different points in time from 1945 to 1970 reflecting the effect of technology changes in the agricultural industry on the energy requirements for production of the crop (20). The machinery, fuel, fertilizer, chemical and irrigation requirements and the annual yield of corn production represent national averages. The irrigation requirement assumes that 3.8 per cent of the corn grown in the United States is irrigated. Energy requirements for delivery of supplies to the farm and transportation of the produced corn to its end-use site are included in the analysis. However, the transportation distances are not

documented. It is assumed that the transportation distances reflect the national average. The harvested corn is collected and dried to 13 per cent moisture content on the farm before delivery to its end-use site.

Blankenhorn, Murphey and Bowersox report the energy analysis of forest biomass production by both intensive and caretaker cultural practices (22). Blankenhorn uses the data of Keener and Roller (21) to determine the energy requirements of the intensive system. The intensive system data are then modified to reflect the cultural practices of the caretaker system. Blankenhorn (22) includes the transportation requirement to deliver the biomass to its processing site, where the biomass is dried and chipped. The transportation distance is set at the value which renders the system a zero net energy producer for trucking, rail and pipeline (50 per cent wood-water slurry) modes of transportation. Table 5.19 lists the transportation distances by truck, rail and pipeline for both intensive and caretaker systems.

Both Pimentel (20) and Blankenhorn (22) include energy requirements for human labor in the energy subsidy of crop production.

Description of analyses

Process analysis is used to determine the energy inputs to crop production. Pimentel (20) and Blankenhorn (22) determine the physical quantities of capital, raw

Table 5.19. Transportation distances for delivery of biomass to processing site (22)

Transportation Mode	Transportation Distance (mi) Intensive	Caretaker
Truck	4,887	4,081
Rail	9,974	9,960
Pipeline	36,471	36,422

materials and utilities required by the systems completing the first level of energy analysis. This portion of the analyses appear to be complete and accurate. The energy embodied in the raw materials and capital is determined by using embodied energy coefficients reported in the literature. The capital energy input is the portion of the energy embodied in the required equipment which is depleted over the growth period of the crops. Pimentel (20) assumes an equipment life of six years farming an area of 62 acres. Blankenhorn (22) assumes an equipment lifetime of six years farming an area of 10,000 acres (crop density of forest biomass is much less than that of corn). The utility energy subsidy of liquid fuels consumed for crop production is the energy content of the fuel (i.e., the energy subsidy of the fuel is ignored), and the energy subsidy of the electricity consumed is the energy content of the fossil consumed to produce electricity {Pimentel (20) uses national averages of Btu of thermal energy consumed per kilowatt hour produced for the year 1970, Blankenhorn (22) does not report an electrical requirement for production of forest biomass}.

Both authors include the energy embodied in human labor in the energy subsidies of the systems. The results of the analyses are presented without the human labor energy subsidy.

State of systems outputs

The primary product of the system analyzed by Pimentel (20) is corn dried to 13 per cent moisture on the farm and transported (distance not reported) to its end-use site. The primary product of the system analyzed by Blankenhorn (22) is harvested forest biomass transported to a processing site (refer to Table 5.19 for distances) where it is chipped and dried. Neither system reports secondary nor waste products.

Energy inputs and outputs of systems

The energy inputs reported by Pimentel (20) are listed in Table 5.20 as a function of the year of corn production. Table 5.21 lists the outputs for corn production reported by Pimentel (20). Table 5.22 lists the energy inputs for intensive and caretaker production of forest biomass reported by Blankenhorn (22). Blankenhorn (22) reports the energy output of forest biomass production as 212×10^6 Btu/ha-yr and 127×10^6 Btu/ha-yr for intensive and caretaker systems, respectively.

Energy parameters of systems

Table 5.23 lists the energy parameters of the corn production system analyzed by Pimentel (20) and Table 5.24 lists the energy parameters of the forest biomass production systems analyzed by Blankenhorn (22).

Table 5.20. Energy inputs required for corn production reported by Pimentel (20)

Input	Energy Subsidy ($\times 10^3$ Btu/acre-yr) 1945[a]	1950[a]	1954[a]	1959[a]	1964[a]	1970[a]
Capital	714	992	1,190	1,389	1,667	1,667
Raw Materials	506	860	1,372	2,012	2,628	4,662
Utilities	2,402	2,896	3,545	4,066	4,578	5,147

a-Year of crop production

Table 5.21. Energy outputs of corn production reported by Pimentel (20)

Year of Production	Energy Output ($\times 10^3$ Btu/acre-yr)
1945	13,600
1950	15,200
1954	16,400
1959	21,600
1964	27,200
1970	32,401

Table 5.22. Energy requirement for production of forest biomass reported by Blankenhorn (22)

Input	Energy Subsidy ($\times 10^3$ Btu/ha-yr) Intensive	Caretaker
Capital	74	31
Raw Materials	10,077	---
Utilities	201,354	63,420

Table 5.23. Energy parameters of corn production system analyzed by Pimentel (20)

Year of Production	Total Energy Subsidy ($\times 10^3$ Btu / acre-yr)	Net Energy ($\times 10^3$ Btu / acre-yr)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
1945	3,622	9,978	3.75	375	---	0.053
1950	4,748	10,452	3.20	320	---	0.065
1954	6,107	10,293	2.69	269	---	0.073
1959	7,467	14,133	2.89	289	---	0.064
1964	8,873	18,327	3.07	307	---	0.061
1970	11,476	20,925	2.82	282	---	0.051

Table 5.24. Energy parameters of forest biomass production systems analyzed by Blankenhorn (22)

System	Total Energy Subsidy ($\times 10^6$ Btu / ha-yr)	Net Energy ($\times 10^6$ Btu / ha-yr)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
Intensive	212	0	1.00	100	---	0.00035
Caretaker	63	0	1.00	100	---	0.00049

Production of alcohol

Comments

The controversy surrounding the possibility of a government supported (i.e., through tax credits, etc.) development of a nationwide gasohol program is both energetic and economic in nature. Proponents claim that the use of gasohol will reduce oil imports while providing a market for grain surpluses causing farm prices to stabilize and a reduction in the national deficit. Opponents argue that farm prices will skyrocket as a result of the widespread use of alcohol and that the production of alcohol from grain consumes more energy than produced (12). It is not clear as to whether the production of anhydrous alcohol from corn is a net energy producer or consumer, nor can the economic results of a gasohol program be absolutely predicted. Thus, the argument continues as to whether a gasohol program should or should not be implemented. However, it is clear that the economics and energetics of gasohol are marginal at best. Gasohol will not solve the United States' liquid fuel crisis. Therefore, a gasohol program should be approached with extreme caution.

The marginal energetics of alcohol producing systems are well-illustrated by the numerous variations in the energy analyses applied to the systems. By altering the basis of the energy analysis, the results can render the production of alcohol as either a slight energy producer or consumer. The methodological variations that appear

in the analyses available in the literature are outlined below.

Specification of system boundary. There is disagreement as to whether the energy subsidy of the biomass from which the alcohol is produced should be included in the energy subsidy of the alcohol. The definition of energy analysis states that the energy required to perform any action that would not occur if the system under consideration were not in existence must be included in the energy subsidy of the system. It has been suggested that grain motor fuel be produced from distressed grain (13) (i.e., grain that is moldy or has started to sprout). This grain has no food value and, if the distressed grain has no other energy uses, must be considered a waste product of the agricultural system that has no embodied energy (i.e., the use of this "waste" grain requires no additional energy subsidy to the agricultural system). Under these circumstances, the grain itself does not add to the energy subsidy of the alcohol producing system. However, the collection of the distressed grain does require significantly more transportation distance than the quality grain because it is more diffuse than the quality grain (i.e., one per cent of the annual grain production is estimated to be distressed.)

Definition of the unit energy equivalence. By defining the energy equivalence as a Btu of crude oil and assuming the alcohol producing system consumes coal or natural gas for the production of required process heat, a significant crude oil savings can be shown through an energy analysis. The definition of the unit energy equivalence is a matter of convention. However, if the same energy equivalence is used in the energy analysis of the liquefaction of coal, a much larger oil savings would result. Limiting the definition of the unit energy equivalence to only one of the non-renewable energy resources is of no use in energy analysis. If the energy equivalence is applied consistently to the energy alternatives under consideration, the same conclusion from comparisons of alternative energy supply systems will result. Furthermore, the use of the limited energy equivalence can distort the interpretation of the results of an analysis when examined without reference points.

Definition of the quality of energy contained in alcohol. Some authors claim that the fuel efficiency of alcohol, in terms of miles per Btu of energy contained in the fuel, is greater than that of gasoline (13). If this claim is valid, it should be considered in the comparison of the energetics of alcohol and gasoline. The non-consideration of the fuel efficiency difference between gasoline and gasohol is not a shortcoming of the convention

for assigning energy equivalences to the outputs of the system, but rather a result of the definition of the outputs of the system (i.e., the specification of system boundary). If the output of the system is defined as a liquid fuel, the alcohol is not of a higher quality than any other liquid fuel. However, if the output of the system is specifically defined as the mechanical energy output of transportation (i.e., the displacement of mass over a distance), the quality of the energy contained in the alcohol would automatically be accounted for.

Definition of the energy outputs of a system. There is disagreement as to whether the secondary products of the system should be considered as energy outputs and as to how this energy should be accounted for. This question stems from a misunderstanding of energy analysis in the sense that the energy analysis applies to a system and not to its products. Thus, if a system produces a material which is considered an energy product, it should be included as an energy output of the system. Analyses appear in the literature in which the energy embodied in the secondary products is subtracted from the energy subsidy of the system(12). Since the secondary product cannot actually displace energy inputs to the system, its energy content should not be subtracted from the energy subsidy. The question concerns the distillers dark grainsproduced as a by-product of grain fermentation. The product is sold as cattle feed, a food product, which is an energy product.

Description of systems

Hopkinson and Day (14) report an energy analysis of alcohol produced from sugar cane grown in Louisiana. Three systems are considered in which all the sugar cane residue (bagasse) is converted to steam (exceeds process heat requirement), enough bagasse is converted to steam to supply the process heat requirements, or the process heat is supplied by fossil fuels. Hopkinson and Day (14) ignore the by-products of the system and the transportation requirement for distribution of the alcohol.

DaSilva, et al., report an energy analysis of three crops, sugar cane, cassava and sweet sorghum, that are being considered for alcohol production by the National Alcohol Program (PNA) in Brazil (15). The energy requirements for crop production are based on cultural practices followed in Brazil and are less energy intensive than American cultural practices. The process heat is supplied by consumption of bagasse for sugar cane and sweet sorghum, and by fossil fuels for cassava. DaSilva (15) ignores the energy requirements for distribution of alcohol, the energy embodied in by-products of the system and the energy embodied in the alcohol plant itself.

Chambers, Herendeen, Joyce and Penner (12) report the energy analysis of alcohol produced from corn. Energy inputs and outputs are reported for a base case alcohol production system which represents national average market

corn {energy inputs determined by Penner and Joyce (16)} and a conventional alcohol production process {energy inputs determined by Scheller and Mohr (17)}. The base case system credits the outputs with the energy embodied in the corn normally used as cattle feed that is displaced by the distillers dark grains by-product (as opposed to the enthalpy of the distillers dark grains). The energy required to distribute the alcohol and the energy embodied in the alcohol plant are ignored. Chambers, et al., (12) determine the effects of various system modifications on the energy inputs required for production of alcohol from corn.

Hopkinson (14) and DaSilva (15) do not include a cooking operation in the industrial process since the crops analyzed are naturally fermentable sugars. Chambers (12) includes the cooking operation in the process as is required for production of alcohol from corn. Table 5.25 lists a brief description of the systems analyzed.

Description of analyses

The energy analyses mentioned almost exclusively rely on process analysis for determination of energy inputs required for the production of crops. Only the analysis by Hopkinson and Day (14) includes the energy embodied in the alcohol plant. However, neither the methodology used to determine the energy embodied in the plant nor the value obtained are reported. An analysis by the ACR Process

Table 5.25. Description of systems analyzed

Author	System	Description
Hopkinson	1	Conversion of all bagasse to steam
	2	Conversion of enough bagasse to steam to supply process heat
	3	Supply of process heat from fossil fuels
DaSilva	4	Sugar cane
	5	Cassava
	6	Sweet sorghum
Chambers	7	Base case (corn)
	8	Process of ACR (18) that is reported to require less process heat
	9	Burn cobs and stalks to supply portion of process heat
	10	Assume enthalpy of distillers dark grains as its energy content
	11	Systems 9 and 10
	12	Systems 8, 9, and 10

Corporation (18) reports the energy embodied in the alcohol plant to be 7000 Btu/yr compared to a total energy subsidy of 304,000 Btu/yr. Thus, neglecting the energy embodied in the alcohol plant is not a significant source of error.

The energy required for crop production has been widely studied and is well documented. Hopkinson (14) and DaSilva (15) rely on the data of Heichel (19) and Pimentel (20) while Chambers, et al., (12) have generated the agricultural energy input independently (16). The process energy requirements are mainly fuel requirements for generation of steam. However, it is not clearly stated in any analysis that the process fuel requirements represent the energy content of the fuels only, or that the energy subsidy of the fuels is included as an energy input. Since such a large amount of fuel is consumed in the production of alcohol, the energy subsidy of the fuels could be a significant energy input.

The option of displacing fossil fuels with crop residuals for generation of process heat is considered in all the analyses. If this option is chosen, additional energy inputs are required for the harvesting, collection and transportation of the residues that are normally left in the field. Only Chambers (12) accounts for this additional energy subsidy by assuming that half of the energy content of the crop residue is productively available. There is also the question of the technical feasibility

of utilizing crop residues due to the possibility of soil depletion (12).

The analyses by Hopkinson (14) and DaSilva (15) include the energy embodied in human labor required for crop production in the energy subsidy of the system. Human labor is now considered a free energy resource in an energy analysis. However, determinations of energy required for crop production often include human energy inputs. The human labor energy input is an insignificant contribution to the total energy subsidy of alcohol production and does not effect the results of the analyses. The unit energy equivalence is defined as a Btu of thermal energy in all analyses reported.

State of systems outputs

In all systems, the primary product is non-delivered anhydrous ethyl alcohol. In the systems analyzed by Hopkinson (14) and DaSilva (15), a by-product of non-delivered steam is produced. The systems analyzed by Chambers (12) include a dried (to 15 per cent moisture) non-delivered distillers dark grains by-product that is sold as cattle feed.

Energy inputs and outputs of systems

Table 5.26 lists the energy inputs and outputs of alcohol producing systems reported by the various authors.

Table 5.26. Energy inputs and outputs of alcohol producing systems

Author	System[a]	Energy Inputs ($\times 10^6$ Btu/ha-yr) Agricultural	Process	Energy Outputs ($\times 10^6$ Btu/ha-yr)
Hopkinson, et al. (14)	1	33.73	1.59	100.00
	2	33.73	1.59	73.02
	3	33.73	42.86	73.02
DaSilva, et al. (15)	4	16.42	---	100.93
	5	10.21	35.25	52.66
	6	31.83	---	118.17
Chambers, et al. (12)	7	32.28	64.91	42.37
	8	32.28	21.05	42.37
	9	32.28	36.67	42.37
	10	32.28	64.91	54.30
	11	32.28	36.67	54.30
	12	32.28	1.93	54.30

a - System descriptions listed in Table 5.25

Energy parameters of systems

Table 5.27 lists the energy parameters of the various systems analyzed. The resource utilization factor (which is zero for these systems) and the capital requirement factor (requires the capital energy subsidy for calculation) are not listed for the systems analyzed.

Direct conversion of solar energy to electricity

Wind energy

See analysis included in summaries of comprehensive energy analysis studies.

Ocean thermal energy

See analysis included in summaries of comprehensive energy analysis studies.

Photovoltaics

Comments. There is optimism among researchers currently involved in the field of solar energy that photovoltaics will eventually emerge as a significant supplier of electricity (34). However, the current method of producing photovoltaic cells is both economically and energetically expensive. There is general agreement that a technical breakthrough is required in the manufacture of photovoltaic cells before the concept will be a viable energy supplier. However, a photovoltaic power pilot plant is now under construction in Saudi Arabia which will be useful in obtaining performance data (34).

Table 5.27. Energy parameters of alcohol producing systems

Author	System[a]	Total Energy Subsidy ($\frac{\times 10^6 \text{ Btu}}{\text{ha-yr}}$)	Net Energy ($\frac{\times 10^6 \text{ Btu}}{\text{ha-yr}}$)	Energy Gain	Overall Process Efficiency (%)
Hopkinson et al.	1	35.32	64.68	2.83	283
	2	35.32	37.70	2.07	207
	3	76.59	-3.57	0.95	95
DaSilva, et al.	4	16.42	84.51	6.15	615
	5	45.46	7.20	1.16	116
	6	31.83	86.34	3.71	371
Chambers, et al.	7	97.19	-54.82	0.44	44
	8	53.33	-10.96	0.79	79
	9	68.95	-26.58	0.61	61
	10	97.19	-42.89	0.56	56
	11	68.95	-14.65	0.79	79
	12	34.21	20.09	1.59	159

a - System description listed in Table 5.25.

Description of systems. Gandel and Sears (4) have estimated the power consumption of manufacturing processes for the fabrication of silicone, cadmium sulfide and gallium arsenide photovoltaic cells. Considering the production of cells as a continuous process, the power requirements reported by Gandel and Sears (4) are the rate at which fuels and electricity are consumed by the system. Thus, the power requirements do not include energy embodied in raw materials or capital. Furthermore, the energy embodied in electrical interconnects, solar array mounting structure and power conditioning equipment, which are needed to obtain useful energy from the cells, are not considered by Gandel and Sears (4). The system to which energy analysis is applied is actually the manufacturing of photovoltaic cells and not a photovoltaic power station. However, it has been suggested (2) that the utility energy subsidy is the major portion of the total energy embodied in photovoltaic cells. Thus, the utility requirements for the fabrication of photovoltaic cells approximately represent the energy embodied in the cells. By considering the output of the cell manufacturing process to be the potential power production capability of the cells produced, energy parameters of the fabrication process can be calculated. These parameters will give insight into the energetics of the generation of electricity from solar radiation via photovoltaic cells.

Description of analysis. The power requirements for fabrication of various photovoltaic cells reported by Gandel and Sears (4) are estimations of the rate of fuels and electricity consumed by a conceptual manufacturing process. Comparison of this quantity of energy to the potential energy output has little significance unless the utility energy subsidy for production of the cells is also the major portion of the total energy subsidy of the photovoltaic power station.

Gandel and Sears (4) do not separate the power requirement of cell manufacture into thermal and electrical energy requirements. The power requirement is assumed to be the rate of consumption of thermal energy. Thus, the unit energy equivalence is defined as a Btu of thermal energy.

State of the systems outputs. The products of the systems analyzed are various photovoltaic cells. The energy output of the system is considered to be the potential energy producing capability of the photovoltaic cells.

Energy inputs and outputs of systems. Table 5.28 lists the energy consumed during a one-year period of cell manufacturing, the power producing capability of the cells produced during that year and the estimated lifetime of the cells.

Table 5.28. Energy requirements and potential energy outputs of photovoltaic cells manufactured during a one-year period

Cell Material	Energy Consumed ($\times 10^{10}$ Btu)	Produced Power Capability ($\times 10^{10}$ Btu/hr)	Cell Lifetime (yrs)
Silicone	13,676	2,691	10
Cadmium Sulfide	17,532	5,382	5
Gallium Arsenide	173	60	10

Energy parameters of the system. Table 5.29 lists the energy parameters of photovoltaic cell production.

Table 5.29. Energy parameters of the production of photovoltaic cells[a]

Cell Material	Total Energy Subsidy ($\times 10^{10}$ Btu)	Net Energy ($\times 10^{10}$ Btu)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor
Silicone	13,676	13,232	1.97	197	---
Cadmium Sulfide	17,532	9,378	1.54	154	---
Gallium Arsenide	173	425	3.46	346	---

a - The energy parameters do not refer to an energy producing system and, therefore, have no real meaning. They do, however, represent a lower limit to the energy subsidy and energy parameters of an electricity producing system utilizing photovoltaic cells.

Summaries of Comprehensive Energy Analysis Studies

Energy Supply Systems Based on Fossil Fuels

Comments

The United States' energy supply systems are based mainly on fossil fuels with small contributions from light water nuclear reactors and hydroelectric power stations (35). For all practical purposes, proposed alternative energy technologies must be able to compete with a fossil fuel based counterpart. Thus, it is necessary to develop the energy parameters of all fossil fuel based energy supply technologies at a high level of confidence. Fossil fuels have a high energy content per unit volume. Thus, the capital energy subsidies for the extraction, transportation and processing of the fuels are relatively small compared to the energy produced. In order to determine the utility and raw material energy subsidies of fossil fuel based energy supply systems, data regarding the operation of fossil fuel processing systems are required. Unfortunately, these data are generally unavailable due to proprietary reasons making accurate energy analyses of fossil fuel based energy supply systems difficult.

Mechler, et al., (28) report specific utility and raw material requirement data as well as general capital cost data of numerous operations associated with fossil fuel based energy supply systems. The energy inputs and outputs of each operation are determined independently allowing the

calculation of the energy parameters of many energy supply systems through the combination of separate operations. The study by Mechler (28) is the only comprehensive evaluation of fossil fuel based energy supply systems that appears in the literature. The results reported by Mechler (28) are used to determine energy parameters which serve as the reference point for the comparisons between alternative and conventional energy supply technologies that are discussed in this study.

Description of systems and state of systems outputs

By combining separate processing, extraction and transportation systems, Mechler (28) develops trajectories which trace various fossil fuels to various end uses. Table 5.30 lists the trajectories developed by Mechler (28).

Description of analysis

The first level of the energy analysis reported by Mechler (28) (i.e., the quantitative determination of utility, raw material and capital requirements of the nameplate processing system) is acceptable. The determination of utility requirements appears to be complete and accurate. Selection of the required raw materials and capital that represent non-negligible energy inputs to the system is based on the experience and judgment of the researcher. Therefore, while the determination of raw material and capital requirements is not complete, the energy embodied

Table 5.30. Description of fossil fuel trajectories analyzed by Mechler (28)

1) Production of non-delivered raw coal, one-half surface and one-half underground mined.

2) Delivered product of trajectory 1), transported by rail 500 miles.

3) Production of non-delivered crude oil (represents national average of domestic oil wells).

4) Delivered product of trajectory 3), transported by liquid pipeline 300 miles (national and regional average).

5) The production of natural gas gathered by pipeline at the well field and dried at a gas liquids plant (represents national average of natural gas production).

6) Delivered product of trajectory 5), transported by pipeline 1000 miles (national and regional average).

7) High Btu pipeline gas produced using coal from trajectory 1), gasified by the Lurgi process at the mine site, transported 1000 miles by pipeline (national and regional average) and distributed by pipeline.

8) Gasoline produced using crude oil from trajectory 3), transported 300 miles by pipeline (national and regional average), refined (regional average) and distributed 70 miles by truck (regional average).

9) Gasoline produced using raw coal from trajectory 1), liquefied at mine site, transported 600 miles by pipeline, refined and distributed 70 miles by truck (regional average).

10) Gasoline produced using oil shale, one-half surface and one-half underground mined, crushed and retorted aboveground (regional estimate), refined (national average) at mine site, transported 300 miles by pipeline (national average) and distributed 70 miles by truck (regional average).

11) Electricity produced using crude oil from trajectory 3), desulfurized and converted (national average) near well site and transmitted 150 miles (regional average).

Table 5.30 (Cont'd.)

12) Electricity produced using natural gas from trajectory 6), converted (national average) and transmitted 150 miles (regional average).

13) Electricity produced using coal from trajectory 2), converted (national average) and transmitted 150 miles (regional average).

14) Electricity produced using pipeline gas (from coal gasification using the Lurgi process) from trajectory 7), converted (national average) and transmitted 150 miles (regional average).

15) Electricity produced using coal from trajectory 1), liquefied at the mine, transported 300 miles by pipeline, converted (national average) and transmitted 150 miles (regional average).

16) Electricity produced using oil shale, one-half surface and one-half underground mined, crushed and retorted aboveground and converted at the mine site and transmitted 150 miles (regional average).

Note: Refer to reference (28) for details concerning the modules comprising the trajectories.

in the reported raw materials and capital is presumably an accurate representation of the raw material and capital energy subsidies. Utility requirements are reported as rates of fuel consumption and raw material and capital requirements are generally reported as dollar costs.

The utility energy subsidy is taken as the energy content of the required fuel and electricity and the raw material and capital energy subsidies are determined using a crude application of input-output methodology (i.e., trade and transportation margins are ignored and an average energy intensity coefficient is often used). As a result, the energy subsidy of each separate system (i.e., module) is systematically underestimated. This underestimation can cause significant error if a large portion of the utility requirement is electricity. The inappropriate use of the input-output analysis is acceptable since the raw material and capital energy subsidies are usually not a large fraction of the total energy subsidy (a characteristic of fossil fuel based systems).

The results of the energy analyses are reported as a total energy subsidy required per unit energy input of feed to the module for each module analyzed. The modules are then combined into trajectories tracing a fossil fuel in the earth to an end-use product. The total energy subsidy of the trajectory is the summation of the energy

subsidies of each module with the contribution from each module proportional to the energy input to each module. The assumption of proportionality between the energy subsidy and the size (i.e., energy throughput) of a module may not be accurate, especially for modules with large capital energy subsidies.

Some of the modules analyzed have multiple energy products such as crude oil refineries. Such modules are analyzed similarly to single product modules with the result reported as an energy subsidy and energy output (summation of all energy products) per unit energy input of feed to the module. The reporting of results in this manner assumes that all energy products of a module have the same energy subsidy per unit energy content, and are produced at the same energy conversion efficiency (thermal efficiency).

Energy inputs, outputs and energy parameters of systems

Table 5.31 lists the total energy subsidy, gross energy output and energy parameters of various fossil fuel based energy producing systems.

Table 5.31. Energy parameters of fossil fuel resources in terms of various end uses (all trajectories are based on 1 x 10^9 Btu/yr resource requirement) (28)

Product[a]	Total Energy Subsidy (x 10^6 Btu/yr)	Net Energy (x 10^6 Btu/yr)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Gross Output (x 10^6 Btu/yr)
Coal[1]	7.8	992.2	129.9	99.23	1.00	1000.0
Coal[2]	23.7	976.3	42.2	97.68	1.00	1000.0
Oil[3]	17.5	955.9	55.6	95.67	1.03	973.4
Oil[4]	19.07	953.3	51.0	95.42	1.03	972.4
Natural Gas[5]	20.7	909.0	44.9	91.08	1.08	929.7
Natural Gas[6]	35.9	822.7	23.9	82.89	1.21	858.6
Pipeline Gas[7]	23.8	591.0	25.8	60.05	1.63	614.8
Gasoline[8]	89.9	810.3	10.0	82.60	1.11	900.2
Gasoline[9]	99.5	570.8	6.7	60.96	1.49	670.3
Gasoline[10]	96.8	536.8	6.5	57.77	1.58	633.6
Electricity[11]	29.0	258.4	9.9	27.93	3.48	287.4
Electricity[12]	31.3	239.1	8.6	26.22	3.70	270.4
Electricity[13]	30.7	266.3	9.7	28.82	3.37	297.4
Electricity[14]	20.5	173.1	9.4	18.97	5.17	193.6
Electricity[15]	18.9	166.8	9.8	18.23	5.39	185.7
Electricity[16]	51.7	151.6	3.9	19.33	4.92	203.3

a-The reference number after the product refers to the trajectory description listed in Table 5.30.

Ocean Thermal Energy Conversion (OTEC), Wind Energy, In-situ Oil Shale Processing, Fluidized Bed Coal Combustion Versus Conventional Coal Combustion and Municipal Waste Disposal

Comments

Perry, et al., (29) report the energy analyses of the following energy supply (or savings) systems:

1. Ocean Thermal Energy Conversion (OTEC);
2. Wind Energy;
3. In-situ Oil Shale Processing;
4. Atmospheric Fluidized Bed Coal Combustion;
5. Pressure Fluidized Bed Coal Combustion;
6. Conventional Coal Combustion;
7. Municipal Waste Disposal.

The analyses are significant not only because they are the only analyses found in the literature applied to the listed systems, but also because the analyses represent the state of the art method of energy analysis. The methodology developed by Perry, et al., (29) at the Institute for Energy Analysis (Oak Ridge Associated Universities) is the basis of the energy analysis methodology suggested in this study.

Description of systems and state of systems outputs

System 1 - OTEC

Description. The system is based on a conceptual design by the Lockheed Missiles and Space Company. The

system is designed to operate at a rated output of 169 MW(e) at a capacity factor of 90 per cent over a lifetime of 35 years, located in tropical waters 20 miles off shore. The system incorporates the Rankine power cycle with ammonia as the working fluid and uses titanium heat exchangers. The system is designed to feed an electric grid as a base-load power station. The design includes transmission lines for the underwater DC transmission of electricity to the grid (a 9 per cent transmission loss is assumed).

State of outputs. The system produces base-load electricity delivered to an on-shore electric grid. No secondary or waste products are reported.

System 2 - wind energy

Description. The system is based on General Electric's design of a horizontal axis, two blade rotor rated at 1500 kw(e) (at a wind velocity of 22.5 mph) operating at a capacity factor of approximately 50 per cent over a lifetime of 30 years. The system is designed to operate in a fuel saver mode and does not include energy storage facilities. The design does not include transmission lines for transmission of the electricity. However, a 9 per cent transmission loss is assumed during the distribution of the electricity. The system is designed for unattended operation in a location with suitable wind conditions (including an 18 mph mean wind velocity).

State of outputs. The system produces delivered electricity in the fuel saver mode. The system has no secondary or waste products.

System 3 - in-situ oil shale processing

Description. The system is based on a computer simulated design of a room and pillar modified in-situ process prepared by Fenix and Scisson, Inc. The oil recovery system is estimated to produce 50,000 barrels of oil per day from 20 gallons per ton Green River oil shale over a lifetime of 17.7 years. The design does not include facilities for disposal or processing of excavated shale, nor for the prerefining of the recovered oil to a crude oil equivalent.

State of outputs. The system produces 50,000 barrels per day of a crude oil (not equivalent to petroleum crude oil) at the mine site. Secondary products of oil contained in excavated shale or the low-Btu gas produced are ignored. The system has no reported waste products.

Systems 4, 5 and 6 - atmospheric (AFB) and pressurized (PFB) fluidized bed coal combustion and conventional coal combustion, respectively

Description. The systems, which are designed to produce electricity delivered to a utility grid, are based on design evaluations prepared by the General Electric Company (ECAS Phase II). The AFB and PFB systems produce

steam that is fed to an advanced steam cycle, whereas the conventional system supplies steam to a conventional steam cycle using stack gas scrubbers to remove SO_2 from the effluent gases. Each system is designed to operate on No. 6 Illinois coal (delivered 300 miles at an energy cost of 970 Btu primary/ton-mile) at a capacity factor of 65 per cent over a lifetime of 30 years. The systems' designs assume a 9 per cent output loss for the transmission of electricity but the designs do not include transmission facilities. Each system is rated at 747 MW(e).

State of outputs. The primary outputs of the systems are delivered electricity (intermediate to peak load). The analyses neglect secondary products. Facilities for handling of waste products are included in the design.

System 7 - municipal waste disposal

Description. The system is based on a Tennessee Valley Authority feasibility study for recovering energy intensive residuals from processed solid municipal wastes as a substitute fuel for electric power generation. The system is estimated to process 2000 tons of raw solid wastes per day over a lifetime of 20 years operating in a fuel displacement mode saving 11.1×10^6 Btu of thermal energy per ton of solid wastes processed. The system design includes the transportation of wastes from regional collection centers to the processing plant (assumed to be 150 miles by train) that is located within 20 miles of a

landfill site. The waste processing produces energy outputs of a fuel and reclamation of energy intensive materials, as well as a condensed waste for the landfill. The system design includes the transportation of the fuel to the electric power station (30 miles by truck) and modifications of the power station required to utilize the fuel. Delivery of the recovered materials to a reclamation plant is not included in the system design.

State of outputs. The system displaces the mining and transportation (150 miles by rail) of coal required for power production at a steam plant and recovers energy intensive materials (not delivered to a reclamation plant) from processed solid wastes. Facilities are included for the disposal of the condensed waste.

Description of analysis

The methodology applied by Perry, et al., (29) is the basis of the methodology suggested in this study.

Energy inputs, outputs and parameters of systems

Table 5.32 lists the total energy subsidy, the energy output and energy parameters of the systems analyzed by Perry (29).

Table 5.32. Energy parameters and outputs of systems analyzed by Perry (29)

System	Total Energy Subsidy (Btu primary / yr)	Net Energy (Btu primary / yr)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Energy Output (Btu/yr)
1	5.84×10^{11}	3.29×10^{12}	6.63	663	---	3.87×10^{12}
2	5.17×10^{8}	1.97×10^{10}	39.03	3903	---	2.02×10^{10}
3	1.28×10^{13}	9.72×10^{13}	8.56	a	a	1.10×10^{14}
4	1.83×10^{12}	1.12×10^{13}	7.16	31	3.10	1.31×10^{13}
5	1.93×10^{12}	1.11×10^{13}	6.79	34	2.83	1.31×10^{13}
6	2.80×10^{12}	1.03×10^{13}	4.68	27	3.43	1.31×10^{13}
7	8.03×10^{11}	7.30×10^{12}	10.09	1009	---	8.10×10^{12}

a - Information required for calculation of parameter not reported.

Nine Electricity Generating Systems

Comments

Pilati and Richards report the energy analysis of nine systems producing electricity from fossil fuels (coal, natural gas, crude oil and oil shale) and nuclear fuels (30). The results of this analysis should either reinforce or add suspicion to the results of the analysis by Mechler (28). However, even though the bases of the analysis are discussed, the details of the analysis are not documented. Thus, the results of Pilati and Richards' analysis (30) cannot be quoted with an acceptable degree of confidence.

Description of systems

Table 5.33 lists descriptions of the systems analyzed by Pilati and Richards (30).

Description of analysis

The analysis is unique in that it is the only analysis completely automated. The approach to determining the energy subsidy of an energy supply system comprised of individual facilities is very similar to the approach of Mechler (28). Pilati (30) determines the capital and operational (i.e., utility and raw material) requirements per unit energy output as well as an energy conversion efficiency (i.e., per cent of feed converted into energy output) for each facility. This approach to energy analysis is the application of process analysis to all facilities

Table 5.33. Description of systems analyzed by Pilati (30)

Resource	System Definition	System
Coal	Coal Mine → Coal Fired Power Plant	1
	Coal Mine → Coal Gasification → Gas Fired Power Plant	2
	Coal Mine → Combined Cycle Power Plant	3
	Coal Mine → Solvent Refined Coal → Coal Fired Power Plant	4
Natural Gas	Gas Production → Gas Utility → Gas Fired Power Plant	5
Crude Oil	Crude Oil Production → Low Gas Refinery → Oil Fired Power Plant	6
Oil Shale	Oil Shale Mine/Retort → Low Gas Refinery → Oil Fired Power Plant	7
Nuclear	LWR Fuel Mining/Processing → LWR Power Plant	8
	HGTR Fuel Mining/Processing → HGTR Power Plant	9

comprising the horizontal trajectory (feed trajectory) of the entire system. The capital and operational requirements are mapped into appropriate sectors for application of input-output analysis and entered into a computational program along with the energy conversion efficiency. The program computes the energy subsidy per unit energy output of each facility through application of energy intensity coefficients. The required energy output of each facility is calculated using the energy conversion efficiency of each facility based on a total system output of 1 Btu thermal energy. In other words, the energy conversion efficiency of the last facility in the horizontal trajectory of the system gives the energy input to that facility based on a total system energy output of 1 Btu thermal (i.e., the last facility in the trajectory has an energy output of 1 Btu thermal). The energy input to the last facility is the energy output of the preceding facility. Thus, the energy output and the feed energy input of each facility in the trajectory can be calculated from the energy conversion efficiency of each facility. The energy subsidy contribution from each facility to the energy subsidy of the entire system can then be calculated from the energy output of each facility.

In order to automate the use of the energy intensity coefficients generated for the application of input-output analysis, the data of capital and operational requirements fed to the program must be of a specific form and represent

a specific value (refer to discussion of input-output methodology). Pilati and Richards (30) do not describe how the data are manipulated and only indicate the data source. Furthermore, Pilati and Richards (30) indicate that the accuracy and consistency of the data are suspect. The system trajectories developed by Pilati and Richards (30) are incomplete in that required transportation facilities are neglected. The unit of the energy equivalence is defined as a Btu of primary energy.

State of systems outputs

The only product of each system analyzed is distributed electricity.

Energy inputs and outputs of systems

Table 5.34 lists the lifetime capital, operational and feed energy requirements per Btu lifetime energy output of the systems analyzed.

Table 5.34. Lifetime energy requirements per Btu lifetime energy output of systems analyzed by Pilati and Richards (30)

	Lifetime Energy Requirements		
System	Capital (Btu Primary / Btu Total Output)	Operational (Btu Primary / Btu Total Output)	Feed (Btu Primary / Btu Total Output)
1	0.02	0.13	3.08
2	0.04	0.32	5.00
3	0.01	0.05	2.53
4	0.03	0.50	5.24
5	0.04	0.44	3.09
6	0.08	0.73	3.08
7	0.03	0.68	4.62
8	0.42	0.21	4.02
9	0.69	0.19	4.26

Energy parameters of systems

Table 5.35 lists the energy parameters of the electricity-generating systems.

Table 5.35. Energy parameters of systems analyzed by Pilati and Richards (30)

System	Total Energy Subsidy (Btu Primary / Btu Output)	Net Energy (Btu Primary / Btu Output)	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
1	0.15	0.85	6.72	31	3.08	0.019
2	0.36	0.64	2.79	19	5.00	0.038
3	0.06	0.94	15.53	39	2.53	0.014
4	0.53	0.47	1.89	17	5.24	0.028
5	0.48	0.52	2.07	28	3.09	0.044
6	0.81	0.19	1.23	26	3.08	0.081
7	0.72	0.29	1.40	19	4.62	0.032
8	0.63	0.37	1.58	22	4.02	0.421
9	0.88	0.12	1.14	19	4.26	0.685

CHAPTER 6

CONCLUSIONS, IMPLICATIONS AND RECOMMENDATIONS

Introduction

The results of energy analyses, when reported as suggested in Chapter 3, offer information that is useful in developing competent energy policies. Energy analysis results give insight into the behavior of energy supply systems on three levels of policy planning. The first level deals with the operation of individual systems as predicted by the absolute values of the energy parameters of the system. The evaluation of energy parameters in this context investigates the sensitivity of the system energetics to energy inputs which are extremely site specific or which dominate the total energy subsidy of the system. A discussion of this level of energy analysis implications is presented for the analyses performed by the author (central receiver solar thermal power station, solar industrial process heat, crop production and production of ethanol from corn) and for the energetics of nuclear power plants and the supply of energy from fossil fuels.

The second level of energy analysis implications considers the supply of energy for specific end uses. This evaluation of system energetics is a relative

comparison of systems competing for the supply of a specific energy product (usually a comparison of alternative and conventional energy supply systems). This level of energy analysis implications will not only match the optimal energy supply system to a specific energy product, but will also indicate if the service performed by the energy product can be performed more efficiently (with the expenditure of less energy) in an alternative manner obtaining the same goals from a different energy form (such as the use of electricity instead of liquid fuels for transportation). It is in this context that the United States' transportation needs and the supply of electricity and heat are discussed.

The information base necessary to develop a competent national energy policy is not complete without an examination of the first two levels of energy analysis implications. Furthermore, a tool is needed to predict the behavior and the future consequences of proposed energy policies. Thus, a dynamic supply and demand model capable of describing a complex network of energy supply systems based on information obtained through the first two levels of energy analysis implications must be developed. This model will define the third level of energy analysis implications. A discussion of the general characteristics of a future energy supply scenario based on the results of the first two levels of energy analysis implications and

a description of the basis for a dynamic energy supply and demand model are presented. Finally, recommendations for further efforts in energy analysis are discussed.

First Level of Energy Analysis Implications

Solar Energy

Comments

In the near future, alternative energy supply systems will be called upon to reduce crude oil and natural gas consumption in the supply of energy to both industrial and residential sectors of the United States. One indicator of a healthy industry in a capitalistic society is the continuous growth of the industry's output and profit. As an industry's productivity increases, its consumption of energy, directly and indirectly (i.e., through the use of capital, raw materials and feed stocks), increases as well. Thus, the energy supply systems of a capitalistic society must produce enough net energy to both satisfy the consumption demands of the society and to re-invest in the construction of new energy supply facilities to allow the growth of the society.

Consider the growth capability of energy supply systems based on the following crude model:

Assume n_o units of an energy supply system exist. Each unit has a specified output, as well as a specified

energy subsidy requirement. Define the energy flows and system properties of each unit as follows:

E_{out} ≡ The annual energy output of each unit

E_{op} ≡ The annual energy subsidy required by each unit excluding the amortized capital energy subsidy

X ≡ The capital requirement factor of each unit

L ≡ Lifetime of each unit

$E_{av}(n)$ ≡ The energy made available during one year of operation from n existing units

G ≡ Energy gain of each unit

g_{max} ≡ Maximum growth rate of the energy supply system

Recall the definition of the energy gain

$$G \equiv \frac{E_{out}}{E_{op} + X \cdot E_{out}}$$

$E_{av}(n)$ is given by

$$E_{av}(n) = n(E_{out} - E_{op})$$
$$= n\,E_{out}\,(1 - \frac{1}{G} + X)$$

The energy made available during the first year of operation is given by

$$E_{av}(n_o) = n_o\,E_{out}\,(1 - \frac{1}{G} + X)$$

The maximum growth rate of the energy supply system is given by

$$g_{max} = \frac{n_1\ max}{n_o}$$

$$n_1\ max = \frac{E_{av}(n_o)}{X \cdot E_{out} \cdot L}$$

$$g_{max} = \frac{(1 - \frac{1}{G} + X)}{(X \cdot L)}$$

Generally, solar alternatives to fossil fuel based end uses of energy are lower gain systems often with higher capital requirement factors and similar lifetimes. Thus, complete displacement of crude oil with solar alternatives may not be acceptable from a growth capability viewpoint.

Although solar energy supply systems are generally lower gain systems compared to their fossil fuel based counterparts, solar energy supply systems operate at a higher overall process efficiency because the energy content of the energy product is freely available. Thus, there is much less energy embodied in the energy products of systems based on solar energy than the energy products of fossil fuel based systems. This result implies that solar energy alternatives can be utilized to effectively reduce the consumption of fossil fuels in the supply of the same energy products. Specifically, the use of solar energy supply systems can reduce the consumption of crude oil without the increased consumption of other fossil fuel resources.

The fact that solar energy supply systems are generally low gain systems suggests that at least a portion of the system's energy subsidy must originate from fossil fuels to render an adequate portion of the system's energy output available for end-use consumption. Thus, solar energy supply systems can be expected to reduce rather than displace fossil fuel consumption. The above mentioned characteristics of solar energy supply systems suggest the

use of such systems in an interim energy supply role allowing the reduction of crude oil and natural gas consumption without the increased consumption of domestic coal resources. The reduction of crude oil and natural gas consumption without the increased consumption of coal will allow the investment of coal for the development and implementation of an acceptable long-term energy supply system that will ultimately displace the consumption of fossil fuels, such as the nuclear breeder reactor.

Central receiver solar thermal power stations

Two individual system designs of a central receiver solar thermal power station are analyzed as described in Appendix A. The major difference between the two system designs is the design philosophy adopted to achieve the lowest possible capital investment with regard to the collector subsystem. The design philosophy of the collector subsystem in system 1 is to maximize the efficiency of the collector subsystem and thereby minimize the total reflective surface area required. The design philosophy of the collector subsystem in system 2 is to minimize the cost of the components utilized in the collector subsystem which results in an increase in the total reflective surface area required. System 1 requires a total of 68,500 square feet of reflective surface area per MW(e) system output (20), while system 2 requires 74,475 square feet of reflective surface area per MW(e) system output (21). However, system 2 requires

only three receivers and towers per 100 MW(e) system output compared to the ten receivers and towers required by system 1 per 100 MW(e) system output (9).

The energy parameters favor the design philosophy of system 2 based on the assumption that both systems have the same lifetime (9). If the use of lower quality components results in a system lifetime of twenty years compared to a system lifetime of thirty years resulting from the use of high quality components, the energetic advantage indicated by the energy parameters of the system utilizing the lower quality components (based on the assumption of equal lifetime) is lost (9).

The capital energy requirement represents 87.7 per cent and 88.4 per cent of the total energy subsidy of systems 1 and 2, respectively (assuming a 1000 mile transportation distance for delivery of prototype components, a system lifetime of thirty years and including the electricity fed back into the system in the energy subsidy of the system) (9). Thus, a reduction in the capital energy investment could significantly improve the energetics of the system. Table 6.1 lists a breakdown of the capital energy subsidy required by systems 1 and 2.

Recall that the energy embodied in the heliostats represents a mass-manufactured product. Not only does mass-manufacturing imply the replacement of human labor (a free energy resource) with automated machinery, but it

Table 6.1. Breakdown of the capital energy subsidy of central receiver power stations (9)

Components	Per Cent of Total Capital Subsidy[a] System 1	System 2
Heliostats	48.7	39.9
Receivers and Towers	21.3	9.3
Balance of Plant	21.7	34.7
Maintenance	8.3	16.1

a - Assuming a transportation distance of 1000 miles for delivery of prototype components and a system lifetime of thirty years.

implies the centralized manufacture of a product that must be transported to its end-use site as well. The 18.7 per cent of the energy embodied in the non-delivered heliostat (as produced at the manufacturing site) which originates from direct energy usage and required capital facilities (9), is assumed to be the energy cost of the use of mass-manufacturing techniques. Thus, mass-manufacturing techniques account for 10.7 and 10.5 per cent of the energies embodied in the installed heliostats of systems 1 and 2, respectively (9). Furthermore, 3.1 and 1.5 per cent of the energies embodied in the installed heliostats of systems 1 and 2, respectively, are required to deliver the heliostats as produced at the manufacturing site 1000 miles to the system site (compare that distance to the transportation distance for a heliostat manufactured in Michigan delivered to Arizona) (9). According to the above calculations, 6.7 and 4.8 per cent of the total capital energy subsidies of systems 1 and 2, respectively, originate from the mass-manufacturing of heliostats. Thus, the energy savings from utilizing decentralized, non-automated practices for heliostat fabrication instead of mass-manufacturing techniques will not significantly improve the energy characteristics of the system (for example, if decentralized practices reduce the energy consumed during mass-manufacturing by 75 per cent, the maximum possible reduction in the capital energy subsidy is 5 per cent). However, 67.5 per cent of the

energy required to install the components, and 23.4 per cent of the energy embodied in the general facilities originate from the direct energy usage and required capital facilities of automated construction practices (9). Thus, 42.8 and 47.9 per cent of the total capital energy subsidies of systems 1 and 2, respectively, originate from the use of automated construction practices (9). Obviously, the energy characteristics of a central receiver power station could be significantly improved by minimizing the direct energy and capital usage and maximizing the use of human labor during the construction of the power station.

It is clear that the energetics of central receiver power stations will not approach those of electricity produced from fossil fuels. Central receiver power stations are low gain systems (approximately 1.6-3.3) (9) with high capital requirement factors (approximately 0.3-0.6) (9). As a result, even the central receiver power stations with the most favorable energetics suffer from a severe growth limitation compared to their fossil fuel based counterparts. A central receiver power station with a gain of 3.3, a capital requirement factor of 0.6 and a system lifetime of thirty years has a maximum growth rate capability of 0.07. On the other hand, fossil fuel based electrical utilities have an energy gain of approximately 9 (1). From the energy analysis by Pilati (13), the capital requirement

factors of fossil fuel based power plants are approximately 0.002 - 0.08. The maximum growth rate capability of a fossil fuel based power plant with an energy gain of 9, a capital requirement factor of 0.08 and a system lifetime of thirty years is 0.40.

Even though central receiver power stations are not acceptable as independent energy supply systems, they can produce electricity, a valuable energy product, at an overall process efficiency of approximately 300 per cent (9) compared to an overall process efficiency of about 30 per cent (1) for the fossil fuel based electrical utilities. Thus, central receiver power stations can effectively reduce the consumption of fossil fuels for the large scale supply of electricity. Furthermore, since central receiver power stations are best suited to supply electricity for peak or intermediate load end uses, such systems are most effective in reducing the crude oil and natural gas, which are commonly consumed in the supply of peak and intermediate load electricity, consumed for the production of electricity. Unfortunately, central receiver power stations are practical only in areas of sufficient solar insolation such as the west and southwest portions of the United States.

Production of industrial process heat from solar radiation

Process heat for industrial usage as well as domestic hot water and hot air for space heating are energy

products produced specifically for consumption to provide some end-use service. Such energy products have no use as investment energies and, as a result, the concept of the growth capability of systems producing these energy products has little significance. Thus, any alternative system which produces process heat at an overall process efficiency greater than that of its fossil fuel based counterpart is a legitimate candidate for the reduction of fossil fuel consumption.

The overall process efficiencies of the solar industrial process heat systems analyzed range from 106 to 363 per cent depending on the system and the utility requirement (reported as a per cent of the system's thermal output required as electrical input) (14). In general, a specific solar industrial process heat system will consume electricity at a constant rate while the system is operational. The efficiency at which the collected heat (in the form of hot water, steam or hot air) is transported to the consumption site determines the length of the operational periods of the system for a given energy demand. Thus, for a given output of the solar industrial process heat system, the utility requirement (in the form of electricity) will vary as a function of the thermal losses in the system. Since electricity is of a much higher quality compared to the output of the system, small increases in the thermal losses of the system can

significantly worsen the energy characteristics of the system. Thus, it is critical that the thermal losses in the system be minimized through proper design and installation.

The utility requirement dominates the total energy subsidies of the solar industrial process heat systems analyzed, comprising 70.6, 59.7 and 53.2 per cent of the total energy subsidies of systems I, II and III, respectively (14). Thus, the use of mass-manufacturing techniques and automated construction practices do not represent a significant portion of the total energy subsidies of solar industrial process heat systems as is observed for central receiver power stations. For example, consider system III in which the non-delivered, non-installed solar collectors, the energy required to deliver the solar collectors 500 miles and the energy required for installation of the components represent 15.9, 0.5 and 11.5 per cent, respectively, of the system's total energy subsidy (14). Thus, 11.2 per cent of the system's total energy subsidy originates from the use of mass-manufacturing techniques and automated construction practices (9, 14).

Crop production

Western (i.e., intensive) cultural practices of crop production rely on the extensive use of products produced from crude oil and natural gas to obtain

maximum crop yields. Table 6.2 lists the breakdown of the energy subsidy for the production of corn and slash pine.

The energy parameters of the production of dried and chipped crops are sensitive to the transportation distance of crop delivery and the moisture content of the crop (through both the drying energy subsidy and the transportation energy subsidy). These results indicate that the use of biomass as a solid fuel in a national energy supply role is far too energy intensive. Furthermore, the large processing energy requirements for the production of a solid fuel suggest that crops may be more efficiently utilized as a feedstock to an energy supply process (such as an alcohol plant) which consumes the crop at its moisture content as stored on the farm.

Although the production of crops as a solid fuel for the supply of energy on a national basis is not energetically attractive, the energy gain of crop production with minimal transportation distance of crop delivery is sufficiently high to allow the internal generation of required motor fuels, process heat, electricity and possibly some fertilizers without significantly reducing the crop output of the farm. For example, the internal supply of the transportation of crop energy subsidy, the utility energy subsidy and one-half of the raw materials energy subsidy for the production of corn would reduce the crop output

Table 6.2. Energy gains and the breakdown of the total energy subsidies of the production of corn and slash pine (15)

Crop	Moisture Content[a] (%)	Energy Gain	Transportation Distance of Crop Delivery[b] (miles)	Per Cent of Total Energy Subsidy: Transportation of Crops Energy Subsidy	Processing Energy Subsidy	Capital Energy Subsidy	Raw Materials Energy Subsidy	Utility Energy Subsidy
Corn	15	6.4	50	12.2	30.9	2.8	46.4	7.7
		3.1	500	58.1	14.7	1.3	22.2	3.7
Slash Pine	33	5.3	50	13.4	57.3	2.3	19.5	7.5
		2.4	500	60.8	26.0	1.0	8.8	3.4

a - Wet basis

b - Distance of crop delivery from farm to processing site

by 6.7 and 23.7 per cent for a 50 and 500 mile transportation distance of crop delivery, respectively (15). The internal generation of a portion of the required energy subsidy could reduce the dependence of the crop industry on both crude oil and natural gas.

Production of alcohol from corn

The production of anhydrous (i.e., 199 proof) ethanol from crops with a high starch or carbohydrate content such as corn and sugar cane has received much attention in small private businesses partially due to the simplicity of the process. The technologies for the saccharification of starches, the fermentation of sugars to ethanol and the distillation of ethanol are well established and of a relatively low level. The establishment of a small alcohol plant does not require a great deal of capital and the government is providing funding for alcohol projects. The combination of these conditions make alcohol production attractive to small scale investors. Unfortunately, alcohol plants are inherently energetically marginal systems and are dangerously close to zero or even negative net energy producers. It is generally recognized that ethanol produced as a motor fuel should be used only in an interim energy supply role to conserve crude oil resources. Thus, the alcohol producing process need only have an overall process efficiency greater than that of a crude oil refinery, which has an overall process efficiency

of approximately 80 per cent (1), to be effective. Even though alcohol production is capable of operating at an overall process efficiency greater than 100 per cent (16), the overall process efficiency of a non-optimally designed and operated alcohol plant may drop below 80 per cent, resulting in an increase rather than a decrease in the consumption of fossil fuels. Thus, it is critical that any alcohol plants implemented have the technical resources available to ensure optimal operation of the plant. Such technical resources are not readily available to a majority of the small scale investors pursuing the production of alcohol.

As an energetically marginal system, it is desirable to identify those areas of energy consumption of an alcohol plant in which conservation will result in the greatest improvement in the energy parameters of the system. Table 6.3 lists the breakdown of the energy subsidy required for the production of alcohol from corn.

The energetics of the alcohol producing system are sensitive to the distance the alcohol must be transported to its end-use site. In fact, the system cannot absorb the energy required to transport the alcohol (via truck) over 1000 miles (with the coal delivered 1000 miles) and still be a net energy producer {i.e., the energy gain of the system with a transportation distance of 1000 miles for delivery of the coal and alcohol is 1.01 (16)}.

Table 6.3. Breakdown of the energy subsidy required for the production of alcohol from corn (16)

Energy Subsidy	Per Cent of Total Energy Subsidy[a]		
	500 mi[b]	1000 mi[b]	1500 mi[b]
Capital	1.4	1.3	1.2
Raw Materials	1.3	1.2	1.1
Electricity and Fuel	25.1	23.1	21.3
Coal[c]	34.9	32.0	29.6
Feedstock (corn)	28.3	26.0	24.0
Transportation Energy for Delivery of Alcohol	8.9	16.4	22.7

a - Assuming solar radiation is the feed to the process

b - Transportation distance of alcohol delivery (truck transportation)

c - Delivered over a distance of 1000 miles via rail transportation

Furthermore, the total energy subsidy required for the production of alcohol is fairly well distributed between the electrical and fuel subsidy, the coal subsidy and the feedstock (corn) subsidy (and the energy required to deliver the alcohol at large transportation distances). Thus, incremental reductions in the individual energy subsidies cannot significantly improve the energetics of the system. However, the energetics of the system can be improved by significantly reducing the energy embodied in the process heat. The reduction of the energy embodied in the process heat consumed by the system could be accomplished by utilizing a solar industrial process heat system for the production of process heat, or by utilizing the waste heat rejected by an electrical utility. The latter alternative is known as the cogeneration concept. It is not clear which alternative to reducing the energy embodied in the process heat would be most effective in improving the energetics of the system due to the following argument:

Even though there is no energy embodied in the waste heat of an electrical utility, the cogeneration concept implies the centralized production of alcohol requiring larger transportation distances for alcohol delivery. On the other hand, solar industrial process heat systems can be utilized by smaller, decentralized alcohol plants where the alcohol would be consumed locally.

Table 6.4 lists the breakdown of the energy subsidies of a 1000 MW(e) boiling water nuclear reactor (BWR) (0.3 per cent tails assays with and without fuel recycle from spent fuel rods) and a coal fired power plant and the energy gains of each system.

Table 6.4 Breakdown of the energy subsidies of a 1000 MW(e) BWR (0.3 tails assays with and without fuel recycle) and a coal fired power plant and the energy gains of each system

System	Energy Gain	Per Cent of Total Energy Subsidy: Mining	Enrichment or Transportation[a]	Capital (power plant)	Others
1000 MW(e)[b] BWR (5)	6.0	16.0	68.0	16.0	---
1000 MW(e)[c] BWR (5)	7.9	21.3	49.3	28.3	1.0
Coal Fired Power Plant (1)	9.7	25.0	52.0	20.5	2.5

a - Represents the percentage of the total energy subsidy required during uranium enrichment for the 1000 MW(e) BWR or the percentage of the total energy subsidy required to transport the mined coal to the power plant

b - 0.3 per cent tails assays, no fuel recycle

c - 0.3 per cent tails assays, recycle of uranium and plutonium from the spent fuel rods

The energy gain and the breakdown of the energy subsidy of a 1000 MW(e) BWR with 0.3 tails assays and recycle of uranium and plutonium from the spent fuel rods are very similar to those of a conventional coal fired power plant interchanging the coal transportation subsidy of the coal fired power plant with the uranium enrichment subsidy of the BWR. Thus, such a nuclear power plant is an acceptable candidate for the long-term supply of energy and is capable of completely displacing the consumption of fossil fuels for the production of electricity. Furthermore, nuclear power plants have the capacity to reduce the consumption of fossil fuels for the production of electricity in the near future as well. Consider the overall process efficiency of a 1000 MW(e) BWR with 0.3 per cent tails assays and recycle of uranium and plutonium from the spent fuel rods. If the thermal energy equivalent of the energy which is released during the fission of the uranium is assumed to be the resource utilized by the system, the overall process efficiency of the 1000 MW(e) BWR is 34.1 per cent (5). However, uranium is not a useful energy resource to energy supply systems other than nuclear reactors. In this context, uranium may be envisioned as a freely available but limited energy resource. If the uranium is considered to be a free energy resource, the overall process efficiency of the 1000 MW(e) BWR becomes 789 per cent (5). Furthermore, the available uranium resource can be

considerably extended through the implementation of the breeder technology. However, as is observed for the central receiver power stations, the nuclear power plants have some end-use limitations in that, due to the long start-up and shut-down periods required for operation of the plant, they are not well suited for the supply of peak or intermediate load end-uses of electricity.

Fossil Fuels

The energy characteristics of systems supplying energy from fossil fuels are very similar regardless of the energy resource. For example, the production of electricity from crude oil, natural gas and coal all have an energy gain of approximately 10 (1). Furthermore, fossil fuel based systems all have low capital energy subsidies with the energy subsidy of the fossil fuel dominating the total energy subsidy of the energy supply system. However, there are subtle differences in the energy subsidies required to extract, process and deliver coal, crude oil and natural gas.

In general, crude oil and natural gas are discovered and extracted during the same operation and, therefore, have similar extraction energy subsidies. Natural gas has a greater relative extraction energy due to its lower energy content and the required drying of the gas (i.e., removal of water and organic condensates) at the field site before it is transported. The energy

required to extract crude oil and natural gas once it is discovered is quite small. However, the total energy expended for the exploration and extraction of crude oil and natural gas yields energy gains of 56 and 45 (1), respectively. The easily accessible fields of crude oil and natural gas are rapidly being exhausted. The energy required to discover and extract crude oil and natural gas can be expected to increase significantly as the demand forces man to drill deeper into the earth, recover second and third generation yields from old wells, and develop more offshore drilling operations. Domestically, crude oil and natural gas are distributed via pipeline (a national average of 300 miles for crude oil and 1000 miles for natural gas) which is the least energy intensive mode of fuel transportation (1). Imported foreign oil must be shipped by supertankers which reduces the energy gain of the distributed crude oil to approximately 35 (7). The energy gains of distributed domestic oil and natural gas are 51 and 24 (1), respectively (a more realistic gain for delivered crude oil is in the 30-35 range since the majority is imported).

Conversely, the energy subsidy required to discover and extract coal is very small giving extracted coal an energy gain of 130 (1). However, the transportation of solids is extremely energy intensive. The delivery of coal a national average distance of 500 miles by rail, the

least energy intensive mode by which to transport solids (1), reduces the energy gain of distributed coal to 42 (1). Coal could be distributed via pipeline as a liquid-solid slurry. Transporting coal by pipeline could significantly enhance its energy characteristics.

Second Level of Energy Analysis Implications

Comments

This level of energy analysis implications can be used to optimally match end uses with supply systems in developing future energy supply scenarios. However, in the presence of an energy crisis, the goal of alternative energy supply systems is not to supply energy as efficiently as possible, but to displace the depleting resources. Currently, the United States is facing a crude oil supply crisis. At this phase of the crisis, the United States is suffering from the depletion of domestic crude oil supply, forcing her to import vast amounts of crude oil. The production of domestic crude oil, which was at its greatest level of 12 MM barrels/day in 1972, is projected to level off at 6-7 MM barrels/day by 1990 (4) including production from new discoveries and synthetic crudes. By the year 2000, the United States' crude oil consumption is expected to reach 20 MM barrels/day (4). The United States cannot develop a stable economy while relying on imported oil, the price of which cannot be controlled nor the supply guaranteed, to supply a large portion of her

energy demands. Furthermore, the foreign crude oil resources are finite as well. Thus, the United States must reduce the level of crude oil consumption to the level of domestic production and to ultimately completely displace the consumption of crude oil not only in order to achieve economic stability, but to avoid a similar crisis when the crude oil resources are depleted planet-wide.

In order to reduce the consumption of crude oil to a level within the levels of domestic production, the United States must employ both conservation and alternative energy supply systems capable of reducing crude oil consumption while producing the energy products at the same rate for whatever crude oil based energy products feasible. A measure of an alternative energy supply system's capability to reduce the consumption of crude oil for the supply of a specific energy product is determined by comparing the overall process efficiencies of the alternative and crude oil based energy supply systems. The inverse of the overall process efficiency represents the total amount of primary energy that is embodied in the product of the system. Recall that the primary energy embodied in a product represents the fossil fuel equivalent (i.e., the summation of the crude oil, natural gas, coal and the fossil fuel equivalent of the hydro and nuclear derived electricity) of the energy resources embodied in that product.

It is possible to define the unit energy equivalence of an energy analysis to be some unit of crude oil, in which case the inverse of the overall process efficiency would represent the crude oil embodied in the products of the system. Defining the unit of energy equivalence in this manner is warranted only if the initial assessment of the nation's energy alternatives fail to identify alternative energy supply systems capable of reducing crude oil consumption without increasing the consumption of other fossil fuels for the following reason. It is necessary to eventually construct a new network of energy supply systems to completely displace the need for fossil fuels. Furthermore, the technologies for such energy supply systems (such as the breeder reactor) are not sufficiently developed to allow the commercialization of these energy supply systems. When the technologies are developed to the stage of commercialization, a vast amount of energy will be required to invest in the construction of the new energy supply systems. The only available energy resource capable of supplying the required energy investment is coal. Thus, the wisest short-term energy policy is to conserve the coal reserves as much as possible by implementing alternative energy supply systems capable of reducing crude oil consumption without increasing the consumption of coal. However, while conservation of coal is emphasized, the productivity of the coal industry must be increased as

quickly as possible to ensure the availability of extracted coal when it is needed.

Comparison of Alternative and Conventional Energy Supply Systems for the Supply of Specific End-Use Products

Tables 6.5, 6.6 and 6.7 list the energy parameters of alternative and conventional systems supplying liquid fuels, electricity and heat (in the form of industrial process heat, domestic hot water and space heating), respectively. All values which appear in Tables 6.5, 6.6 and 6.7 are either the results of analyses performed by the author (documented in the Appendices of the report and summarized in Chapter 4) or documented in the literature survey of Chapter 5. The parameters and system descriptions listed in Tables 6.5, 6.6 and 6.7 serve as the basis for the values and systems listed in Tables 6.8, 6.9 and 6.10.

Discussion of the Provision of Transportation Services

In 1979, 10 MM barrels/day of the 18 MM barrels/day of crude oil consumed in the United States provided liquid fuels for transportion (4). The potential exists for a tremendous reduction in the consumption of crude oil to provide transportation fuels by increasing the efficiency at which the thermal energy content of the fuel is converted to the transportation service. For example, it is estimated that the consumption of crude oil for transportation can be

Table 6.5. Comparison of liquid fuel supply systems

System	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
Gasoline from crude oil (1)	10.0	82.60	1.11	---
Gasoline from coal (1)	6.7	60.96	1.49	---
Gasoline from oil shale (1)	6.5	57.77	1.58	---
Alcohol from corn[a] (9)	1.11	111.00	---	0.013

a - Production of 199 proof alcohol from corn, 500 mile delivery distance for coal (used for process heat) and 500 mile distribution distance for alcohol

Table 6.6. Comparison of electricity producing systems

System	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
Conventional Crude Oil Plant (1)	9.9	27.93	3.48	---
Conventional Coal Plant (1)	9.7	28.82	3.37	---
Liquefied Coal Plant (1)	9.8	18.23	5.39	---
Gasified Coal Plant (1)	9.4	18.97	5.17	---
Natural Gas Plant (1)	8.6	26.22	3.70	---
Synthetic Crude from Oil Shale Plant (1)	3.9	19.33	4.92	---
Central Receiver Power Station (9)[a]	3.32	332	---	0.301
Nuclear (5)[b]	7.89	34.1 (789)[c]	2.74 (--)[c]	0.036
Wind Power (8)[d]	39.03	39.03	---	---
Photovoltaics (10)[e]	1.97	1.97	---	---

Table 6.6. Continued

a - Mitre Corporation system design, 500 mile prototype component delivery distance, 30 year system lifetime

b - 1000 MW(e) boiling water reactor, 0.3 per cent tails assays, recycle of uranium and plutonium from spent fuel rods

c - Values in parentheses represent parameters based on the assumption that the thermal equivalent of the energy released during fission from uranium is freely available

d - Supply of peak load electricity without storage capability, rated output of 1500 kw(e)

e - Includes the direct energy consumed (assumed to be thermal energy) during the production of silicon photovoltaic cells

Table 6.7. Comparison of process heat, space heating, and domestic hot water supply

System	Energy Gain	Overall Process Efficiency (%)	Resource Utilization Factor	Capital Requirement Factor
Crude Oil (1)[a]	51.0	95.42	1.03	---
Natural Gas (1)[b]	23.9	82.89	1.21	---
Coal (1)[c]	42.2	97.68	1.00	---
Gasified Coal (1)[d]	23.8	60.05	1.63	---
Solar Thermal				
- process heat (9)[e]	3.63	363.00	---	0.081
- domestic hot water (11)[f]	2.32	232.00	---	0.271
- domestic hot water and space heating (12)[g]	5.47	547.00	---	0.183
Biomass (9)[h]	3.41	341.00	---	0.004

Table 6.7. Continued

a - Domestic crude oil, delivered 300 miles by pipeline, not desulfurized

b - Domestic natural gas, dried at well site, delivered 1000 miles by gas pipeline

c - Raw coal, delivered 500 miles by rail, not desulfurized

d - Coal gasified at mine site using the Lurgi process, delivered 1000 miles by gas pipeline

e - 60-80^{o}C industrial hot water supplied from evacuated tubular collectors, 5% of the thermal output required as electrical input, located in southwest

f - Supply of 50% of domestic hot water requirement from flat plate collectors located in Phoenix, 6.5% of the thermal output required as electrical input

g - Supply of 63% of the total domestic heat requirement (space heating and domestic hot water) from 65 m^2 of collector area, heat storage capability, no electrical input considered, located in West Germany

h - Intensive production of slash pine in Louisiana, biomass delivered 100 miles to processing site for chipping and drying

reduced to 4.5 MM barrels/day by the year 2000 as a result of increasing the average car mileage to 36.5 mpg (4). However, the consumption of 4.5 MM barrels/day of crude oil is itself a sizable quantity of energy representing approximately 70 per cent of the estimated domestic production of crude oil. The alternative resources to the production of liquid fuels are coal, oil shale and biomass. The production of liquid fuels from biomass could only supply a small portion (i.e., less than 20 per cent based on the displacement of 1 MM barrel/day of crude oil, which is ten per cent of the current consumption of crude oil for transportation) of the liquid fuel demand leaving the burden of liquid fuel supply on the non-renewable resources of coal and oil shale.

The lack of attractive alternative liquid fuel producing systems suggests the examination of an alternative transportation system based on electrical energy. From the overall process efficiencies listed in Tables 6.5 and 6.6, the primary energies embodied in both liquid fuels and electricity can be estimated. However, the desired parameter is the energy required to provide the transportation service. Thus, the inverse of the overall process efficiency is divided by the efficiency at which the energy product is converted into the desired end use, resulting in a parameter representing a relative measure of the energy required for transportation services. Table 6.8 lists the end use

Table 6.8. Comparison of the relative primary energy consumed per unit of transportation work provided by various energy supply systems

System	End-Use Conversion Efficiency	Overall Process Efficiency	Relative Primary Energy Consumed Per Unit Transportation Work Provided[b]
Gasoline from Crude Oil	0.5[a]	0.826	2.42
Gasoline from Coal	0.5[a]	0.607	3.28
Gasoline from Oil Shale	0.5[a]	0.578	3.47
Alcohol from Corn	0.5[a]	1.110	1.80
Electricity from Crude Oil	0.9	0.279	3.98
Electricity from Coal	0.9	0.288	3.86
Electricity from Natural Gas	0.9	0.262	4.24
Electricity from Liquefied Coal	0.9	0.182	6.09
Electricity from Gasified Coal	0.9	0.190	5.85
Electricity from Oil Shale Crude	0.9	0.193	5.75
Central Receiver Power Station	0.9	3.32	0.33
Nuclear Energy	0.9	0.341 (7.89)[c]	3.26 (0.14)[c]

a - End-use conversion efficiency of 0.5 is intended to reflect the increase in car mileage

b - Values are defined as: $\frac{1}{\text{Overall Process Efficiency}} \cdot \frac{1}{\text{End-use Conversion Efficiency}}$

c - See Table 6.6

conversion efficiencies and the relative measure of the energy required for transportation of alternative and conventional transportation energy supply systems. Note that the use of the end-use conversion efficiency assumes that the energies embodied in the various conversion facilities are similar. Also, note that systems producing electricity from wind energy and the use of photovoltaic cells are not included in Table 6.8 because the systems represented by the parameters listed in Table 6.6 are not suitable for the production of electricity as a transportation fuel.

The complete provision of transportation services using liquid fuels from coal, oil shale and a small portion from biomass will consume the domestic coal and oil shale reserves at an extremely fast rate. On the other hand, the use of electricity from central receiver power stations or nuclear reactors as a transportation fuel can reduce the consumption of crude oil for the production of transportation fuels up to 94 per cent without increasing the consumption of other fossil fuels.

Electricity

A power plant is generally classified according to the end use of, or the demand cycle satisfied by, the electricity produced. The end uses of electricity are classified as either the supply of peak, intermediate or base load electricity. Base load power plants generate a constant supply of electricity while intermediate and peak load power

plants generate enough electricity to meet the fluctuating demand above the base load supply. A power plant capable of supplying all end uses of electricity is characterized by short start-up and shut-down time requirements and produces electricity from an energy resource which is continuously available. Fossil fuel based power plants are suitable for the supply of all end uses of electricity. However, the alternative electricity supply systems are not. Table 6.9 lists the embodied energy and the end uses of the electricity produced by conventional and alternative electricity supply systems.

Of the alternative energy supply systems, the electricity with the least embodied primary energy is produced from nuclear power plants (excluding electricity from wind energy). Furthermore, nuclear energy has the fewest location limitations. At the present rate of consumption of U^{235} for the production of light water nuclear reactor fuel, domestic U^{235} resources are estimated to last 40 to 60 years (17). However, a by-product of the production of light water nuclear fuel is U^{238}, the feedstock of the breeder nuclear reactor. In fact, sufficient U^{238} is stockpiled at the Oak Ridge enrichment plant to operate 400 1000 MW(e) breeder power plants for a period of 500 years (17). Thus, the reduction of the consumption of fossil fuels for the production of electricity by the implementation of light water nuclear reactors is not only the largest

Table 6.9. Embodied energies and end-uses of electricity produced by various systems

System	End-Use[a]	Primary Energy Embodied in the Electricity[b]
Crude Oil Power Plant	b,i,p	3.58
Coal Power Plant	b,i,p	3.47
Natural Gas Power Plant	b,i,p	3.81
Gasified Coal Power Plant	b,i,p	5.27
Liquefied Coal Power Plant	b,i,p	5.49
Oil Shale Power Plant	b,i,p	5.17
Nuclear Power Plant	b	2.43 (0.13)[c]
Central Receiver Power Station	i,p	0.31
Wind	p	0.03
Photovoltaics	p	0.51

a - b ≡ base load; i ≡ intermediate load; p ≡ peak load

b - Values are the inverse of the overall process efficiency of the system

c - See Table 6.6

scale and the least location restricted alternative to electricity production, but the depletion of domestic U^{235} resources in the production of light water reactor fuel will produce enough U^{238} to allow the fabrication of sufficient breeder reactor fuel to supply the United States' energy consumption for thousands of years (17).

Unfortunately, the feasibility of electricity production from nuclear light water reactors at a smaller scale such as 50 MW(e) or less has not been demonstrated. In applicable regions of the United States, solar energy based alternatives are effective in reducing fossil fuel consumption for the smaller scale production of electricity. The repowering of existing fossil fuel based power plants with steam produced using the central receiver (i.e., power tower) concept could become a very effective method for the reduction of crude oil consumption for the production of electricity in the west and southwest regions of the United States. However, the operation of fossil fuel (primarily coal) based power plants will be required for the small scale production of electricity for a major portion of the nation.

Heat

Currently, the process heat consumed by the industrial sector and heat consumed for the supply of hot water and space heating by the residential sector are produced primarily by the direct combustion of natural gas and, to

a lesser extent, by the combustion of fuel oil and the conversion of electricity. As mentioned in the discussion of solar process heat systems, heat is an energy product suitable for end-use consumption only, and is not considered an energy form suitable for investment end uses. Thus, the dynamic behavior of a heat supplying system is not an important consideration. The important characteristic of a heat supplying system is the total primary energy embodied in the end-use energy form (i.e., such as steam, hot water or hot air). The heat supply systems described in Table 6.8 represent the supply of available thermal energy and not the end-use product itself (with the exception of the solar heat supply systems). Thus, the use of an end-use conversion efficiency is required to compare various heat supply systems according to the production of specific energy products.

Table 6.10 lists the primary energy embodied in heat for the supply of industrial process heat, domestic hot water and space heating produced by various supply systems.

The potential exists for the significant reduction of fossil fuel consumption for the supply of heat through the use of solar process heat, space heating and domestic hot water supply systems. Solar heat supply systems can be installed at the site of consumption, which guarantees a supply of energy to the consuming system. However, such systems cannot practically supply the entire heat demand of

Table 6.10. Primary energy embodied in the heat products of various supply systems

Energy Resource	End Use[a]	Overall Process Efficiency	End Use Conversion Efficiency	Location	Primary Energy Embodied in Energy Product[b]
Crude Oil[d]	p,s,d	0.954	0.60	no restriction	1.75
Coal[d]	p,s,d	0.977	0.60	"	1.71
Natural Gas[d]	p,s,d	0.829	0.85	"	1.42
Gasified Coal[d]	p,s,d	0.601	0.85	"	1.96
Electricity from Crude Oil[d]	p,s,d	0.279	0.95	"	3.77
Electricity from Coal[d]	p,s,d	0.288	0.95	"	3.65
Electricity from Natural Gas[d]	p,s,d	0.262	0.95	"	4.02
Electricity from Gasified Coal[d]	p,s,d	0.190	0.95	"	5.54
Solar Energy	p	3.63	1.00	southwest, west United States	0.28
Solar Energy[d]	d	2.32	1.00	Phoenix	0.43
Solar Energy[d]	p,s,d	5.47	1.00	West Germany	0.18
Electricity from Central Receiver Power Station[d]	p,s,d	3.32	0.95	southwest, west United States	0.30
Electricity from Nuclear Energy[d]	p,s,d	0.341 (7.89)[c]	0.95	no restriction	3.09 (0.13)[c]
Biomass[d]	p,s,d	5.74	0.60	"	0.29

Table 6.10. Continued

a - p ≡ process heat
d ≡ domestic hot water
s ≡ space heating

b - Values are calculated as follows:

$$\frac{1}{\text{overall process efficiency}} \cdot \frac{1}{\text{end-use conversion efficiency}}$$

c - See Table 6.6

d - System represents production and delivery of a fuel and does not include the end-use conversion facilities

the existing system due to thermal storage requirements. Furthermore, they suffer from locations restricted to the west and southwest regions of the United States. Electricity from central receiver power stations suffer from similar limitations. The combustion of biomass to produce process heat has no location or demand limitations, but the production of biomass cannot absorb large transportation requirements without a dramatic increase in the energy embodied in the heat produced. Thus, the use of biomass to supply heat is limited to relatively small areas with regard to the production site and the end-use site. Electricity from nuclear energy can effectively reduce the consumption of fossil fuels for the supply of heat without location or demand limitations. However, an increase in the supply of energy from nuclear power stations cannot be expected for at least 10 to 15 years from now. The combination of the above observations indicate the unavoidable use of coal for the supply of heat as the supply of natural gas and fuel oil begin to decline. The direct combustion of coal poses environmental problems and requires a large expenditure of energy for transportation, especially if used for the small-scale, decentralized supply of heat. Thus, the use of gasified coal appears to be the most viable alternative to the depleting resources of natural gas and fuel oil.

Third Level of Energy Analysis Implications

General Characteristics of a Future Energy Supply Scenario: Transition into a New Era

It is clear that the crude oil supply crisis now facing the United States is just the beginning of the decline of the fossil fuel energy supply era. However, the political and industrial sectors of this country are looking upon the vast domestic coal reserves as the solution to the crude oil supply crisis and not beyond the consumption of the vast, but indeed finite, coal reserves. The most essential feature of the energy policy adopted for this nation is the guarantee of the availability of adequate energy resources to allow the construction and implementation of the energy supply system or network of energy supply systems that will displace the need for fossil fuels. Furthermore, this energy supply system must have a sufficiently high energy gain with regard to the capital requirement factor in order to have the capacity to support a healthy industrial and, thus, economic growth. At the present stage of technological development, the only acceptable long-term energy supply system candidate is the breeder nuclear power plant. Even the breeder technology is a long way from commercialization due to safety design problems with regard to both operation of the plant and disposal of waste products (17). In addition to the technical problems associated with the breeder concept, enough public concern and political

pressures exist to have caused President Carter to cancel the plans to construct the first breeder reactor in the United States (17). In short, the technology to displace the need for fossil fuels does not presently exist and will probably not become available for at least another 20 to 30 years.

In 1979, the United States consumed 37 quads of crude oil, 20 quads of natural gas, 15 quads of coal, 2.75 quads of nuclear power and less than 1 quad of hydroelectric power and other energy resources (18). During the period from 1820 to 1979, the United States has consumed approximately 1095 quads of coal, leaving 3905 quads of the estimated 5000 quads of domestic recoverable coal reserves (22). Liquid fuels and synthetic pipeline gas can be produced from coal at energy gains of 6.7 and 25.8, respectively, with resource utilization factors of 1.49 and 1.63, respectively (1). Thus, the displacement of 37 quads of liquid fuels and 20 quads of natural gas will require the production of 94 quads of coal (assuming the energy subsidies required for the production of liquid fuels and synthetic gas must originate from coal as well). Note that the initial capital investment energy is neglected due to the small capital requirement factor of the systems {i.e., less that 0.01 (3)}. Assume that coal will displace crude oil and natural gas by the year 2010. This would require a coal production growth of 6.4 per cent annually and would

leave 2436 quads of the recoverable domestic reserves non-extracted. If the total domestic demand for energy did not increase above the 1979 consumption level, the coal reserves would be able to meet the demand for only 22 years beyond the year 2010, or a total of 53 years from the year 1979.

Furthermore, consider the energy that would be required to construct an energy supply system, based on the breeder nuclear reactor, capable of producing a net energy of 78 quads, the total United States' consumption in 1979 (18). The energy gain and capital requirement factor of a pressurized water reactor with 0.3 per cent tails assays and no recycle of fuel are 4.09 and 0.036, respectively (5). Assume the breeder reactor doubles the capital requirement factor and reduces the remaining energy subsidy by 80 per cent {due to a 98.6 per cent reduction in volume of fuel required (17)}. The energy gain and the capital requirement factor of the breeder power plant would be 8.8 and 0.072, respectively. An energy production rate of 86.9 quads per year would be required of the breeder energy supply system and 188 quads of coal would be required to construct the initial supply system (i.e., energy required for replacement of depreciated plants would be supplied by the breeder system itself) based on a system lifetime of 30 years. Thus, 8 per cent of the coal reserves remaining after the displacement of crude oil and natural gas with coal would be required to construct the breeder energy supply system.

The above calculations indicate that ample reserves presently exist to make the transition from fossil fuels to a long-term energy supply system. It is also clear that the United States faces an era of mandatory energy conservation if the industries are to grow (which is essential to a stable American economy) without increasing energy consumption. However, even if a zero energy consumption growth rate can be achieved, if coal is utilized to displace the depleting crude oil and natural gas resources, the time frame in which the long-term energy supply system must be developed and implemented is simply not adequate. Obviously, the most competent and responsible short-term energy policy (based on the presently available information) is based on the reduction of crude oil and natural gas consumption with an emphasis on the conservation of the domestic coal reserves. In other words, the United States must extend the life of its domestic crude oil and natural gas reserves without the extensive utilization of domestic coal and preferably without a dependence on foreign crude oil. This goal is obtainable through the implementation of short-term, high overall process efficiency alternative energy supply systems such as central receiver power stations, light water nuclear reactors, solar process and domestic heat, biomass, wind energy, ocean thermal energy, etc., which can significantly increase the effective efficiency of crude oil and natural gas consumption, and the implementation of mandatory

energy conservation practices emphasizing human labor instead of automation and decentralized manufacturing to reduce transportation requirements. These measures should be accompanied by the rapid expansion of coal production and the construction of facilities for the production of gaseous and liquid fuels from coal for the following reasons. The fabrication of building materials such as steel and concrete required for the construction of an energy supply system as well as the construction itself are highly energy intensive processes requiring electricity and liquid and gaseous fuels. The capability to produce these energy products from coal must exist in the event that crude oil and natural gas resources are depleted prior to the construction of a long-term energy supply system.

Dynamic Energy Analysis

Presently, the most important application of a dynamic energy analysis is the modeling of a transition era in which the net work of current energy supply systems changes through the implementation of alternative energy supply systems over a period of time. The change in the network of energy supply systems must be implemented utilizing the fixed fossil fuel resources. However, once an alternative energy supply system is producing energy, any of the system's energy outputs not consumed may be utilized as operational or capital energy subsidies for any other energy supply system. The structure of the

energy supply model is illustrated in Figure 6.1. The definitions of the model parameters are listed in Table 6.11.

To use the model, an initial network of energy supply systems {i.e., $mm(t_o,n)$}, an initial available energy {i.e., $e_{accumulation}(t_o)$} and the desired growth rate of all N energy supply systems are set. Note that in order to use a conventional growth rate, all systems must be initially present in some quantity. Also note that the energy resources are either fixed in magnitude and the rate of consumption is not limited (i.e., fossil and nuclear fuels) or the resource is renewable and the rate of consumption is limited (solar energies). The model has three independent variables, $e_{consumption}(t_i)$, $g(n)$ and $e_{accumulation}(t_i)$. Two variables are set and the other is calculated according to the constitutive relations and energy balances listed in Table 6.12 and Table 6.13., respectively.

Table 6.11. Definition of energy supply model parameters

Parameter	Definition
n	The nth energy supply system of N total energy supply systems. The energy subsidies and the energy output of each unit of the nth energy supply system are fixed and specified.
t_i (i=0,1,2...)	The specific year in the time span being evaluated.
t_c(n)	The period required for the construction of a unit of the nth energy supply system.
t_l(n)	The operational lifetime of a unit of of the nth energy supply system.
m(t_i,n)	The number of units of the nth energy supply system for which construction is begun at time t_i.
mm(t_i,n)	The number of mature units of the nth energy supply system at time t_i, requiring operational energy and producing an energy output.
mr(t_i,n)	The number of replacement units required for the nth energy supply system at time t_i requiring capital energy investment.
e_c(n)	The total capital energy subsidy of a unit of the nth energy supply system amortized over the construction period t_c(n). e_c(n) is the required input of m(t_i,n) and mr(t_i,n).

Table 6.11. Continued

Parameter	Definition
$e_{op}(n)$	The annual operational energy subsidy of a unit of the nth energy supply system. $e_{op}(n)$ is the required input of $mm(t_i,n)$.
$e_r(k,n)$	The specific (i.e., the kth) annual energy resource required by a unit of the nth energy supply system.
$e_{out}(n)$	The annual energy output of a unit of the nth energy supply system.
q(n)	Qualifier of the energy output of the nth energy supply system. q(n) indicates the appropriate consumption rate of the output of the nth energy supply system {i.e., a total energy consumption is specified for each year of the time span being evaluated and the consumption of the output of each system is specified as a portion of the total energy consumption according to q(n)}. However, any produced energy that is not consumed is delegated to an available energy reserve regardless of its qualifier.
g(n)	The growth rate of the nth energy supply system. g(n) is constant for each evaluation of the energy supply model.
$e_{consumption}(t_i)$	The total energy consumption for the year t_i.

Table 6.11. Continued

Parameter	Definition
$e_{excess}(t_i)$	The annual summation of all produced energies that are not consumed.
$e_{recycle}(t_i)$	The annual energy required for operational energy and investment energy.
$e_{accumulation}(t_i)$	The summation from time t_o to t_i of $e_{excess}(t_i) - e_{recycle}(t_i)$.

Table 6.12. Constitutive relationships for dynamic energy supply model

(1) $$mm(t_i,n) = \begin{cases} mm(t_o,n) \; ; \; t_i < t_c(n) \\ \{1 + g(n)\}^{t_i - t_c(n)} \cdot mm(t_o,n) \; ; \; t_i \geq t_c(n) \end{cases}$$

(2) $$m(t_i,n) = g(n)^{t_i} \cdot mm(t_o,n)$$

(3) $$mr(t_i,n) = \begin{cases} 0 \; ; \; t_i < t_l(n) \\ \{1 + g(n)\}^{t_i - t_l(n)} \cdot mm(t_o,n) \; ; \; t_l(n) + t_c(n) > t_i \geq t_l(n) \\ \left[\{1 + g(n)\}^{t_i - t_l(n)} - \{1 + g(n)\}^{t_i - t_l(n) - t_c(n)}\right] \cdot mm(t_o,n) \; ; \; t_i \geq t_l(n) + t_c(n) \end{cases}$$

Table 6.13. Energy balances for dynamic energy supply model

(1) $$\sum_{n=1}^{N} \{mm(t_i,n) \cdot e_{out}(n)\} = \sum_{n=1}^{N} \{e_{consumption}(t_i) \cdot q(n)\} + e_{excess}(t_i)$$

(2) $$e_{recycle}(t_i) = \sum_{n=1}^{N} \left[\{m(t_i,n) + mr(t_i,n)\} \cdot e_c(n) + mm(t_i,n) \cdot e_{op}(n) \right]$$

(3) $$e_{accumulation}(t_i) = e_{excess}(t_i) - e_{recycle}(t_i)$$

Key to Figure 6.1

a - energy resource
$mm(t_i,n) \cdot e_r(k,n)$

b - operational energy
$mm(t_i,n) \cdot e_{op}(n)$

c - investment energy
$\{m(t_i,n) + mr(t_i,n)\} \cdot e_c(n)$

d - energy consumption according to type of energy product
$e_{consumption}(t_i) \cdot q(n)$

e - excess energy
$e_{excess}(t_i)$

f - recycle energy
$e_{recycle}(t_i)$

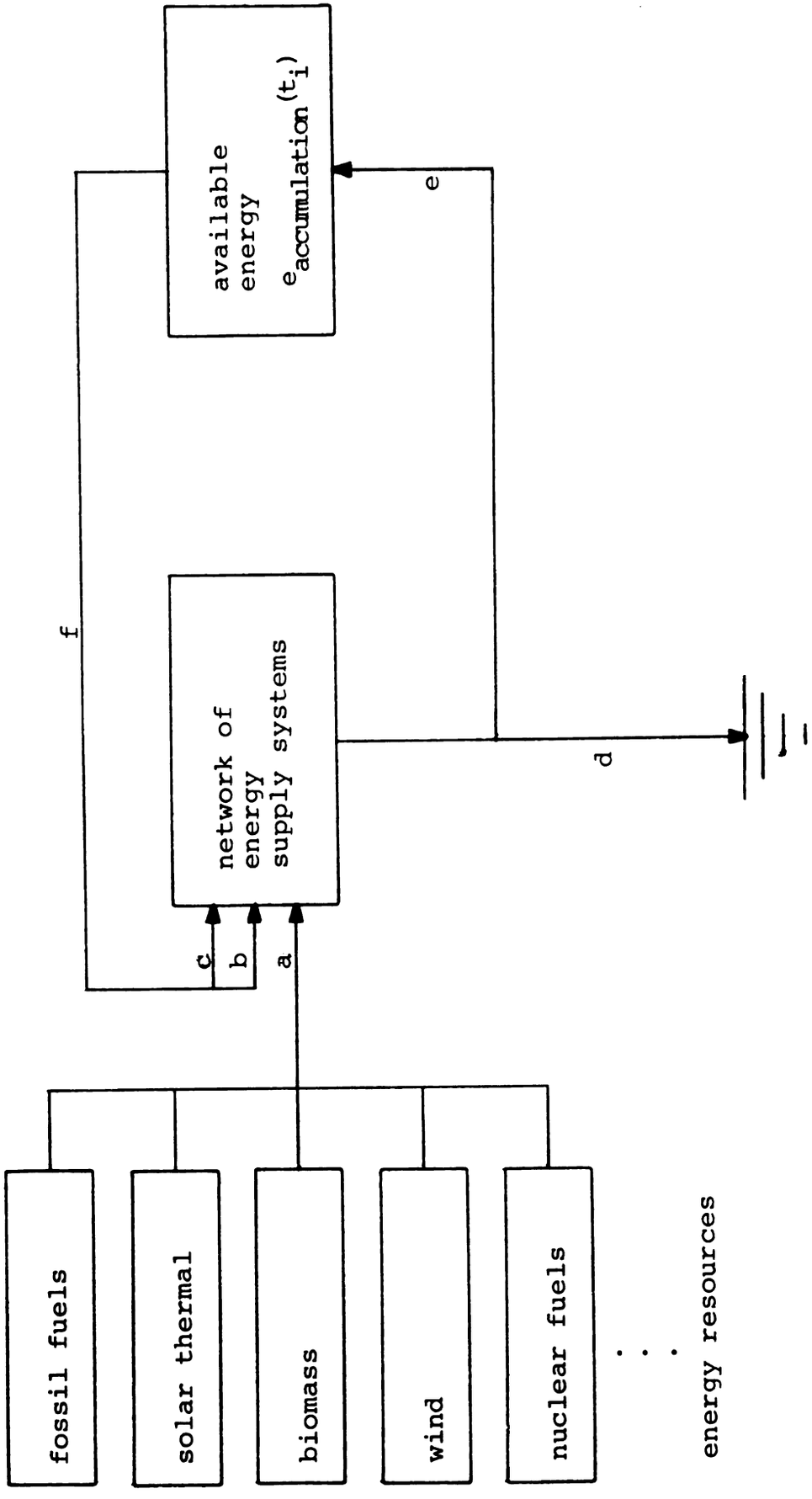


Figure 6.1. Energy Supply Model

The model may be operated by yearly increments calculating either $e_{accumulation}(t_i)$ or $e_{consumption}(t_i)$ by setting the growth rates and one of the other two independent variables and using the constitutive relationships and the energy balances. The desired behavior of the transition of the energy supply network is the maximum lifetime of fossil fuel resources (even at the expense of U^{235} depletion) with a sufficient $e_{accumulation}(t_i)$ to allow construction of the long-term energy supply system at an annual total energy consumption capable of sustaining the United States at an acceptable standard of living. The most effective transition can be found via trial and error. However, it should be possible to incorporate the described structure of the energy supply model into an existing systems management routine which translates the structure into a differential form and allows the injection of systematic policy adjustments until the desired goal is met. Such an effort is currently underway utilizing the systems management routine described by Forrester (19).

Recommendations for Further Efforts in Energy Analysis

Comments

The science of energy analysis lacks research efforts in its development, application and interpretation. The necessary research efforts in each area are discussed below.

Development

Currently, energy analysis relies on input-output theory to estimate the embodied energies of materials and energy products based on dollar interactions between the sectors of the economy. This interaction needs to be defined in terms of the physical flows of materials and energy rather than dollar flows to eliminate the large degree of uncertainty in the resulting energy intensity coefficients.

Application

In order to develop a competent energy policy, the energy parameters of all energy supply systems must be precisely and accurately defined. This requires not only the application of energy analysis to all configurations of the energy supply systems currently in existence, but to every proposed alternative energy supply system as well. Energy analysis needs to be institutionalized in the same manner as economic analysis, such that both tools are utilized in the development and evaluation of energy supply systems. Furthermore, the concepts of energy analysis should become a part of the educational process in the same manner as economic analysis, such that the parameters of energy analysis are as widely recognized and understood as those of economic analysis.

The application of energy analysis to energy supply systems is the most urgent task of the development of a

national energy policy. The energy parameters listed in this report are by and large based on isolated analyses and have no confirmation or an acceptable level of confidence. These parameters must be accurately known in order to develop an energy policy program.

Interpretation

The ultimate consequences of any proposed energy policy can only be predicted through a dynamic energy supply and demand model. Thus, an acceptable model and the analysis of that model must be developed and tested, followed by the evaluation of proposed energy policies based on the energy parameters of the systems utilized in those policies.

APPENDIX A

APPENDIX A

ENERGY ANALYSIS OF CENTRAL RECEIVER SOLAR THERMAL POWER STATIONS

General Approach

The capital required to construct, and the utilities and raw materials required to operate a proposed large scale energy supply system that is presently at the pilot plant or small scale stage of development, are based on operational data of the pilot plant or small scale system and theoretical calculations. The large degree of uncertainty that exists in the estimated capital, raw materials and utility requirements is propogated to an energy analysis based on those requirements. Thus, comparison between such proposed large scale energy supply systems and conventional energy supply systems based on the absolute values representing the results of the energy analyses is questionable. However, energy analysis can be used to screen various designs of a proposed alternative energy supply system in order to identify those designs with the best energy characteristics.

Alternative energy supply systems often require the fabrication of components that are at the prototype stage of development. Such prototype components are not products of the established industries included in the economic

structure of the United States (8). Thus, process analysis must be used to estimate the energy embodied in these components. The rigorous extension of process analysis to prototype components requires the estimation of utility, raw material and capital requirements of a conceptual manufacturing process. Such studies generally do not exist. Furthermore, if such a study is found, it is most often too incomplete to serve as the basis for an extension of process analysis.

A Central Receiver Solar Thermal Power Station (abbreviated as CRSTPS) is a proposed large scale energy supply system presently at the pilot plant stage of development and requires the fabrication of components (i.e., heliostats, receivers and towers) that are at the prototype stage of development. For convenience, the energy analysis of the CRSTPS is divided into two phases, estimation of the energy embodied in the prototype components and the energy analysis of the system itself. Data describing an envisioned process for the manufacture of heliostats, receivers and towers are not available. Information obtained from the disaggregation of energy intensity coefficients is used to extrapolate manufacturing data from established industries (considered to utilize manufacturing techniques similar to those envisioned for the manufacture of the prototype components) and allow the extension of process analysis.

The operation of a CRSTPS is similar to a conventional power station in that steam is produced to drive a

turbogenerator that generates electricity. In order to collect enough solar radiation (as heat) to produce steam of a sufficient quality to drive conventional turbogenerators, concentration ratios similar to parabolic dish concentrating solar collectors are required. A field of heliostats focused on a single receiver are utilized to approximate the reflective surface of an enormous parabolic dish. The total reflective surface area required to supply heat for the operation of a power station is a function of the efficiency of the heliostat field for the production of electricity for a specific end use (i.e., peak, intermediate or base load electricity).

The solar radiation collection subsystem of the CRSTPS (including the heliostats, receivers and towers) comprisesa large fraction of the total capital investment of the system. The design of the total solar radiation collection subsystem is strongly influenced by the design of the heliostats and the layout of the heliostat fields, which also determine the efficiency of the collector field. This is the area in which the major variations in system designs of a CRSTPS are found. A trade-off occurs in capital cost reduction by either maximizing the efficiency of the collector field, thus minimizing the total reflective surface area required, or by minimizing the cost of the components of the collector field, which lowers the efficiency of the collector field and increases the total reflective surface area required.

The high efficiency collector field requires the heliostat to have low optical losses (i.e., a high quality reflective surface) and optimal focusing properties. The better the focusing properties, the smaller the area and depth (referred to as the focal point region) of the image produced by the field are. Furthermore, the smaller the reflective surface area per receiver, the smaller the focal point region. The efficiency of the receiver is influenced by its ability to contact the entire image at the focal point on an absorbing surface with minimal reflective losses. The image, which in reality defines a region rather than a point, is most efficiently absorbed by a cavity receiver. However, if the image becomes too large, the size of a suitable cavity receiver would be impractical forcing the use of an open absorber receiver. The efficiency of a reflective surface decreases as the angle between the incident solar radiation and the normal to the reflective surface increases (referred to as cosine losses). Cosine losses can be minimized by positioning the field only in one quadrant of the area surrounding the receiver requiring smaller heliostat fields. Thus, the high efficiency collector field approach to system design utilizes a high quality reflective surface (including optical and focusing properties) and optimal reflective surface area to receiver ratio to allow proper field geometry and positioning along with the use of cavity receivers. The lower efficiency collector field uses a lower

quality reflective surface and fewer receivers and towers (and perhaps open absorber receivers).

Two system designs are analyzed that reflect the two approaches to collector field design. The high efficiency collector field system is described in a design evaluation (design report 1) performed by Martin Marietta (1) and the lower efficiency collector field system is described in a design evaluation (design report 2) performed by the Mitre Corporation (2).

Description of Data

Comments

The data required for both phases of energy analysis (i.e., estimation of the energy embodied in the prototype components and the analysis of the entire system) are taken from the design report describing the system under analysis.

High Efficiency Collector System

The data describing the system based on the high efficiency collector system are contained in a system evaluation performed by the Martin Marietta Corporation (1) (i.e., design report 1). The data describing the prototype components are presented as the conventional components required to manufacture the prototype components in terms of 1977 dollars. The remaining components required by the system are also presented in terms of 1977 dollars.

The general facilities (i.e., buildings, roads, etc.) are reported as a single subcontracted item in terms of the purchaser's price in 1977 dollars. This dollar value represents all energies embodied in the general facilities including transportation requirements, equipment, direct energy usage and required raw materials. The dollar values reported for the components of the system represent the energy embodied in the delivered component only. The energy required for the installation of components (other than the general facilities) is estimated from information available from the disaggregation of energy intensity coefficients.

The raw materials required for the operation of the system (not to be confused with the raw materials required to construct the system) are either negligible or they are included in the maintenance allowance of the system (excluding the thermal storage materials). The thermal storage materials required during the lifetime of the system are reported in terms of separate costs for the non-delivered materials (i.e., the producer's cost) and the delivery requirement in 1977 dollars. The maintenance allowance is reported as an annual expenditure that is assumed to represent the purchaser's cost for maintenance services (similar to the subcontracted cost for the general facilities) in 1977 dollars. The utility requirement of the system is reported as a percentage of the system's electrical output that is fed back to the system.

Lower Efficiency Collector System

The data describing the system based on the lower efficiency collector system are contained in a system evaluation performed by the Mitre Corporation (2) (i.e., design report 2). The data describing the prototype components are presented as the purchaser's cost of materials required to manufacture the prototype components in 1976 dollars. The remaining system components are presented as the purchaser's cost of the components in 1976 dollars. The data describing the general facilities and the maintenance requirements are presented in the same manner as indicated in design report 1, in 1976 dollars. The energy required for the installation of components is estimated from information available from the disaggregation of energy intensity coefficients. There are no reported raw material requirements (i.e., raw materials not included in the maintenance allowance) or utility requirements.

Determination of Energy Embodied in Prototype Components

General Approach for Extension of Process Analysis to Prototype Component Manufacturing Systems

The only data available are the producer's prices of components or materials required to manufacture the heliostats, receivers and towers (i.e., the raw material requirements). The purchaser's prices are modified to producer's prices that are converted to embodied energies. The remaining energy inputs of utilities (direct energy usage) and energy requirements for capital facilities, services, trade

and transportation are estimated from the energy embodied in the non-delivered raw materials using information obtained from the disaggregation of the energy intensity coefficient of a similar (referred to as an analogous) industry that is one of the 357 producing economic sectors (8). This procedure allows the estimation of the energy embodied in a non-delivered product. The delivery of the prototype component to the system site is assumed to be accomplished by truck transportation {requiring 7,000 Btu primary/ton-mile (4)}. The distance of delivery is varied in order to evaluate the sensitivity of the energy parameters to the transportation requirements. The analogous industries assumed for the manufacture of the prototype components are listed in Table A.1.

Table A.1. Analogies between manufacture of prototype components and established industries

Prototype Component	Analogous Industry	I-O Sector
Heliostat	Auto Industry	5903
Receiver	Boiler Shops	4006
Tower	New Construction	1103

Note that the analogy between heliostat manufacture and the auto industry is made to incorporate the mass manufacturing energy intensity into the heliostat. The Department of Energy is considering mass manufacturing techniques as tools for cost reduction in the production of heliostats.

Definition of Nameplate Processing Systems Responsible for the Manufacture of Prototype Components

The extension of process analysis to the manufacture of the prototype components includes the system that fabricates the component and the system that delivers the component. The definition of the nameplate processing systems responsible for the manufacture and delivery of the prototype components are shown in Figure A.1.

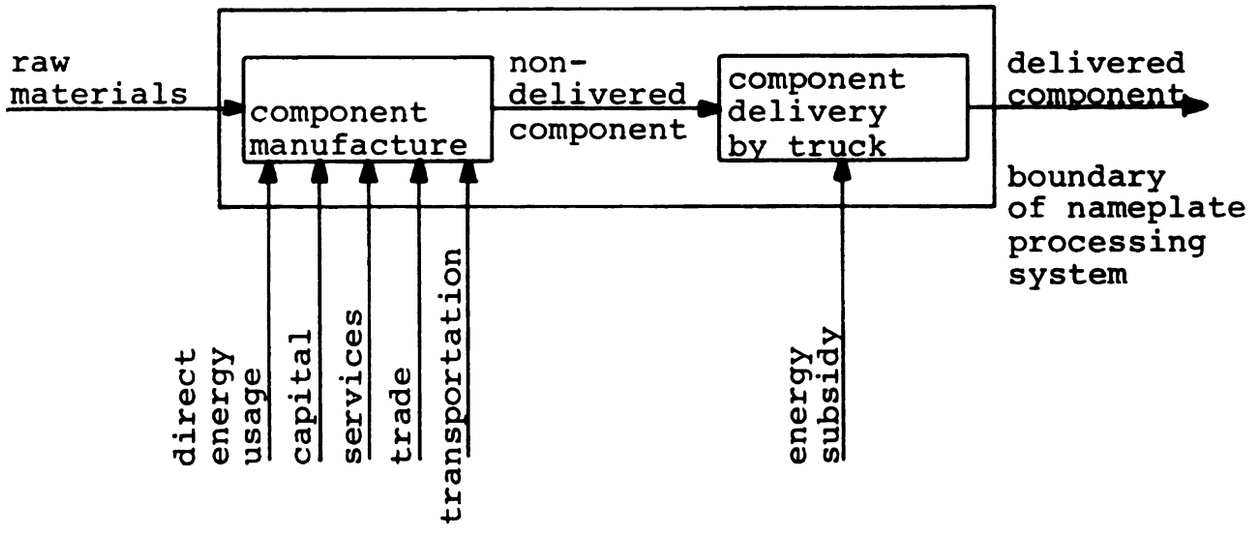


Figure A.1. Definition of nameplate processing system for manufacture of prototype component

Application of Process Analysis to the Prototype Component Manufacturing Systems

Comments

Process analysis is used to determine the raw material requirements for fabrication of the prototype components and the energy required for component delivery.

Heliostats

Raw material requirements

Tables A.2 and A.3 list the raw material requirements for fabrication of the 23,310 heliostats described in design report 1 and one heliostat described in design report 2, respectively.

Delivery requirements

Perry, et al., (4) report private, inter-city truck transportation to require 7000 Btu primary energy per ton-mile of work. The mass manufactured and delivered portions of the 23,310 heliostats described in design report 1 (i.e., the mirror assembly and the support structure) and the 22,500 heliostats described in design report 2 (excluding concrete, sand and the cone and assuming that the tracking and drive mechanism of each heliostat weighs 500 lbs.) are 60,650 tons (1) and 29,273 tons (2), respectively. Table A.4 lists the transportation energy requirements as a function of the transportation distance for the delivery of the heliostats.

Table A.2. Raw materials required for fabrication of the 23,310 heliostats described in design report 1 (1)

Component	Purchaser's Price ($\times 10^6$ \$1977)	I-O Sector
Mirror	9.010	3501
Mirror Assembly	35.400	4004
Heliostat Support Structure	30.800	4004
Azimuth Drive Assembly	19.300	4905
Elevation Drive Assembly	16.920	4905
Motors	4.640	5304
Position and Limit Indicators	5.740	5305
Power Distribution Equipment from Electric Plant	1.940	5308
Calibration Equipment*	0.810	6201
Field Control Electronics*	10.300	5308
Computer Hardware*	0.100	5101
Signal Distribution Equipment and Wiring*	0.410	5308
Foundation*	6.080	3610
Site Preparation*	0.200	1103

*Considered on site installation, not assembled at manufacturing site. Appropriate trade and transportation margins are those for sales to final demand.

Table A.3. Raw materials required for fabrication of one heliostat described in design report 2 (2)

Material	Purchaser's Price ($ 1976)	I-O Sector
Glass	551	3501
Support	309	4004
Hub	105	4004
Concrete*	100	3610
Low carbon steel	36	4004
Silver	20	3805
Adhesive	25	2704
Acrylic	20	2801
Cone*	137	4006
Sand*	17	900
Tracking & drive	780	4905

*See Table A.2

Table A.4. Energy required for heliostat delivery

Transportation Distance (Miles)	Transportation Energy ($\times 10^9$ Btu Primary) Design Report 1	Design Report 2
100	42	20
500	212	102
1,000	425	205

Receivers

Raw material requirements

The system of piping through which the working fluid is transported to and from the receiver (referred to as risers and downcomers) can be included in either the receiver or tower raw material requirements. The risers and downcomers are reported with the receivers in design report 1 and with the towers in design report 2. Tables A.5 and A.6 list the raw material requirements for the fabrication of the 15 receivers described in design report 1 and the 3 receivers described in design report 2, respectively.

Delivery requirements

A cost of $730,000 (1977) is reported in design report 1 for the delivery of the receivers (1). The price deflator for services is 1.883 $1977/$1967 (7), and the energy intensity coefficient for the truck transportation sector (6503) is 54,968 Btu primary per $1967 producer's price (5). The trade and transportation margins for sales to final demand are zero for sector 6503 (5). The energy required for receiver delivery as described in design report 1 is calculated to be 21×10^9 Btu primary. The total weight of the three receivers described in design report 2 is 1200 tons (2). Table A.7 lists the energy required for delivery of the three receivers described in design report 2 as a function of the transportation distance.

Table A.5. Raw materials required for fabrication of the 15 receivers described in design report 1 (1)

Component	Purchaser's Price ($\times 10^6$ \$1977)	I-O Sector
Absorber	2.540	4006
Drum	0.400	4006
Doors, casing, lining and insulation	1.940	4006
Piping	1.880	4208
Support structure, platform*	5.520	4004
Instrumentation and control*	1.150	5305
Riser and horizontal piping to receiver*	8.610	4208
Field erections and installation*	4.250	1103

*See Table A.2

Table A.6. Raw materials required for fabrication of the 3 receivers described in design report 2 (2)

Material	Purchaser's Price ($\times 10^6$ \$1976)	I-O Sector
Tubing	3.600	4208
Support structure	0.375	4006
Insulation	0.900	3620

Table A.7. Energy required for delivery of receivers described in design report 2

Transportation Distance (Miles)	Transportation Energy ($\times 10^9$ Btu primary)
100	1
500	4
1000	8

Towers

Raw material requirements

Tables A.8 and A.9 list the raw materials required for fabrication of the 15 towers described in design report 1 and the 3 towers described in design report 2, respectively.

Table A.8. Raw materials required for fabrication of the 15 towers described in design report 1 (1)

Component	Purchaser's Price ($\times 10^6$ \$1977)	I-O Sector
Tower and platform	26.660	4004
Tower foundation and site preparation	4.800	3610

Table A.9. Raw material requirements for fabrication of the 3 towers described in design report 2 (2)

Material	Purchaser's Price ($\times 10^6$ \$1976)	I-O Sector
Steel structure	1.500	4004
Concrete	3.000	3610
Slip forms	1.500	3611
Risers and downcomers *	0.072	4208

*See Table A.2.

Delivery requirements

The towers are assumed to be constructed at the system site. Thus, the towers do not have a delivery requirement.

Application of Input-Output Analysis to Prototype Component Manufacturing Systems

Comments

Input-Output analysis is used to calculate the energy embodied in the non-delivered raw materials required for fabrication of prototype components.

Heliostats

Tables A.10 and A.11 list the deflation of heliostat cost data, Table A.12 lists the required trade and transportation margins, and Tables A.13 and A.14 list the producer's prices and the embodied energies of raw materials required for heliostat fabrication. Note that the trade and transportation margins for sales to the auto industry are appropriate for raw materials used at the manufacturing site.

Table A.10. Deflation of heliostat cost data reported in design report 1

I-O Sector	Purchaser's Price (x 10^6 $1977)	$1977/$1967 (7)	Purchaser's Price (x 10^6 $1967)
3501	9.010	1.647	5.471
4004	66.200	2.120	31.226
4905	36.220	1.958	18.498
5304	4.640	1.774	2.616
5305	5.740	1.774	3.236
5308	1.940	1.774	1.094
5101*	0.100	1.023	0.098
5308*	10.710	1.774	6.037
6201*	0.810	1.370	0.591
3610*	6.080	1.838	3.308
1103*	0.200	2.165	0.092

*See Table A.2.

Table A.11. Deflation of heliostat cost data reported in design report 2

I-O Sector	Purchaser's Price ($1976)	$1976/$1967 (7)	Purchaser's Price ($1967)
2704	25	2.575	9.709
2801	20	1.583	12.634
3501	551	1.603	343.731
3805	20	2.977	6.718
4004	450	1.953	230.415
4905	780	1.520	513.158
900*	17	1.674	10.155
3610*	100	1.721	58.106
4006*	137	1.953	70.148

*See Table A.2.

Table A.12. Trade and transportation margins

I-O Sector	6501	6503	6504	6505	6506	6901	6902	Totals
			(Sales to Auto-Industry) (6)					
2704	4.1	3.7	0.0	0.0	0.0	5.9	0.0	13.7
2801	1.6	2.4	0.0	0.0	0.0	3.2	0.0	7.2
3501	1.5	1.4	0.0	0.0	0.0	12.3	0.0	15.2
3805	0.6	0.6	0.0	0.0	0.0	1.7	0.0	2.9
4004*	3.0	2.0	0.0	0.0	0.0	5.0	0.0	10.0
4905	0.0	0.0	0.0	0.0	0.0	8.0	0.0	8.0
5304	0.0	0.8	0.0	0.0	0.0	2.1	0.0	2.9
5305*	0.0	0.0	0.0	0.0	0.0	5.0	0.0	5.0
5308*	0.0	0.0	0.0	0.0	0.0	3.0	0.0	3.0
			(Sales to Final Demand) (5)					
900	15.0	9.0	8.0	0.0	0.0	0.0	0.0	32.0
1103	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3610	0.0	4.0	0.0	0.0	0.0	19.0	0.0	23.0
4006	1.0	1.0	0.0	0.0	0.0	4.0	0.0	6.0
5101	0.0	0.0	0.0	0.0	0.0	5.0	1.0	6.0
5308	0.0	0.0	0.0	0.0	0.0	3.0	0.0	3.0
6201	0.0	0.0	0.0	0.0	0.0	7.0	0.0	7.0

*No interaction with auto-industry, margins for sales to final demand used

Table A.13. Producer's prices and embodied energies of raw materials required for fabrication of the 23,310 heliostats described in design report 1

I-O Sector	Producer's Price ($\times 10^6$ \$1967)	Btu Primary / \$1967 (5)	Embodied Energy ($\times 10^9$ Btu Primary)
3501	4.639	107405	498
4004	28.103	131635	3699
4905	17.018	63646	1083
5304	2.540	67105	170
5305	3.074	41307	127
5308	1.061	63182	67
6501	1.019	92917	95
6503	0.437	54968	24
6901	2.459	37501	92
1103*	0.092	85922	8
3610*	2.547	148220	378
5101*	0.092	40810	4
5308*	5.856	63182	370
6201*	0.550	48425	27
6503*	0.417	54968	23
6901*	2.361	37501	89
6902*	0.001	37329	0

*See Table A.2

Table A.14. Producer's prices and embodied energies of raw materials required for fabrication of one heliostat described in design report 2

I-O Sector	Producer's Price ($1967)	Btu Primary / $1967 (5)	Embodied Energy (x 10^6 Btu Primary)
2704	8.379	185521	1.588
2801	11.724	226289	2.653
3501	291.484	107405	31.306
3805	6.523	164813	1.075
4004	207.374	131635	27.298
4905	472.105	63646	30.048
6501	12.709	92917	1.181
6503	10.123	54968	0.556
6901	95.944	37501	3.598
700*	6.905	114908	0.793
3610*	44.742	148220	6.632
4006*	65.939	111172	7.331
6501*	2.225	92917	0.207
6503*	3.940	54968	0.217
6504*	0.812	262498	0.213
6901*	13.846	37501	0.519

*See Table A.2

Receivers

Tables A.15 and A.16 list the deflation of the receiver cost data, Table A.17 lists the required trade and transportation margins and Tables A.18 and A.19 list the producer's prices and embodied energies of the raw materials required for receiver fabrication. Note that the appropriate trade and transportation margins for raw materials required at the manufacturing site are those for sales to the boiler shop industry.

Table A.15. Deflation of receiver cost data reported in design report 1

I-O Sector	Purchaser's Price ($\times 10^6$ \$1977)	$\frac{\$1977}{\$1967}$ (7)	Purchaser's Price ($\times 10^6$ \$1967)
4006	4.880	1.977	2.468
4208	1.880	2.461	0.764
4208*	8.610	2.461	3.499
4004*	5.520	2.120	2.604
5305*	1.150	1.774	0.648
1103*	4.250	2.165	1.963

*See Table A.2

Table A.16. Deflation of receiver cost data described in design report 2

I-O Sector	Purchaser's Price ($\times 10^6$ $1976)	$\frac{\$1976}{\$1967}$ (7)	Purchaser's Price ($\times 10^6$ 1967)
3620	0.900	1.808	0.498
4006	0.375	1.953	0.192
4208	3.600	2.365	1.522

Table A.17. Trade and transportation margins

I-O Sector	6501	6503	6505	6506	6901	6902	Totals
(Sales to Boiler Shop Industry) (6)							
3620	8.3	0.0	0.0	0.0	8.3	0.0	16.6
4006	0.9	0.6	0.0	0.0	1.9	0.0	3.4
4208	0.3	1.2	0.0	0.0	11.2	0.0	12.7
(Sales to Final Demand) (5)							
1103	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4208	0.0	1.0	0.0	0.0	11.0	0.0	12.0
4004	3.0	2.0	0.0	0.0	5.0	0.0	10.0
5305	0.0	0.0	0.0	0.0	5.0	0.0	5.0

Table A.18. Producer's prices and embodied energies of raw materials required for fabrication of the 15 receivers described in design report 1

I-O Sector	Producer's Price ($\times 10^6$ \$1967)	Btu Primary / \$1967 (5)	Embodied Energy ($\times 10^9$ Btu Primary)
4006	2.384	111172	265
4208	0.667	78483	52
6501	0.025	92917	2
6503	0.024	54968	1
6901	0.132	37501	5
1103*	1.963	85922	169
4208*	3.079	78483	242
4004*	2.344	131635	309
5305*	0.616	41307	25
6501*	0.078	92917	7
6503*	0.087	54968	5
6901*	0.547	37501	21

*See Table A.2

Table A.19. Producer's prices and embodied energies of raw materials required for fabrication of the three receivers described in design report 2

I-O Sector	Producer's Price (x 10^6 $1967)	Btu Primary / $1967 (5)	Embodied Energy (x 10^9 Btu Primary)
3620	0.415	162859	68
4006	0.185	111172	21
4208	1.329	78483	104
6501	0.048	92917	4
6503	0.019	54968	1
6901	0.215	37501	8

Towers

Tables A.20 and A.21 list the deflation of tower cost data, Table A.22 lists the required trade and transportation margins and Tables A.23 and A.24 list the producer's prices and embodied energies of the raw materials required for tower fabrication. Note that the trade and transportation margins for sales to the new construction industry are appropriate for raw materials required at the manufacturing site.

Table A.20. Deflation of tower cost data reported in design report 1

I-O Sector	Purchaser's Price (x 10^6 $1977)	$\frac{\$1977}{\$1967}$ (7)	Purchaser's Price (x 10^6 $1967)
3610	4.800	1.838	2.612
4004	26.660	2.120	12.575

Table A.21. Deflation of tower cost data reported in design report 2

I-O Sector	Purchaser's Price (x 10^6 $1976)	$\frac{\$1976}{\$1967}$ (7)	Purchaser's Price (x 10^6 $1967)
3610	3.000	1.721	1.743
3611	1.500	1.721	0.872
4004	1.500	2.050	0.732
4208*	0.072	2.374	0.030

*See Table A.2

Trade A.22. Trade and transportation margins

I-O Sector	6501	6503	6504	6505	6506	7004	6901	6902	Totals
				(sales to new construction) (9)					
3610	0.6	4.1	0	0	0	0	18.2	3.9	26.8
3611	0.1	0.1	0	0	0	0	10.8	4.5	15.5
4004	2.6	2.1	0	0.4	0	0	4.3	0	9.4
				(sales to final demand) (5)					
4208	0	1	0	0	0	0	11	0	12

Table A.23. Producer's prices and embodied energies of raw materials required for fabrication of the 15 towers described in design report 1

I-O Sector	Producer's Price (x 10^6 $1967)	Btu Primary / $1967 (5)	Embodied Energy (x 10^9 Btu Primary)
3610	1.912	148220	283
4004	11.393	131635	1500
6501	0.343	92917	32
6503	0.371	54968	20
6505	0.050	222024	11
6901	1.016	37501	38
6902	0.102	37329	4

Table A.24. Producer's prices and embodied energies of raw materials required for fabrication of the three towers described in design report 2

I-O Sector	Producer's Price ($\times 10^6$ \$1967)	Btu Primary / \$1967 (5)	Embodied Energy ($\times 10^9$ Btu Primary)
3610	1.276	148,220	189
3611	0.737	113,661	84
4004	0.663	131,635	87
6501	0.030	92,917	3
6503	0.088	54,968	5
6505	0.003	222,024	1
6901	0.443	37,501	17
6902	0.107	37,329	4
4208*	0.026	78,483	2
6503*	0.000	54,968	0
6901*	0.003	37,501	0

*See Table A.2

Summary of the application of input-output analysis to prototype component manufacturing systems

Table A.25 lists the energies embodied in the non-delivered raw materials required at the manufacturing and the system sites, and the delivery energy requirements for distribution of the raw materials to the respective sites.

Table A.25. Summary of results of input-output analysis applied to prototype components

Prototype Component	Design Report	Number of Units	Embodied Energy ($\times 10^9$ Btu Primary)			
			Raw Materials Required at Manufacturing Site		Raw Materials Required at System Site	
			Energy Embodied in Non-delivered Materials	Delivery Energy	Energy Embodied in Non-delivered Materials	Delivery Energy
Heliostats	1	23,310	5645	211	786	111
	2	22,500	2114	120	332	26
Receivers	1	15	317	8	745	33
	2	3	193	13	---	---
Towers	1	15	1783	105	---	---
	2	3	360	30	2	0

Application of the Disaggregation of the Energy Intensity Coefficients to Prototype Component Manufacturing Systems

Tables A.26, A.27 and A.28 list the percentages of the total energy input of the analogous industries required for utilities (direct energy usage), capital, materials, services, trade and transportation (3). By assuming the energy embodied in the non-delivered raw materials required at the manufacturing site for fabrication of the prototype components represents the materials energy input, the remaining energy inputs can be estimated. Table A.29 lists the energy embodied in the non-delivered prototype components fabricated at the manufacturing site.

Table A.26. Disaggregation of the auto-industry's energy intensity coefficient (sector 5903) (3)

Component	% Total Energy Requirement
Direct Energy Usage	15.45
Capital	3.23
Materials	72.30
Transportation	1.52
Services	4.39
Trade	1.73

Table A.27. Disaggregation of the boiler shop industry's energy intensity coefficient (sector 4006) (3)

Component	% of Total Energy Requirement
Direct Energy Usage	11.77
Capital	1.86
Materials	80.92
Transportation	1.14
Services	2.77
Trade	1.44

Table A.28. Disaggregation of the new construction industry's energy intensity coefficient (sector 1103) (3)

Component	% of Total Energy Requirement
Direct Energy Usage	20.77
Capital	2.62
Materials	65.34
Transportation	2.31
Services	4.21
Trade	4.75

Table A.29. Energy embodied in non-delivered prototype components fabricated at the manufacturing site

Component	Design Report	# of Units	Embodied Energy ($\times 10^9$ Btu Primary)	
			Non-delivered Raw Materials Required at Manufacturing Site	Non-delivered Component Fabricated at Manufacturing Site
Heliostats	1	23,310	5645	7808
	2	22,500	2114	2924
Receivers	1	15	317	392
	2	3	193	239
Towers	1	15	1783	2729
	2	3	360	551

Definition of the Nameplate Processing System

The nameplate processing system is defined to be the Central Receiver Solar Thermal Power Station. The system consists of the heliostat field, controls for the operation of the heliostat field, receivers, towers, the electric plant subsystem, thermal heat storage subsystem, facilities required for transportation of energy and materials between solar energy collection (i.e., heliostats, receivers and towers), electric plant and thermal storage subsystems, and required general facilities. The inputs to the system are the required capital, a feed of solar radiation and raw materials consisting of the working fluid, thermal storage materials and maintenance supplies. The system does not require an external supply of utilities. The output of the system is a non-distributed supply of intermediate to peak load electricity.

Application of Process Analysis

Comments

The inputs and outputs of the systems are quantitatively identified according to the categories outlined in Chapter 3.

Inputs

Inputs 1-3 and 8-10

The energies embodied in the delivered, non-installed heliostats, receivers and towers (including the component

fabricated at the manufacturing site and additional materials required at the system site) are estimated by extending process analysis to conceptualized manufacturing systems. The remaining components and general facilities comprising the balance of the system are listed in Tables A.30 and A.31. The energy required for the installation of components is estimated using information obtained from the disaggregation of the new construction industry's energy intensity coefficient.

Table A.30. Remaining components and general facilities required by the system described in design report 1 (1)

Component	Purchaser's Price ($\times 10^6$ \$1977)	I-O Sector
Thermal Storage		
Storage tanks & heaters	14.050	4006
Insulation	3.460	3620
Piping and supports	4.210	4208
Valves, strainers, filters	2.040	4208
Pumps	1.030	4901
Steam drums	0.190	4006
Heat exchangers	18.570	4006
Attemperators	0.040	4006
Support structure	0.140	4004
Instrumentation & control	0.220	5305
Foundations	0.080	3610
Safety protection equipment	0.080	5305
Turbine plant equipment		
Turbine generator	15.600	4301
Foundations	0.120	3620
Standby exciters	0.010	4907
Lubricating system	0.010	4907
Weather-proof housing	0.130	4006
Heat rejection equipment	4.050	4006
Condensing systems	1.500	4006
Regenerative heat exchangers	0.510	4006
Pumps	0.250	4901
Piping and tanks	0.400	4208
Water circulation/treatment systems	0.620	4907
Electric plant equipment		
Generator circuits	0.270	5303
Station service & startup transformers	0.810	5302
Auxiliary power sources	0.120	5304
Switchboards	0.020	5303
General station grouping systems	0.180	5305
Fire protection equipment	0.020	4907
Cathodic and freeze protection	0.100	5308
Electrical structure and wiring containers	0.720	5308
Power wiring	0.190	5308

Table A.30. Continued

Component	Purchaser's Price (x 10^6 $1977)	I-O Sector
Master control		
Computer	0.060	5101
Peripheral equipment	0.040	5305
Control panels and boards	0.490	5305
Interface equipment	0.120	5305
Control wiring	0.130	5308
Miscellaneous plant equipment		
Transportation & lifting equipment	1.200	4604
Air & water service systems	0.800	4907
Communication equipment	0.070	5604
Furnishings & fixtures	0.200	2307
Transmission plant equipment	0.420	5308
Other		
Contractor field office supplies*	0.910*	1103
Temporary construction*	2.440*	1103
Construction equipment	3.420	4501
Construction services	5.000	1103
Spare parts	2.050	4907
Yard work*	3.370*	1103
Turbine building*	0.800*	1103
Ad/control building*	0.800*	1103
Maintenance/warehouse building*	0.380*	1103
Fire pumphouse*	0.030*	1103
Condensate pumphouse*	0.020*	1103
Gate house*	0.010*	1103

*Represents a contract cost for services including materials, direct energy usage and capital required to construct the facility.

Table A.31. Remaining components and general facilities required by the system described in design report 2 (2)

Component	Purchaser's Price ($\times 10^6$ \$1976)	I-O Sector
Thermal storage (steel ingots)	23.940	4006
Turbogenerator	15.000	4301
Control system	9.500	5305
Electric plant	0.750	5308
Master control center*	0.250*	1103
Maintenance yard*	0.500*	1103
Waste treatment*	0.300*	1103
Motor pool (including vehicles)	0.200	5903
Rail heat	0.500	6104
Service road*	1.000*	1103
Land preparation*	3.500*	1103
Spare parts	5.000	4907
Cooling tower	7.000	4006

*See Table A.30

Inputs 4-5

The feed required by both systems is solar radiation. Neither system requires an external supply of utilities. The raw materials required by system 1 during the lifetime of the system are listed in Table A.32. The system described in design report 2 does not require raw materials in addition to maintenance supplies.

Table A.32. Raw materials required by the system described in design report 1 (1)

Raw Material	Producer's Price ($\times 10^6$ \$1977)	I-O Sector
Thermal storage material	8.670	2701
Delivery cost	1.550	6503

Inputs 6-7

Neither system reports secondary or waste products requiring additional handling not included in the general facilities. The output of both systems is non-delivered electricity.

Input 11

Table A.33 lists the annual expenditure for the maintenance of each system. The trade and transportation margins for the maintenance and repair sector (sector 1202) for sales to final demand are zero. Thus, the purchaser's

prices reported in the design reports are equal to the producer's prices for the maintenance services.

Table A.33. Maintenance requirements

Design Report	Producer's Prices	I-O Sector
1	2.385×10^6 $1977/year	1202
2	2×10^6 $1976/year	1202

Outputs

A portion of the electricity produced in each system must be fed back for operation of the system. The system described in design report 1 requires a maximum electrical utility feedback of four per cent of the system's gross electrical output. The electrical feedback required by the system described in design report 2 is not reported and is assumed to be four per cent of the gross electrical output as well. Table A.34 lists the energy outputs of each system.

Table A.34. Energy outputs of systems

Design Report	Rated Output MW(e)	Capacity Factor	Gross Energy Output ($\times 10^9$ Btu/yr)	Energy Output ($\times 10^9$ Btu/yr)
1	150	0.5	2242	2153
2	100	0.5	1495	1435

Application of Input-Output Analysis

Note that input-output analysis is applied to both annual and lifetime cost data. These data are analyzed separately to study the sensitivity of each system's energy characteristics to the system's lifetime. Table A.35 and Table A.36 list the deflation of cost data, Table A.37 lists the required trade and transportation margins, and Table A.38 and Table A.39 list the producer's prices and embodied energies of the remaining components, general facilities and maintenance requirements. Table A.40 lists a summary of the application of input-output analysis.

Table A.35. Deflation of cost data reported in design report 1

I-O Sector	Purchaser's Price (x 10^6 $1977)	$1977 / $1967 (7)	Purchaser's Price (x 10^6 $1967)
	(lifetime cost data)		
1103*	13.760	2.165	6.356
2307	0.200	1.788	0.112
2701**	8.670	1.905	4.551
3610	0.080	1.838	0.044
3620	3.580	1.705	2.100
4004	0.140	2.120	0.066
4006	39.040	1.977	19.747
4208	6.650	2.461	2.702
4604	1.200	1.964	0.611
4901	1.280	1.730	0.740
4907	3.510	1.932	1.817
5101	0.060	1.023	0.059
5302	0.810	1.460	0.555
5304	0.120	1.774	0.068
5305	1.130	1.774	0.637
5308	1.560	1.774	0.879
4301	15.600	1.970	7.919
4501	3.420	2.144	1.595
5303	0.290	1.729	0.168
5604	0.070	1.501	0.047
6503**	1.550	1.883	0.823
	(annual cost data)		
1202	2.385	1.883	1.267

*See Table A.30

**Represents a producer's price

Table A.36. Deflation of cost data reported in design report 2

I-O Sector	Purchaser's Price ($\times 10^6$ \$1976)	$\frac{\$1976}{\$1967}$ (7)	Purchaser's Price ($\times 10^6$ \$1967)
	(lifetime cost data)		
1103*	5.550	1.988	2.792
4006	30.940	1.953	15.842
4301	15.000	1.821	8.237
4907	5.000	1.520	3.289
5305	9.500	1.661	5.719
5308	0.750	1.661	0.452
5903	0.200	1.376	0.145
6104	0.500	1.645	0.304
	(annual cost data)		
1202	2.000	1.752	1.142

*See Table A.30

Table A.37. Trade and transportation margins (sales to final demand) (5)

I-O Sector	6501	6503	6504	6505	6506	6901	6902	Total
1103	0	0	0	0	0	0	0	0
2307	6	4	0	0	0	12	0	22
3610	0	4	0	0	0	19	0	23
3620	10	3	0	0	0	11	0	24
4004	3	2	0	0	0	5	0	10
4006	1	1	0	0	0	4	0	6
4208	0	1	0	0	0	11	0	12
4301	0	0	0	0	0	1	0	1
4501	1	1	0	0	0	12	0	14
4604	1	2	0	0	0	5	0	8
4901	1	2	0	0	0	10	0	13
4907	0	0	0	0	0	7	0	7
5101	0	0	0	0	0	5	1	6
5302	1	2	0	0	0	2	0	5
5303	0	0	0	0	0	6	1	7
5304	1	0	0	0	0	2	1	4
5305	0	0	0	0	0	5	0	5
5308	0	0	0	0	0	3	0	3
5604	0	0	0	0	0	1	1	2
5903	1	1	0	0	0	3	11	16
6104	1	0	0	0	0	1	0	2

Table A.38. Producer's prices and embodied energies of remaining components, general facilities and maintenance services required by the system described in design report 1

I-O Sector	Producer's Price (x 10^6 $1967)	Btu Primary / $1967 (5)	Embodied Energy (x 10^9 Btu Primary)
	(lifetime energy inputs)		
1103*	6.356	85,922	546
2307	0.087	65,885	6
2701**	4.551	291,465	1326
3610	0.034	148,220	5
3620	1.596	162,859	260
4004	0.059	131,635	8
4006	18.562	111,172	2064
4208	2.378	78,483	187
4301	7.840	74,377	583
4501	1.372	72,010	99
4604	0.562	63,180	36
4901	0.644	59,006	38
4907	1.690	68,763	116
5101	0.055	40,810	2
5302	0.527	78,657	41
5303	0.156	49,712	8
5304	0.065	67,105	4
5305	0.605	41,307	25
5308	0.853	63,182	54
5604	0.046	34,870	2
6501	0.451	92,917	42
6503	0.350	54,968	19
6503**	0.820	54,968	45
6901	1.930	37,501	72
6902	0.003	37,329	0
	(annual energy input)		
1202	1.267	61,453	78

*See Table A.30

**Represents raw materials required by system described in design report 1

Table A.39. Producer's prices and embodied energies of remaining components, general facilities and maintenance services required by the system described in design report 2

I-O Sector	Producer's Price (x 10^6 $1967)	Btu Primary / $1967 (5)	Embodied Energy (x 10^9 Btu Primary)
	(lifetime energy inputs)		
1103*	2.792	85,922	240
4006	14.891	111,172	1,655
4301	8.155	74,377	606
4907	3.059	68,763	210
5305	5.433	41,307	224
5308	0.438	63,182	28
5903	0.122	71,313	8
6104	0.298	116,790	35
6501	0.163	92,917	15
6503	0.160	54,968	8
6901	1.253	37,501	47
6902	0.016	37,329	1
	(annual energy input)		
1202	1.142	61,453	70

*See Table A.30

Table A.40. Summary of the application of input-output analysis

Design Report	Embodied Energy: Lifetime Energy Input ($\times 10^9$ Btu Primary)			Annual Energy Input ($\times 10^9$ Btu Primary/Yr)
	Non-delivered Non-installed Remaining Components	Non-delivered General Facilities and Raw Materials	Delivery Energy	Maintenance
1	3538	1872	178	78
2	2766	240	71	70

Application of the Disaggregation of Energy Intensity Coefficients

The direct energy usage and the capital required to install the components at the system site are estimated by assuming the installation energies to be similar to the energy requirements of the new construction industry (sector 1103). The energy embodied in the non-delivered, non-installed components are assumed to represent the material energy input of the new construction industry. Table A.28 lists the material input to be 65.34 percent of the sector's total energy input. Table A.41 lists the installation energy requirements.

Table A.41. Energy required for the installation of components at the system site

Design Report	Energy Embodied in the Non-delivered Non-installed Components ($\times 10^9$ Btu Primary)	Energy Required for Installation ($\times 10^9$ Btu Primary)
1	15998	8486
2	6814	3615

APPENDIX B

APPENDIX B

ENERGY ANALYSIS OF THE PRODUCTION OF INDUSTRIAL PROCESS HEAT FROM SOLAR RADIATION

General Approach

There exist examples of systems that supply process heat (i.e., hot water, hot air or steam) from solar radiation currently in operation for several industrial processes. Also, the solar collectors utilized in such systems are well developed in terms of the collector design and materials of construction that give reliable operation with minimal costs. As a result, the materials and components required in the design specifications of a proposed solar industrial process heat system can be defined with a high level of certainty. However, both the manufacture of the solar collector and the installation of the system are not well developed and current practices are far from optimal. The energy embodied in the solar collector and the energy required for installation of the system are estimated in the same manner as applied to the central receiver solar thermal power stations (i.e., the fabrication of collectors is assumed to be analogous to manufacturing practices utilized in the auto industry and the installation is assumed to be analogous to construction

practices utilized in the new construction industry). The remaining components required in the system are the products of well-established industries and their embodied energies are estimated by the direct application of input-output analysis.

It is common for designs of solar industrial process heat systems to ignore the raw material (i.e., working fluid and maintenance supplies) and utility (i.e., electricity for operation of pumps, fans, etc.) requirements of the system. The energy embodied in the raw materials is usually a negligible energy input. However, the required electricity is not negligible. The importance of the utility requirement of the system is amplified by the fact that the input (electricity) is of a higher quality than the output (process heat) of the system. The utility requirement of systems that supply domestic hot water and space heating (established for the assessment of operational data) has been observed to exceed the energy output of the system (1), usually as a result of improper installation. Conversely, an electricity requirement of approximately five per cent of the system's heat output represents a superior system design and installation (1). The utility requirement is treated as a variable to study the sensitivity of the system's energy parameters to the utility requirement.

The energy embodied in the delivered, non-installed solar collectors listed in Table B.1 are determined in the

Table B.1. Description of solar collectors analyzed (6)

Collector	Weight of Unit Produced at the Manufacturing Site (lb/ft^2)	Solar Energy Collectable During Lifetime of Collector ($\times 10^6$ Btu/ft^2)			Collector Lifetime (yrs)
		W^a	A^a	S^a	
Flat plate - copper	4.62	7.2	7.2	7.2	35
aluminum	5.01	2.4	7.2	2.0	10
steel	16.91	6.0	7.2	4.8	28
Evacuated tubular	5.96	9.0	9.0	9.0	30
Winston concentrating	4.51	9.0	9.0	6.0	20
Fresnel lens concentrating	3.21	2.7	2.7	2.7	10
Parabolic trough concentrating	9.10	9.0	9.0	9.0	--

a - Form of energy produced; W ≡ hot water, A ≡ hot air, S ≡ steam

same manner as applied to the prototype components of the central receiver solar thermal power station. Energy analysis is then applied to the three solar industrial process heat systems listed in Table B.2.

Description of Data

Data describing the system and raw material requirements for collector fabrication are taken from system and collector evaluations performed by the Mitre Corporation (2, 3). Raw material requirements for collector fabrication are described as the purchaser's price of components in 1976 and 1974 dollars. The remainder of the components required by each system are described as vendor quotes for the purchase of the components in terms of the purchaser's price in 1976 or 1974 dollars. There are no general facility, raw material (other than those included in the maintenance supplies) or utility requirements reported for the systems analyzed. The maintenance requirement of the system is reported as an annual expenditure for the purchaser's price of the service in 1976 dollars.

Estimation of Energy Embodied in Collectors

General Approach to the Estimation of the Energy Embodied in Solar Collectors

The analysis utilized to estimate the energy embodied in the delivered, non-installed collectors is the same analysis applied to the prototype components of the

Table B.2. Description of system analyzed (2)

System	Description
I	Supply of 60-80°C hot water using evacuated tubular collectors for textile plant in South Carolina
II	Supply of 80-100°C hot water using copper flat plate collectors for can-washing operation of a soup canning plant in Southern California
III	Supply of 100-150°C hot air using Winston concentrating collectors for plastic curing operation located in California

central receiver solar thermal power station. Refer to the General Approach for Extension of Process Analysis to Prototype Component Manufacturing Systems and the Definition of the Nameplate Processing Systems Responsible for the Manufacture of Prototype Components in Appendix A for details.

Application of Process Analysis to Solar Collectors

Comments

Process analysis is used to quantitatively identify the raw materials required for collector fabrication and the energy required for delivery of the collectors to the system site.

Raw materials

Table B.3 lists the raw material requirements for fabrication of the collectors analyzed.

Delivery requirements

The solar collectors are assumed to be transported from the manufacturing site to the system site via truck transportation. Perry, et al., (5) report private inter-city trucking to require 7000 Btu primary per ton mile. Table B.4 lists the energy required for delivery of the collectors as a function of transportation distance (based on collector weights listed in Table B.1).

Table B.3. Raw materials required for fabrication of the collectors analyzed

Collector	Component	Purchaser's Price ($1976/ft^2)	I-O Sector
Flat Plate (2)	Absorber - copper	2.25	4006
	aluminum	1.35	3808
	steel	2.50	4006
	Selective coating-		
	black chrome	0.70	2704
	copper oxide	0.50	2704
	Headers/tubes-		
	copper	0.30	3807
	aluminum	0.15	3808
	steel	0.50	4208
	Glazings (each)-		
	glass	0.75	3501
	tedlar	1.25	2801
	Insulation-		
	fiberglass	0.35	3620
	foamglass	0.70	3620
	Anti-reflective coating	0.50	2704
	Collector box (steel)	0.30	4006
Evacuated Tubular (2)	Glass	1.44	3501
	Reflector	0.50	2704
	Header (copper)	0.75	3807
	Insulation	0.75	3620
	Gasket	0.30	3618

Table B.3. Continued

Collector	Component	Purchaser's Price ($1976/ft^2)	I-O Sector
Winston Concentrating (2)	Reflector (steel)	0.50	4006
	Absorber (copper)	0.75	4006
	Selective coating	0.20	2704
	Insulation	0.75	3620
	Box	0.30	4006
	Cover glass	0.75	3501
	Sealant	0.30	2704
Fresnel Lens Concentrating (2)	Lens (plastic)	3.40	2801
	Absorber and coating	0.95	4006
	Box	0.30	4006
	Insulation	0.75	3620
	Tracking mechanism	1.00	4905
Parabolic Trough Concentrating (3)	Support structure		
	steel structure	1.09[a]	4004
	concrete foundation *	0.36[a]	3610
	Trough mirror and support		
	reflective surface (alzac aluminum)	1.66[a]	3808
	aluminum support	1.92[a]	3808
	Receiver		
	pyrex tube	2.13[a]	3501
	absorber pipe	0.31[a]	3808
	selective coating	0.44[a]	2704

Table B.3. Continued

Collector	Component	Purchaser's Price ($1976/ft^2)	I-O Sector
Parabolic Trough Concentrating (3) (Continued)	Tracking mechanism		
	gears	2.00[a]	4905
	bearing	0.66[a]	4902
	chain	0.24[a]	4907
	motors and sensors	1.00[a]	5304
	miscellaneous	1.45[a]	4907

a - Value has units of ($1974/ft^2)

*Not a raw material required at the manufacturing site.

Table B.4. Energy required to deliver collectors

Collector	Transportation Energy (Btu Primary/ft^2) 50 mi[a]	100 mi[a]	500 mi[a]
Flat Plate			
Copper	807	1614	8068
Aluminum	877	1754	8768
Steel	2959	5919	29593
Evacuated Tubular	1043	2086	10430
Winston Concentrating	789	1579	7893
Fresnel Lens Concentrating	562	1124	5618
Parabolic Trough Concentrating	1593	3185	15925

a - Transportation distance

Application of Input-Output Analysis to Solar Collectors

Table B.5 lists the deflation of collector cost data, Table B.6 lists the required trade and transportation margins and Table B.7 lists the producer's prices and embodied energies of the raw materials required for collector fabrication.

Summary of Results of the Application of Input-Output Analysis to Solar Collectors

Table B.8 lists the energy embodied in the non-delivered raw materials required at the manufacturing site and the system site and the energy required for delivery of the raw materials required at the system site.

Application of the Disaggregation of Energy Intensity Coefficients to the Solar Collectors

The total energy embodied in the non-delivered collector is estimated by assuming the energy embodied in the non-delivered raw materials required for collector fabrication is analogous to the material energy contribution to the total energy requirement of the auto industry (sector 5903). Inspection of the disaggregation of the auto industry's energy intensity coefficient (see Table A.26) gives the material contribution to be 72.30 per cent of the sector's total energy requirement (4). Table B.9 lists the total energy embodied in the non-delivered collectors fabricated at the manufacturing site.

Table B.5. Deflation of collector cost data

Collector	I-O Sector	Purchaser's Price ($1976/ft^2)	$1976/$1967 (9)	Purchaser's Price ($1967/ft^2)
Flat Plate	2704[a]	1.20	2.575	0.466
	2704[b]	1.00	2.575	0.388
	2801	1.25	1.583	0.790
	3501	0.75	1.603	0.468
	3620[c]	0.70	1.808	0.387
	3620[d]	0.35	1.808	0.194
	3807[e]	0.30	1.658	0.181
	3808[f]	1.58	1.822	0.823
	4208[g]	0.50	2.365	0.211
	4006[h]	2.50	1.953	1.280
	4006[i]	2.25	1.953	1.152
	4006	0.30	1.953	0.154
Evacuated Tubular	2704	0.50	2.575	0.194
	3501	1.44	1.603	0.898
	3807	0.30	1.808	0.166
	3620	0.75	1.808	0.415
	3618	0.75	1.658	0.452
Winston Concentrating	2704	0.50	2.575	0.194
	3501	0.75	1.603	0.468
	3620	0.75	1.808	0.415
	4006	1.55	1.953	0.794
Fresnel Lens Concentrating	2801	3.40	1.583	2.148
	3620	0.75	1.808	0.415
	4006	1.20	1.953	0.640
	4905	1.00	1.520	0.658
Parabolic Trough Concentrating	2704	0.44[j]	1.720[k]	0.256
	3501	2.13[j]	1.490[k]	1.430
	3808	3.89[j]	1.505[k]	2.585
	4004	1.09[j]	1.646[k]	0.662
	4902	0.66[j]	1.393[k]	0.474
	4905	2.00[j]	1.464[k]	1.366
	4907	1.69[j]	1.474[k]	1.147
	5304	1.00[j]	1.404[k]	0.712
	3610*	0.36[j]	1.513[k]	0.238

Table B.5. Continued

a through i - Variations in Flat Plate collector design

- a - black chrome selective coating
- b - copper oxide selective coating
- c - foamglass insulation
- d - fiberglass insulation
- e - copper headers/tubes
- f - aluminum absorber, headers/tubes
- g - steel headers/tubes
- h - steel absorber
- i - copper absorber

j - value has units of ($1974/ft^2)

k - Value has units of ($1974/$1967)

* - See Table B.3

Table B.6. Trade and transportation margins

I-O Sector	6501	6503	6504	6505	6506	6901	6902	Totals
	(sales to auto industry) (8)							
2704	4	4	0	0	0	6	0	14
2801	2	2	0	0	0	3	0	7
3501	2	1	0	0	0	12	0	15
3618	9	0	0	0	0	7	0	16
3620*	10	3	0	0	0	11	0	24
3807	1	1	0	0	0	2	0	4
3808	1	1	0	0	0	3	0	5
4004*	3	2	0	0	0	5	0	10
4006*	1	1	0	0	0	4	0	6
4208*	0	1	0	0	0	11	0	12
4902	0	1	0	0	0	7	0	8
4905	0	0	0	0	0	8	0	8
4907*	0	0	0	0	0	7	0	7
5304	0	1	0	0	0	2	0	3
	(sales to final demand) (7)							
3610	0	4	0	0	0	19	0	23

*No interaction with auto industry - sales to final demand used

Table B.7. Producer's prices and embodied energies of raw materials required for collector fabrication

Collector	I-O Sector	Producer's Price ($1967/ft^2)	Btu Primary $1967 (7)	Embodied Energy (x 10^3 Btu primary/ft^2)
Flat Plate	2704[a]	0.401	189521	76
	2704[b]	0.334	189521	63
	2801	0.735	226289	166
	3501[c]	0.398	107405	43
	3620[d]	0.294	162859	48
	3620[e]	0.147	162859	24
	3807[f]	0.174	107150	19
	3808[g]	0.782	256521	201
	4208[h]	0.186	78483	15
	4006[i]	1.203	111172	134
	4006[j]	1.083	111172	120
	4006	0.145	111172	16
	6501	0.156	92917	15
	6503	0.113	54968	6
	6902	0.362	37501	14
Evacuated Tubular	2704	0.167	189521	32
	3501	0.763	107405	82
	3807	0.434	107150	46
	3620	0.315	162859	51
	3618	0.139	88343	12
	6501	0.087	92917	8
	6503	0.034	54968	2
	6902	0.186	37501	7
Winston Concentrating	2704	0.167	189521	32
	3501	0.398	107405	43
	3620	0.315	162859	51
	4006	0.746	111172	83
	6501	0.067	92917	6
	6503	0.033	54968	2
	6901	0.145	37501	5
Fresnel Lens Concentrating	2801	1.998	226289	452
	3620	0.315	162859	51
	4006	0.602	111172	67
	4905	0.605	63646	39
	6501	0.091	92917	8
	6503	0.062	54968	3
	6901	0.188	37501	7

Table B.7. Continued

Collector	I-O Sector	Producer's Price ($1967/ft^2)	Btu Primary $1967 (7)	Embodied Energy (x 10^3 Btu primary/ft^2)
Parabolic	2704	0.220	189521	42
Trough	3501	1.216	107405	131
Concentrating	3808	2.456	256521	630
	4004	0.596	131635	78
	4902	0.436	85795	37
	4905	1.257	63646	80
	4907	1.067	68763	73
	5304	0.691	41307	29
	6501	0.085	92917	8
	6503	0.085	54968	5
	6901	0.580	37501	22
	3610*	0.183	148220	27
	6503*	0.010	54968	1
	6901*	0.045	37501	2

a through i - See Table B.5

*See Table B.3

Table B.8. Summary of results of the application of input-output analysis to the solar collectors

Collector	Embodied Energy (x 10^3 Btu primary/ft^2)		
	Non-delivered Raw Materials Required at the Manufacturing Site	Non-delivered Raw Materials Required at the System Site	Energy Required for Delivery of Raw Materials Required at the System Site
Flat Plate			
Copper[a]	451	---	---
Aluminum[a]	513	---	---
Steel[a]	461	---	---
Evacuated Tubular	223	---	---
Winston Concentrating	209	---	---
Fresnel Lens Concentrating	609	---	---
Parabolic Trough Concentrating	1100	27	3

a - Assumes collector utilizes a copper oxide selective coating, fiberglass insulation and two glazings (one glass, one tedlar)

Table B.9. Energy embodied in the non-delivered collectors fabricated at the manufacturing site

Collector	Embodied Energy ($\times 10^3$ Btu primary/ft^2) Non-delivered Raw Materials	Non-delivered Collector
Flat Plate		
Copper	451	624
Aluminum	513	710
Steel	461	638
Evacuated Tubular	223	308
Winston Concentrating	209	289
Fresnel Lens Concentrating	609	842
Parabolic Trough Concentrating	1100	1521

Definition of Nameplate Processing System

Solar industrial process heat systems are usually designed to interface with existing processes to displace other fuels utilized to supply process heat. Solar industrial process heat systems are actually utility supply systems. Thus, the process heat is consumed at its production site and does not require transportation facilities in addition to the system itself. As a utility supply system, the nameplate processing system consists of the solar collectors, pumps or fans and plumbing required to interface the solar process heat system with the existing system, materials (including support structure of the collector array) required to install the solar process heat system and any additional controls required for system operation.

The obvious output of the solar process heat system is thermal energy. However, as a fuel displacement system, the output of the system is the energy embodied in the fuel it displaces. The fuel savings output will exceed the thermal output of the solar process heat system due to the energy subsidy of the displaced fuel and the thermal losses occurred during consumption of the displaced fuel for production of the process heat. This analysis considers the output of the solar process heat systems to be the thermal energy produced. Thus, the energy parameters resulting from the analysis represent the lower bounds of the energy characteristics of the systems.

Application of Process Analysis

Inputs

The inputs to the nameplate processing system are identified according to the categories outlined in Chapter 3.

Inputs 1-3, 8-10

Table B.10 and Table B.11 list the collectors and their embodied energies and the additional components required by the systems analyzed, respectively. The energies required to install the components are estimated using information obtained from the disaggregation of the energy intensity coefficients.

Inputs 4-5

The feed to each system is freely available solar radiation. The energies embodied in raw materials not included in the maintenance supplies are considered to be negligible. Each system has an electrical utility requirement reported as a percentage of the system's thermal output. The utility requirement of each system is varied (5, 10 and 20 per cent of the thermal output required as an electrical input) to study the system's energy parameters' sensitivity to the utility requirement.

Table B.10. Collectors required by the systems analyzed

System	Collector (2)	Reflective Surface Area Required(2) (ft^2)	Embodied Energy (x 10^9 Btu Primary) Non-delivered Non-installed Collector	Delivery Requirement 50 mi[a]	100 mi[a]	500 mi[a]
I	evacuated tubular	2.5×10^5	77	0.3	0.5	2.6
II	copper flat plate	150,000	94	0.1	0.2	1.2
III	winston concentrating	135,000	39	0.1	0.2	1.1

a - transportation distance

Table B.11. Remaining components required by the systems analyzed (2)

System	Components	Purchaser's Price ($\times 10^3$ \$1976)	I-O Sector
I	Plumbing	83.300	4208
	Valves	28.800	4208
	Pumps	28.800	4901
	Control	12.500	5305
	Storage	243.800	4006
II	Pumps	7.000	4901
	Valves	7.000	4208
	Plumbing	42.000	4208
	Controls	12.000	5305
III	Ductwork	18.300	4006
	Valves	7.300	4208
	Controls	13.500	5305
	Fans	8.600	4903
	Storage	142.500	4006
	Heat Exchangers	86.400	4006

Inputs 6-7

None of the systems have reported secondary or waste products. The primary product of each system is thermal energy consumed at its production site.

Input 11

Table B.12 lists the annual expenditures for the maintenance of the systems analyzed.

Table B.12. Annual maintenance requirements (2)

System	Purchaser's Price (x 10^3 $1976/yr)	I-O Sector
I	17.800	1202
II	21.600	1202
III	27.132	1202

Outputs

Table B.13 lists the energy outputs of the systems analyzed.

Table B.13. Annual energy outputs of systems analyzed (2)

System	Thermal Energy Output (x 10^6 Btu/yr)
I	67,850
II	38,250
III	29,565

Application of Input-Output Analysis

Table B.14 lists the deflation of remaining components and maintenance cost data, Table B.15 lists the required trade and transportation margins and Table B.16 lists the producer's prices and embodied energies of the remaining components and maintenance requirements. Table B.17 lists the energy contents and embodied energies of the utility requirements. Note that the trade and transportation margins for the electrical utility sector are zero. Thus, the energy required for the delivery of electricity is negligible.

Table B.14. Deflation of remaining component and maintenance cost data

System	I-O Sector	Purchaser's Price ($\times 10^3$ \$1976)	$\frac{\$1976}{\$1967}$ (9)	Purchaser's Price ($\times 10^3$ \$1967)
		(lifetime cost data)		
I	4208	112.100	2.365	47.400
	4006	243.800	1.953	124.834
	4901	28.800	1.520	18.947
	5305	12.500	1.661	7.526
II	4208	49.000	2.365	20.719
	4901	7.000	1.520	4.605
	5305	12.000	1.661	7.225
III	4006	247.200	1.953	126.575
	4208	7.300	2.365	3.087
	4903	8.600	1.520	5.658
	5305	13.500	1.661	8.128
		(annual cost data)		
I	1202	17.800	1.752	10.160
II	1202	21.160	1.752	12.078
III	1202	27.132	1.752	15.486

Table B.15. Trade and transportation margins (7)
(sales to final demand)

I-O Sector	6501	6503	6504	6505	6506	6901	6902	Totals
		(% of purchaser's price)						
1202	0	0	0	0	0	0	0	0
4006	1	1	0	0	0	4	0	6
4208	0	1	0	0	0	11	0	12
4903	0	1	0	0	0	7	0	8
5305	0	0	0	0	0	5	0	5
		($1967/x 10^6 Btu)						
6801	0	0	0	0	0	0	0	0

Table B.16. Producer's prices and embodied energies of remaining components and maintenance requirements

System	I-O Sector	Producer's Price ($\times 10^3$ \$1967)	Btu Primary / \$1967 (7)	Embodied Energy ($\times 10^6$ Btu Primary)
		(lifetime energy input)		
I	4208	41.712	78483	3274
	4006	117.344	111172	13045
	4901	16.484	59006	973
	5305	7.150	41307	295
	6501	1.438	92917	134
	6503	2.101	54968	115
	6901	12.478	37501	468
II	4208	18.233	78483	1431
	4901	4.006	59006	236
	5305	6.864	41307	284
	6501	0.046	92917	4
	6503	0.299	54968	16
	6901	3.101	37501	116
III	4006	118.981	111172	13227
	4208	2.717	78483	213
	4903	5.205	66579	347
	5305	7.722	41307	319
	6501	1.266	92917	118
	6503	1.353	54968	74
	6901	6.205	37501	233
		(annual energy input)		
I	1202	10.160	61453	624
II	1202	12.078	61453	742
III	1202	15.486	61453	952

Table B.17. Annual energy embodied in delivered utility requirements

System	Per Cent of Thermal Energy Output	Electrical Requirement ($\times 10^6$ Btu/yr)	Btu Primary / Btu Electric (7)	Embodied Energy ($\times 10^6$ Btu Primary/yr)
I	5	3,400	3.8951	13,200
	10	6,800	3.8951	26,400
	20	13,600	3.8951	52,900
II	5	1,900	3.8951	7,400
	10	3,800	3.8951	14,900
	20	7,700	3.8951	29,800
III	5	1,500	3.8951	5,800
	10	3,000	3.8951	11,500
	20	5,900	3.8951	23,000

Summary of Results of Input-Output Analysis

Table B.18 lists the embodied energies of the non-delivered, non-installed remaining components and their delivery requirements, and the annual embodied energies of the delivered maintenance and utility requirements.

Table B.18. Summary of the results of input-output analysis

System	Embodied Energies				
	Lifetime Inputs ($\times 10^6$ Btu Primary)		Annual Inputs ($\times 10^6$ Btu Primary/yr)		
	non-delivered non-installed remaining components	delivery requirement	utility and maintenance requirement		
			5[a]%	10[a]%	20[a]%
I	17587	717	13824	27024	53524
II	1951	136	8142	15642	30542
III	14106	425	6752	12452	23952

a - % of thermal output required as electrical input

Application of the Disaggregation of Energy Intensity Coefficients

The energy required to install the components of each system are estimated by assuming the energy embodied in the non-delivered, non-installed components of each system is analogous to the material contribution to the total energy requirement of the new construction industry (sector 1103). Inspection of the disaggregation of the new construction industry's energy intensity coefficient gives the material input to be 65.34 per cent of the industry's total energy requirement (4) (see Table A.28). Table B.19 lists the energy embodied in the non-delivered, non-installed components and the energy embodied in the installed, non-delivered components.

Table B.19. Energy embodied in the installed, non-delivered components of the systems analyzed

	Embodied Energy (x 10^6 Btu Primary)	
System	non-delivered non-installed components	installed, non-delivered components
I	94,587	144761
II	95,551	146237
III	53,121	81299

APPENDIX C

APPENDIX C

ENERGY ANALYSIS OF CROP PRODUCING SYSTEMS

General Approach

When viewed as an energy supply system, crop production can be envisioned as a process that converts solar radiation into stored chemical energy as biomass. Thus, the feed to the system is solar radiation; the raw materials are seeds, fertilizers, chemicals and water; the utilities are motor fuels and electricity; and the capital is farm equipment. The inputs required for the production of a specific crop are dictated by the cultural practices followed for the planting, growth, harvesting, collection, processing and delivery of the crop. Western cultural practices for crop production are generally intensive (i.e., commercial fertilizers are extensively used and farm operations are automated with machinery replacing human labor wherever possible) with the goal of maximizing crop yield per unit area of land in order to supply a rapidly growing population with food. The same intensive cultural practices are being considered for crop production as an energy resource with the rationalization that such cultural practices will be required to provide enough

energy to make a significant contribution in the supply of energy for the United States. It is critical that the energetic characteristics of the supply of energy from biomass in a nation-wide role be understood prior to the formulation and implementation of such an energy policy. Thus, the cultural practices adopted for this energy analysis represent the most effective use of commercial fertilizers and automated farming operation resulting in maximum crop yields without irrigation.

It is suspected that a large portion of the energy subsidy required for intensive crop production originates from fertilizers, agricultural chemicals and seeds. The standard industrial classification of a 357 sector economy (1) allots single sectors for all fertilizers and general agricultural chemicals. Thus, it is necessary to extend process analysis to estimate the energies embodied in the various fertilizers, chemicals and seeds required for production of the crops analyzed. The results of the application of process analysis to various fertilizers, agricultural chemicals and seeds reported by Roller and Keener (2) are listed in Table C.1.

Note that the unit energy equivalence is defined to be a MJ of thermal energy for the raw materials listed in Table C.1. In general, fertilizers and agricultural chemicals have little embodied electrical energy. For example, the electrical energy contributions to the total embodied primary energies of the fertilizers (sector 2702)

Table C.1. Energy embodied in various fertilizers, agricultural chemicals and seeds reported by Roller and Keener (2)

Raw Material	Embodied Energy (MJ thermal/kg)
Nitrogen	64.40
P_2O_5	11.96
K_2O	11.96
Lime	0.28
Herbicides	101.20
Insecticides	101.20
Alfalfa seeds	31.84
Corn seeds	7.37
Kenaf seeds	25.23
Slash pine planting trees	0.26 MJ/tree
Wheat seeds	5.07
Napier grass seeds	a

a - Keener and Roller do not report a value for the energy embodied in napier grass seeds. They do, however, report a seed energy requirement of 1791.9 MJ thermal/hm^2 per growth cycle for production of napier grass

and the agricultural chemicals (sector 2703) producing sectors are less than ten per cent (10). Thus, the embodied thermal energies reported in Table C.1 are assumed to be equivalent to the embodied primary energy.

The energies embodied in the non-delivered capital and utilities are estimated through input-output analysis. The energies required for delivery of the capital, raw materials and utilities (excluding electricity), as well as the energy required to transport the produced biomass (as collected and stored on the farmstead) to its end-use site, are estimated through an extension of process analysis. Perry, et al., (3) report for-hire truck transportation to require 5,000 Btu primary per ton-mile of work. The capital, raw materials and utilities are assumed to be transported an average of 500 miles by truck to the farmstead. The transportation distance of the delivery of the produced biomass to its end-use site is varied in order to study the sensitivity of the energy parameters of crop production to the transportation distance of the delivery of the produced biomass.

The products of the crop producing systems analyzed are considered to be an energy fuel, in the form of biomass, ready for consumption. Thus, the processing of the biomass is comprised of chipping and drying operations. Blankenhorn, et al., (4) report chipping and drying operations to consume 84.3 MJ electric per tonne dry

biomass and 2790 MJ thermal per tonne water removed, respectively. The energy consumed during the chipping and drying operations is the utility requirement of the operations. Assuming the capital and raw material requirements of the operations are negligible energy inputs, the total energy required for chipping and drying is the energy embodied in the energy consumed.

Description of Data

The analysis is based on the equipment, seed, fertilizer, chemical, fuel and electricity requirements for the production of various crops reported by Roller and Keener (2). The material and equipment requirements represent intensive crop production cultural practices and the fertilization usage represents the maximum crop yields possible without irrigation. The fertilizer and chemical requirements are reported as kg per hm^2 per growth cycle of nitrogen, P_2O_5, K_2O_5, lime, herbicides and insecticides. The fuel requirement is reported as liters of motor fuel per hm^2 per growth cycle (assumed to be diesel fuel) and the electricity requirement is reported as 17 kwh per hm^2 per year (excluding production of slash pine). The equipment requirement is reported as both the actual units and the cost (in 1974 dollars purchaser's price) of equipment utilized for crop production from an area of 162 hm^2 per growth cycle. The fraction of the equipment's embodied energy depleted

per hm^2 during its service for crop production is considered to be the embodied energy of the delivered equipment required divided by 162 hm^2 and multiplied by the ratio of the growth cycle of the crop and the life span of the equipment (8 years).

Table C.2 lists the crops analyzed and the characteristics of each.

Definition of Nameplate Processing System

The nameplate processing system is defined to include all equipment, fertilizers, chemicals, fuels and electricity used at the farmstead for farming operations. It is not defined to include any general facilities associated with the farm operations, such as housing or work sheds. Note that while the general facilities used to maintain the equipment and store the crops are not included in the nameplate processing system, the electricity required to operate these general facilities are. This is an acceptable definition of system boundaries since the life spans of the general facilities are much longer than the growth cycles such that the energy contribution from the general facilities is negligible.

The output of the nameplate processing system is the harvested, collected and stored crop on the farmstead. The crop is then transported from the farmstead to the end-use site where processing of the crop is assumed to occur. Thus, process analysis must be extended forward

Table C.2. Expected yields, location of production, energy contents, growth cycles and moisture contents of the crops analyzed

Crop	Location of Production (2)	Yield[a] (2) ($\frac{\text{tonne}}{\text{hm}^2 \text{ growth cycle}}$)	Energy Content[a] (2) (MJ/kg)	Growth Cycle (2) (yr)	Moisture Content (Wet Basis) (%)
Alfalfa	Ohio	36.43	17.72	3	15 (5)
Corn	Ohio	19.30	18.07	1	15[b] (5)
Kenaf	Florida	19.50	17.00	1	15 (5)
Napier Grass	Puerto Rico	151.50	17.08	3	15 (5)
Slash Pine	Louisiana	290.20	17.00	20	33 (4)
Wheat	Ohio	7.35	17.50	1	14 (5)

a - Value is based on the dry weight of the whole plant

b - Moisture content of corn allowed to predry at the farmstead before storage

along the horizontal trajectory to determine the energy requirements for delivery and processing of the products.

Application of Process Analysis

Nameplate Processing System

Comments

The inputs and outputs of the nameplate processing system are quantitatively identified according to the categories outlined in Chapter 3.

Inputs

Inputs 1-3

Table C.3 lists the quantity of specific farm equipment required for the production of the various crops analyzed from 162 hm^2 of land during the growth cycle of each crop. Table C.4 lists the total weight and purchaser's price of the equipment required for the production of each crop. Installation of the farm equipment is not required.

Inputs 4-5

The feeds to the crop producing systems are solar radiation. Tables C.5 and C.6 list the raw materials and utilities required for crop production, respectively.

Table C.3. Weights of specific farm equipment and the quantities (i.e., number of units) of each unit required for production of the crops analyzed (2)

Unit	Weight of Unit (kg)	Number of Units Required for Production of Crop					
		Alfalfa	Corn	Kenaf	Napier Grass	Slash Pine	Wheat
70 Hp tractor	3727	2	2	2	2	1	2
Skidding,wheeled tractor	3727	---	---	---	---	1	---
Moldboard plow 40 cm (4-16 in)	552	1	1	1	1	---	1
Chisel plow, 2.1 m (7 ft)	580	---	---	---	---	1	---
Disc, 3.7 m (12 ft)	1007	1	1	1	1	1	1
Springtooth, 3.7 m (12 ft)	254	1	1	1	1	1	1
Seed drill, 2.9 m (9.5 ft)	786	1	---	---	1	---	---
Corn planter 76 cm (6-30 in)	1395	---	1	1	---	---	1
Tree planter	227	---	---	---	---	1	---
Sprayer, 3.0 m (10 ft)	454	1	1	1	1	1	1
Cultivator, 76 cm (6-30 in)	750	---	---	---	---	---	---
Direct cut forage harvester	1534	1	1	1	1	---	1
2-row forage harvester	1582	---	---	---	---	---	---
Forage wagon	1818	2	2	2	2	---	2
Chain saw	14	---	---	---	---	2	---

Table C.4. Total weight and the purchaser's price of equipment required for production of the crops analyzed from 162 hm^2 per growth cycle (2)

Crop	I-O Sector	Weight of Equipment (kg/162 hm^2 growth cycle)	Purchaser's Price ($1974/162 hm^2 growth cycle)
Alfalfa	4400	15,677	43,850
Corn	4400	16,286	45,170
Kenaf	4400	16,286	45,170
Napier Grass	4400	15,677	43,850
Slash Pine	4400	10,004	32,550
Wheat	4400	16,286	43,000

Table C.5. Quantities of seed, fertilizer, and chemicals required for production of crops analyzed (2)

Raw Material	Quantity Required for Crop Production (kg/hm^2 growth cycle)					
	Alfalfa	Corn	Kenaf	Napier Grass	Slash Pine	Wheat
Seed	13.4	16.8	9.0	a	3400 trees	112.0
Nitrogen	---	235.0	200.0	1674.0	1400.0	115.0
P_2O_5	446.0	110.0	99.0	1402.0	261.0	40.0
K_2O	1233.0	193.0	209.0	2382.0	464.0	62.0
Lime	4130.0	1320.0	1230.0	4650.0	8400.0	1230.0
Herbicides and Insecticides	13.4	4.5	4.5	4.5	4.5	---

a - Production of napier grass has a seed energy requirement of 1791 MJ primary/hm^2 growing cycle (2)

Table C.6. Quantities and energy contents of utilities required for production of crops analyzed (2)

	Diesel Fuel Required		Electricity Required	
Crop	Quantity ($\frac{\text{liters}}{\text{hm}^2 \text{ growth cycle}}$)	Energy Content[a] ($\frac{\text{MJ}}{\text{hm}^2 \text{ growth cycle}}$)	Quantity ($\frac{\text{kwh}}{\text{hm}^2 \text{ growth cycle}}$)	Energy Content[b] ($\frac{\text{MJ}}{\text{hm}^2 \text{ growth cycle}}$)
Alfalfa	297.3	11,445.5	51.0	183.5
Corn	80.0	3,079.9	17.0	61.2
Kenaf	80.1	3,083.7	17.0	61.2
Napier Grass	440.0	16,939.2	51.0	183.5
Slash Pine	1,428.0	54,975.5	17.0	61.2
Wheat	71.8	2,764.2	17.0	61.2

a - Thermal energy content of diesel fuel is 38.5 MJ/l (6)

b - Thermal energy equivalence of a kwh of electricity is 3.60 MJ/kwh (6)

Inputs 6-7

Crop production has no secondary products or waste products requiring special handling facilities.

Inputs 8-10

The definition of the nameplate processing system does not include any general facilities.

Input 11

The energy embodied in the required maintenance of the farm equipment (in addition to the electrical requirement for operation of the farm shop) is assumed to be a negligible energy input.

Outputs

Table C.7 lists the energy outputs of the crop producing systems.

Table C.7. Energy outputs of crop producing systems

Crop	Energy Output (MJ/hm^2 growing cycle)
Alfalfa	645,500
Corn	348,800
Kenaf	331,500
Napier Grass	2,587,600
Slash Pine	4,933,400
Wheat	128,600

Extension of Process Analysis

Energy embodied in raw materials

Table C.8 lists the energy embodied in the non-delivered raw materials required for crop production.

Table C.8. Energy embodied in the non-delivered raw materials required for crop production

Crop	Energy Embodied in Non-delivered Raw Materials ($MJ\ primary/hm^2$ growth cycle)
Alfalfa	23,020
Corn	19,707
Kenaf	17,590
Napier Grass	156,612
Slash Pine	102,529
Wheat	9,538

Delivery requirements

Delivery of inputs

The energies required for delivery of the inputs required for crop production are estimated according to the weights of the capital (equipment), raw materials and utilities, a delivery distance of 500 miles and an energy requirement of 0.00581 MJ primary/kg-mile for truck transportation (3). A specific gravity of 0.8491 kg/liter is assumed for diesel fuel (7) and a weight of 5 kg per planter is assumed for slash pine planter trees. The energy required for the delivery of electricity is assumed to be negligible and the weight of equipment to be delivered is calculated as the total weight of equipment required for crop production from 162 hm^2 per growth cycle of the crop divided by 162 hm^2 and multiplied by the ratio of the growth cycle and the life span of the equipment. Table C.9 lists the weight of the capital, raw material and utility inputs to be delivered to the farm and the energy required for delivery of the inputs.

Delivery of outputs

The crop weight that is transported from the farm site to the processing (i.e., drying and chipping) site includes the dry crop weight and the moisture content of the crop as it is stored at the farm site. Table C.10

Table C.9. Weights of capital, raw material and utility inputs for crop production and the energy required for delivery of the inputs

Crop	Input	Weight to be Transported (kg/hm^2 growth cycle)	Transportation Requirement (kg-mile / hm^2 growth cycle)	Energy Required for Delivery (MJ primary / hm^2 growth cycle)
Alfalfa	Capital	36.29	18,145	105
	Raw Materials	5,835.80	2,917,900	16,953
	Utilities	252.44	126,219	733
Corn	Capital	12.57	6,283	37
	Raw Materials	1,879.30	939,650	5,459
	Utilities	67.93	33,964	197
Kenaf	Capital	12.57	6,283	37
	Raw Materials	1,751.50	875,750	5,088
	Utilities	68.01	34,006	198
Napier Grass	Capital	36.29	18,145	105
	Raw Materials	10,325.50	5,016,250	29,144
	Utilities	373.60	186,802	1,085
Slash Pine	Capital	154.38	77,191	448
	Raw Materials	27,529.50	13,764,750	79,973
	Utilities	1,212.51	606,257	3,522
Wheat	Capital	12.57	6,283	37
	Raw Materials	1,559.00	779,500	4,529
	Utilities	60.97	30,483	177

lists the weight to be transported and the energy required for transportation as a function of the transportation distance of delivery of the crops analyzed.

Table C.10. Weight to be transported and the energy required for transportation of the crops analyzed

Crop	Weight to be Transported (kg/hm^2 growth cycle)	Energy Required for Transportation (MJ primary/hm^2 growth cycle)		
		50 mi[a]	100 mi[a]	500 mi[a]
Alfalfa	42,859	12,450	24,900	124,500
Corn	22,706	6,600	13,190	65,960
Kenaf	22,941	6,660	13,330	66,640
Napier Grass	178,235	51,780	103,550	517,770
Slash Pine	433,134	125,830	251,650	1,258,260
Wheat	8,547	2,480	4,970	24,830

a - Transportation distance for delivery of crops

Processing of crops

Table C.11 lists the utility requirements for drying and chipping of the crops analyzed. The capital and raw material energy requirements for drying and chipping are assumed to be negligible. The thermal energy required for the drying operation is assumed to be supplied from natural gas.

Table C.11. Utility requirements for drying and chipping of crops analyzed

Crop	Yield (tonne/hm^2 growth cycle)		Utility Requirement for Drying and Chipping	
	Dry Basis	Wet Basis	Drying (MJ thermal / hm^2 growth cycle)	Chipping (MJ electric / hm^2 growth cycle)
Alfalfa	36.42	42.85	17,900	3,100
Corn	19.30	22.71	9,500	1,600
Kenaf	19.50	22.94	9,600	1,600
Napier Grass	151.50	178.24	74,600	12,800
Slash Pine	290.20	433.13	398,800	24,500
Wheat	7.35	8.55	3,300	600

Application of Input-Output Analysis

Table C.12 lists the deflation of equipment cost data and Table C.13 lists the producer's prices and embodied energies of the non-delivered equipment required for crop production. Note that for sales to final demand, the total trade and transportation margins represent 25 per cent of the purchaser's price for farm machinery (sector 4400) (8). The equipment cost representing the embodied energy of the equipment depleted during crop production is calculated as the total cost of the equipment required for crop production from 162 hm^2 per growth cycle divided by 162 hm^2 and multiplied by the ratio of the growth cycle and the life span of the equipment. Table C.14 lists the energy contents and embodied energies of the non-delivered utilities required for crop production. Table C.15 lists the energy contents and the embodied energies of the delivered utilities required for crop processing. Note that the trade and transportation margins for sales to final demand for the electric (6801) and natural gas (6802) utilities are zero (8).

Table C.12. Deflation of equipment cost data

Crop	Purchaser's Price of Equipment ($1974/hm^2 growth cycle)	$\frac{\$1974}{\$1967}$ (9)	Purchaser's Price of Equipment ($1967/hm^2 growth cycle)
Alfala	101.505	1.440	70.489
Corn	34.853	1.440	24.204
Kenaf	34.853	1.440	24.204
Napier Grass	101.505	1.440	70.489
Slash Pine	502.315	1.440	348.830
Wheat	33.179	1.440	23.041

Table C.13. Producer's prices and embodied energies of non-delivered equipment required for crop production

Crop	I-O Sector	Producer's Price ($1967/hm^2 growth cycle)	MJ Primary / $1967 (8)	Embodied Energy (MJ primary / hm^2 growth cycle)
Alfalfa	4400	52.867	80.341	4247
Corn	4400	18.153	80.341	1458
Kenaf	4400	18.153	80.341	1458
Napier Grass	4400	52.867	80.341	4247
Slash Pine	4400	261.628	80.341	21019
Wheat	4400	17.281	80.341	1388

Table C.14. Energy contents and embodied energies of the non-delivered utilities required by the nameplate processing system for crop production

Crop	Utility	I-O Sector	Energy Content ($\frac{MJ}{hm^2 \text{ growth cycle}}$)	$\frac{MJ\ Primary}{MJ}$ (8)	Embodied Energy ($\frac{MJ\ Primary}{hm^2 \text{ growth cycle}}$)
Alfalfa	Fuel	3101	11446[a]	1.2157	13914
	Electricity	6801	184[b]	3.8951	715
Corn	Fuel	3101	3080[a]	1.2157	3744
	Electricity	6801	61[b]	3.8951	238
Kenaf	Fuel	3101	3084[a]	1.2157	3749
	Electricity	6801	61[b]	3.8951	238
Napier Grass	Fuel	3101	16939[a]	1.2157	20593
	Electricity	6801	184[b]	3.8951	715
Slash Pine	Fuel	3101	54976[a]	1.2157	66834
	Electricity	6801	61[b]	3.8951	238
Wheat	Fuel	3101	2764[a]	1.2157	3360
	Electricity	6801	61[b]	3.8951	238

a - MJ electric

b - MJ thermal

Table C.15. Energy contents and embodied energies of the delivered utilities required for crop processing (i.e., drying and chipping operations)

Crop	Operation	I-O Sector	Energy Content ($\frac{MJ}{hm^2 \text{ growth cycle}}$)	MJ Primary / MJ (8)	Embodied Energy ($\frac{MJ \text{ primary}}{hm^2 \text{ growth cycle}}$)
Alfalfa	Drying	6802	17900[b]	1.1077	19828
	Chipping	6801	3100[a]	3.8951	12075
Corn	Drying	6802	9500[b]	1.1077	10523
	Chipping	6801	1600[a]	3.8951	6232
Kenaf	Drying	6802	9600[b]	1.1077	10634
	Chipping	6801	1600[a]	3.8951	6232
Napier Grass	Drying	6802	74600[b]	1.1077	82634
	Chipping	6801	12800[a]	3.8951	49857
Slash Pine	Drying	6802	398800[b]	1.1077	441751
	Chipping	6801	24500[a]	3.8951	95430
Wheat	Drying	6802	3300[b]	1.1077	3655
	Chipping	6801	600[a]	3.8951	2337

a - MJ electric

b - MJ thermal

APPENDIX D

APPENDIX D

ENERGY ANALYSIS OF ALCOHOL PRODUCTION FROM CORN

General Approach

The production of ethanol from corn is basically the same energy supply system analyzed in Appendix C, with the cooking, fermentation and distillation of the corn, which is harvested, collected and stored at the farmstead, to produce a liquid fuel in place of the drying and chipping of that same corn for the production of a solid fuel. However, the production of a liquid fuel is much more energy intensive than the production of a solid fuel. Thus, a rigorous energy analysis must be applied to the processing system that converts corn into ethanol.

The technology and the components utilized for the production of alcohol are conventional allowing the straightforward application of input-output analysis to the material and energy flows of the nameplate processing system as identified through the application of process analysis. The energy subsidy of the corn (as stored on the farmstead) required by the system is taken from the analysis performed in Appendix C. The corn is assumed to be transported 500 miles via for-hire inter-city truck transportation from the farmstead to

the alcohol plant and a transportation distance of 500 miles via private inter-city truck transportation is assumed for the delivery of the by-products of the alcohol plant. The transportation distances for the delivery of the required coal to the alcohol plant (via rail transportation) and the delivery of the alcohol to its end-use site (via private inter-city truck transportation) are varied in order to indicate the sensitivity of the system's energy parameters to these transportation distances.

Note that a dollar cost for the installation of equipment is reported in the design report describing the alcohol plant and the energy required for these operations is based on the reported cost. The same energy requirement is also estimated from information obtained from the disaggregation of energy intensity coefficients for comparison purposes.

Definition of Nameplate Processing System

The inputs and outputs of the nameplate processing system are defined by the capital, raw material and utility requirements and the products of the alcohol plant described in a design evaluation performed by the Raphall Katzen Associates (1). The alcohol plant requires inputs of delivered corn, coal, chemicals and capital. The outputs of the plant are 199 proof ethanol, distiller's dark grains, fusel oil and 40 weight per cent aqueous ammonia sulfide solution (all products are non-delivered).

Description of Data

The data describing the inputs and outputs of the nameplate processing system are contained in a design report of a grain motor fuel plant assembled by the Raphall Katzen Associates (1). The capital investment is reported as the purchaser's price in 1978 dollars for the components required by the system operations listed in Table D.1 purchased as sales to final demand, the required field materials purchased as sales to the new construction industry (sector 1103) and the buildings and structures representing a sub-contracted fee paid to the new construction industry for the construction of the buildings and structures. The installation of components and field materials is reported as the purchaser's price in 1978 dollars for the installation service.

The required raw materials are reported as an annual purchaser's price in 1978 dollars and the required utilities are reported as the annual quantities of fuel or electricity consumed. The feedstock requirement is reported as the annual quantity of delivered corn (at a 15 per cent moisture content) processed.

Application of Process Analysis

Inputs

Inputs 1-3, 8-10

Table D.2 lists the purchaser's price of required components and field materials. The installation of the

Table D.1. Definition of operations required for production of alcohol from corn (1)

Section	Operation
100	Grain storage
200	Cooking and saccharification
300	Fungal Amylase production
400	Fermentation
500	Distillation
600	Residue feed processing
700	Storage and shipping
800	Utilities

Table D.2. Purchaser's prices of required components and field materials (1)

I-O Sector	Purchaser's Price (x 10^3 $1978)								
	Equipment								
	100[a]	200[a]	300[a]	400[a]	500[a]	600[a]	700[a]	800[a]	Field Materials
3000	--	--	--	--	--	--	--	--	33.0
3610	--	--	--	--	--	--	--	--	389.0
3620	--	--	--	--	--	--	--	--	212.0
4004	--	--	--	--	--	--	--	--	336.0
4006	--	700.8	684.0	1641.4	1451.7	3936.3	1040.0	3614.6	--
4208	--	17.8	--	--	--	47.1	38.0	--	2194.0
4502	743.9	--	--	--	--	189.3	62.0	--	--
4503	--	--	--	--	--	--	--	300.0	--
4601	34.0	--	--	--	--	--	--	--	--
4602	80.5	--	--	--	--	45.6	18.7	--	--
4604	--	--	--	--	--	--	60.0	30.0	--
4901	--	21.8	161.0	56.4	23.1	8.7	21.4	316.5	--
4903	51.5	--	68.3	64.0	--	145.7	41.8	910.0	--
4906	--	--	--	--	--	810.0	--	--	--
4907	75.0	3.3	--	--	--	934.0	111.3	450.0	--
5304	--	10.0	354.0	1.5	--	--	--	--	--
5305	--	--	--	--	--	--	--	--	389.0
5308	--	--	--	--	--	--	--	--	275.0

a - System operation defined in Table D.1

components and field materials and the construction of buildings and structures are reported as 11141 x 10^3 and 13478 x 10^3 $1978 purchaser's price (sector 1103), respectively (1).

Inputs 4-5

The feed to the system is freely available solar radiation. Table D.3 and Table D.4 list the annual raw material and utility requirements, respectively. The system is reported to require 543,977 tons/yr. of delivered corn (at a moisture content of 15 per cent) (1). The energies required for delivery of the corn and coal to the alcohol plant are estimated by extending process analysis to the delivery systems and the energy content and subsidy of the corn is estimated by extending process analysis to the crop producing system.

Table D.3. Raw material requirements (1)

Raw Material	Purchaser's Price ($1978/yr)	I-O Sector
Yeast	316800	2701
Miscellaneous Chemicals	422633	2701
Solvent	7223	2701
Iodine Sterilizing Solution	17028	2701

Table D.4. Utility requirements

Utility	Unit Quantity	Quantity Required (1) (unit/yr)	Energy Content (2) (Btu/unit)	Energy Consumed for Production of Alcohol ($\times 10^9$ Btu/yr)	I-O Sector
Coal	ton	97899	21.3×10^6	2085.2	700
Tractor Gasoline	gal	285120	125075	35.7	3101
Electricity	Kwh	65.8×10^6	3413	224.7	6801

Inputs 6-7

Energy required for delivery of the primary (ethanol) and secondary (distiller's dark grains, fusel oil, ammonia sulfied solution) products is estimated by extending process analysis to the delivery system. There are no waste products reported that require handling facilities not included in the nameplate processing system.

Input 11

Data describing the maintenance requirement of the system is not reported. The energy required for maintenance is assumed to be negligible.

Outputs

Table D.5 lists the energy outputs of the system.

Table D.5. Energy outputs of alcohol plant

Energy Product	Unit Quantity	Quantity Produced (1) (unit/yr)	Energy Content (2) (Btu/unit)	Energy Output ($\times 10^9$ Btu/yr)
Alcohol	gal	50×10^6	84060 (1)	4203
Distiller's Dark Grains	ton	173448	8169 (1)	2834
Fusel Oil	gal	224000	149690 (2)	34

Extension of Process Analysis

Energy Subsidy and Content of Delivered Corn

Table D.6 lists the energy content and energy subsidy of the delivered corn required by the system.

Table D.6. Energy content and subsidy of delivered corn (15 per cent moisture content) (7)

Quantity Required (ton/yr)	Energy Content of Corn[a] (7) ($\times 10^6$ Btu/ton)	Energy Subsidy of Delivered Corn (7) (Btu primary / Btu)	Energy Content of Feed to System ($\times 10^9$ Btu/yr)	Energy Subsidy of Feed to System ($\times 10^9$ Btu primary/yr)
543977	12.073	0.278	6567	1824

a - Based on corn energy content of 17 MJ/kg dry basis and an energy penalty of 2.79 MJ/kg of water content (7)

Energy Required for Delivery of Coal and Products of System

Delivery of the coal (assumed to be via rail transportation) and the delivery of the system's products (assumed to be via private inter-city truck transportation) are reported to require 1500 and 7000 Btu primary/ton-mile, respectively (3). Table D.7 lists the energies required for delivery of coal and the system's products as a function of the transportation distance.

Table D.7. Energies required for delivery of coal and the system's products

Material	Quantity (1) (tons/yr)	Transportation Distance (miles)	Energy Requirement ($\times 10^9$ Btu primary/yr)
Coal	97899	500	73
		1000	147
		1500	220
Alcohol	164675[a]	500	576
		1000	1153
		1500	1729
Distiller's Dark Grain	173448	500	607
Fusel Oil	738[a]	500	3
Ammonia Sulfide Solution	26058	500	91

a - Assumes a density of 0.7893 g/cm^3 (4)

Application of Input-Output Analysis

Table D.8 lists the deflation of the cost data, Table D.9 lists the required trade and transportation margins, Table D.10 lists the producer's prices and embodied energies of the required capital and raw materials, and Tables D.11 and D.12 list the embodied energies and energies required for delivery of the required utilities.

Table D.8. Deflation of cost data

I-O Sector	Purchaser's Price ($\times 10^3$ \$1978)	$\frac{\$1978}{\$1967}$ (8)	Purchaser's Price ($\times 10^3$ \$1967)	Purchaser
	(lifetime cost data)			
1103[a]	13478	2.403	5609	final demand
1103[b]	11141	2.403	4636	
4006	13069	2.279	5735	
4208	103	2.663	39	
4502	995	2.275	437	
4503	300	2.713	111	
4601	34	2.042	17	
4602	145	2.042	71	
4604	90	2.112	43	
4901	609	2.011	303	
4903	1281	2.065	620	
4906	810	2.065	392	
4907	1574	2.065	762	
5304	366	1.932	189	
3000	33	1.891	18	new
3610	389	2.018	193	construction
3620	212	2.018	105	industry
4004	336	2.328	144	(sector 1103)
4208	2194	2.663	824	
5305	389	1.932	201	
5308	275	1.932	142	
	(annual cost data)			
2701	734	2.401	318	final demand

a - Buildings and structures
b - Installation

Table D.9. Trade and transportation margins

I-O Sector	6501	6503	6504	6505	6506	6901	6902	Totals	Purchaser
				(% of purchaser's price)					
1103	0	0	0	0	0	0	0	0	final
2701	2	1	0	0	0	3	2	8	demand (5)
4006	1	1	0	0	0	4	0	6	
4208	0	1	0	0	0	11	0	12	
4502	0	1	0	0	0	5	0	6	
4503	0	1	0	0	0	8	0	9	
4601	0	1	0	0	0	4	0	5	
4602	0	2	0	0	0	5	0	7	
4604	1	2	0	0	0	5	0	8	
4901	1	2	0	0	0	10	0	13	
4903	0	1	0	0	0	7	0	8	
4906	0	1	0	0	0	7	0	8	
4907	0	0	0	0	0	7	0	7	
5304	0	1	0	0	0	2	1	4	
				($1967/10^{6} Btu)					
3101	0.0058	0.0195	0.0266	0.0	0.0201	0.4948	0.3604	--	
6801	0.0	0.0	0.0	0.0	0.0	0.0	0.0	--	
				(% of purchaser's price)					
3000	0	1	0	0	0	8	28	37	new
3610	0	1	0	0	0	18	1	20	construction
3620	6	1	0	0	0	7	5	19	industry (9)
4004	2	2	0	0	0	4	0	8	(sector 1103)
4208	0	1	0	0	0	11	5	17	
5305*	0	0	0	0	0	5	0	5	
5308*	0	0	0	0	0	3	0	3	

Table D.9. Continued

* No interaction with new construction industry - margins for sales to final demand used

Table D.10. Producer's prices and embodied energies of required capital and raw materials

I-O Sector	Producer's Price ($\times 10^3$ \$1967)	Btu Primary \$1967 (5)	Embodied Energy ($\times 10^9$ Btu Primary)
	(lifetime energy inputs)		
1103[a]	5,609	85,922	482
1103[b]	4,636	85,922	398
3000	11	129,402	1
3610	154	148,220	23
3620	85	162,859	14
4004	133	131,635	17
4006	5,390	111,172	599
4208	718	78,483	57
4502	408	75,541	31
4503	101	76,704	8
4601	16	62,372	1
4602	66	68,636	5
4604	39	63,180	2
4901	263	59,006	16
4903	571	66,579	38
4906	361	76,370	28
4907	709	68,763	49
5304	182	67,105	12
5305	191	41,307	8
5308	138	63,182	9
6501	70	92,917	7
6503	98	54,968	6
6901	585	37,501	22
6902	72	37,329	2
	(annual energy inputs)		
2701	293	291,465	85
6501	6	92,917	1
6503	3	54,968	--
6901	10	37,501	--
6902	6	37,329	--

a,b - See Table D.9

Table D.11. Energy embodied in utilities

I-O Sector	Energy Content ($\times 10^9$ Btu/yr)	Btu Primary / Btu (5)	Embodied Energy ($\times 10^9$ Btu Primary/yr)
700	2085	1.0087	2103
3101	38	1.2157	43
6801	225	3.8951	875

Table D.12. Energy required for delivery of utilities (excluding coal)

I-O Sector	Purchaser's Price ($\times 10^3$ $1967/yr)	Btu Primary / $1967 (5)	Embodied Energy ($\times 10^9$ Btu Primary/yr)
6501	0.22	92917	0.02
6503	0.74	54968	0.04
6504	1.00	262498	0.26
6506	0.76	121420	0.09
6901	18.65	37501	0.70
6902	13.59	37329	0.51

Application of the Disaggregation of Energy Intensity Coefficients

The energy required for the installation of the components and field materials can be estimated by assuming that the energy embodied in the non-delivered components and field materials is analogous to the material contribution to the total energy requirement of the new construction industry (sector 1103). Examination of the disaggregation of the new construction industry's energy intensity coefficient indicates that 65.34 per cent of the sector's total energy requirement originates from the materials input (6) (see Table A.28). The energy embodied in the non-delivered components and raw materials of the alcohol plant is 918×10^9 Btu primary. Thus, the energy required for installation of the components and field materials is 487×10^9 Btu primary as estimated using information obtained from the disaggregation of the new construction industry's energy intensity coefficient. This value is in good agreement with the installation energy estimated from the cost of the service (398×10^9 Btu primary compared to 487×10^9 Btu primary).

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