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TITLE: Energy Resource Conservation In New Large Power Plants

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This thesis evaluates new, large power generating plants of the various types expected to be practicable in the time span of the next 50 years. By using thermodynamic principles, the plants are evaluated on the basis of conservation of energy; the basic assumption is that the best policy is the one that conserves available resources.

On this basis and excluding other factors such as environmental or social acceptance, the leading candidate is the plant that makes the most efficient use of all resources to produce a unit of beneficial energy. This thesis emphasizes those resources that will be in abundant supply during the next 50 years. Resources used in this comparison are solar energy, coal, nuclear fission, and possible use of organic wastes.

Three applications of energy are studied: work energy, thermal energy, and hydrogen production. The first law energy trajectory technique was found to be the soundest means of evaluating power producing plants. Simply defined, an energy trajectory is the energy system from the resource energy in nature through the use of energy by man. The energy-trajectory efficiency is determined by the energy beneficially used divided by the resource energy required to produce the end-use energy.

Each energy trajectory is further broken down into handling or processing steps, called nodes; nodal efficiencies are gathered from the literature. A power plant is only one node of a trajectory.

From a total of 90 energy trajectories studied, the most efficient plants from an energy conservation standpoint were found to be:

For work energy applications, coal and nuclear thermal-cycle electric plants;

For thermal energy applications, coal and organic waste plants (for example straw) fired directly;

For hydrogen production, coal and organic waste plants utilizing an open cycle process.

It was further concluded that the energy trajectories which include hydrogen or other synthetic fuels are not as efficient as alternate, more direct, energy trajectories. Solar energy was found to be competitive only for thermal applications and then only when little or no energy storage is required.

The technique used in this thesis provides an adequate basis of evaluation if the policy for large power conversion systems is to conserve energy resources. In addition, the technique could be modified to compare energy trajectories that are weighted for preferred resource use.

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This thesis arose from the author's interest in large scale solar power plants and an interest in generating methods to evaluate the usefulness of such plants. Interestingly enough, continued studies and evaluations led to a constantly changing viewpoint. Evaluation of solar concepts quickly led to a major engineering problem - - that of energy storage. Attacking the storage problem led to the use of hydrogen as one of the best candidates for storing energy. Evaluation of hydrogen-producing methods indicated that the closed thermochemical-cycle, water-separation system looked promising. However, further study led to the conclusions of this thesis; that open-cycle chemical separation was superior to the closed cycle; that energy converted for storage (e.g., hydrogen) consumes more of the energy resources than using, for example, coal or straw for the same end results; and that, in fact, solar plants do not make effective use of energy resources.

Along the way I had many helpful discussions with experts in the field: Dr. Kenneth E. Cox of the University of New Mexico and Editor of Hydrogen, CRC Press; Dr. Mel. G. Bowman of Los Alamos Scientific Laboratory; Dr. George E. Sauter of Lawrence Livermore Laboratory; Dr. J.L. Russell of General Atomics; Dr. G.M. Reistad of Oregon State University; Dr. C.A. Rohrmann of Battelle-Pacific Northwest Laboratories; Dr. Craig B. Smith of Applied Nucleonics and Editor of the Efficient Electricity Use; Dr. K. Maddox of Development Sciences; Dr. Pollard of Energy Analysis; Dr. T.A. Chubb of the Naval Research Laboratory; Dr. Carlos Bamberger of Oak Ridge National Laboratory; and George F. Bailey of Washington Public Power Supply

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ENERGY RESOURCE CONSERVATION IN NEW LARGE POWER PLANTS

I. INTRODUCTION AND SUMMARY

A. Purpose

This thesis is an evaluation, on the basis of energy resource conservation, of new large power plants. The time period of the evaluation is the next 50 years and the plant sizes considered are equivalent to the present 1,000 MWe, or larger, electricity generating plants.

For this thesis, energy-resource conservation is defined as utilizing the least amount of resource energy (joules) to accomplish a specific end-use requirement. This is in recognition of the fact that the natural energy sources available to man's use today, although abundant, are finite. This study emphasizes those sources that are, and will be, abundant for the next 50 years.

The term "power plants" is used to include large power conversion systems, including chemical systems for conversion of resources to convenient energy forms for distribution and use. Hydrogen, an example of a synthetic fuel, has been considered as a convenient means of storing energy and also as a medium for energy transport. Consequently, hydrogen production is included in this study.

This evaluation includes a preference for renewable energy sources over non-renewable sources, but only if the overall energy-resource utilization is not drastically increased. Social or political inputs that could be used to quantify the preference were not considered here. Also, this analysis was limited to thermodynamic considerations; economic parameters were only indirectly considered.

B. Background

The original purpose of the study was to gain a technical insight into future large power plants; it was initiated from the author's deep interest in and concern for the energy future including the role of solar energy. The storage of energy produced from large solar-power plants is a major engineering problem. Hydrogen has been recognized as one of the best storage mediums because of its high-density energy. Production of hydrogen by closed thermochemical water-separation cycles has been proposed by many[1,2,3] to be the best production process.

The study was expanded beyond that of solar power plants and hydrogen production to provide a better basis and perspective on which to evaluate the role of solar energy and hydrogen.

Thermodynamics was selected as the method for evaluating the energy-conversion systems. The second-law available-energy concept, net energy analysis, and the first-law energy-balance were considered as candidates for energy-system comparisons.

The thesis conclusions apply only to the energy systems covered and only to the nodal thermodynamic-efficiencies used; however, the systems were selected to cover broad categories and effort was made to select realistic efficiencies. As such, the conclusions are considered by the author to be generally correct.

C. Summary

The first law of thermodynamics is the basis for what proved to be the best technique for evaluating the energy systems studied. As such, this method should continue to be used for relative evaluation of power plants. The second-law concept of available energy provides insight; however, the available-energy concept, as well as a net-energy analysis, only slightly modified the results yielded from first-law considerations.

It was found that the power plants should only be compared by considering the complete trajectory of energy (or energy chain), including the end use of the energy. This is because a variety of energy sources were considered, the power conversion products were varied, and the energy could be used for work or heat. The efficiency as used in this thesis for energy system comparisons is thus the efficiency determined by the product of all of the nodal efficiencies, that are connected in series, to make up the total trajectory. The trajectory is defined as the energy domain controlled by man from the time that the resource is removed from its natural environment until the energy is completely returned to natural processes. Inefficiencies relating to natural processes prior to man's intervention or subsequent to man's release of the energy are not considered. Likewise, energy that is not utilized is not considered; i.e., coal left in the mine, solar rays not intercepted, etc. are not considered as losses of energy. The chain nodes are the specific handling, transport, or conversion links in the trajectory.

The incorporation of a hydrogen link in the energy chain is not an effective utilization of resources; alternate energy trajectories were found to be more efficient. Hydrogen does not even appear to be a good candidate for energy storage or transport, for the next 50 years, since some other energy chains allow better conservation of the resources. Also, closed-cycle production of hydrogen requires more energy input than does open-cycle production.

In general, coal, organic waste, and uranium provide the best utilization of the resources for man's needs for the next 50 years. Details are contained in the following chapters.

II. THERMODYNAMIC CONSIDERATIONS

A. General

Consider the period between the years 1977 and 2027, the next 50 years. During this period the fossil fuel supplies are expected to dwindle to such an extent that energy production (conversion) on a large scale will have to shift from a reliance on natural gas and oil to other energy sources. These alternate sources will probably be coal and sources of nuclear fission, including uranium, thorium, and plutonium. In the mean time, efforts will be made to harness the solar energy. Fusion power probably will not provide large quantities of energy before the end of the period discussed here.

Why convert source energies to hydrogen or electric energies? Why not use solar energy or coal or crude oil directly? The answer is that electricity, hydrogen, and gasoline are more convenient forms of energy for many uses. Hydrogen is considered in this study because of its many positive attributes for energy storage, as an energy carrier and as a fuel; it is also an example of a synthetic fuel. Bi-gas and liquified synthetic fuel are also considered.

Available sources of energy that can be utilized to produce hydrogen and electricity are, natural gas, oil, coal, organic wastes, the sun, uranium (and thorium and plutonium), secondary solar sources (wind, hydro, ocean thermal), and other sources such as tides and geothermal processes. Basically, any energy form can be converted to electricity, hydrogen energy, or other convenient forms. The resources that are considered in this thesis are solar energy, coal, nuclear fission, and the possible use of organic wastes.

The Rankine cycle, utilizing a steam turbine, is likely to continue to be used for large-scale production of electricity during the next 50 years, even if the energy source being utilized is the sun's rays. This is due to considerations of economics and the most efficient use of the energy resource. Hydrogen is considered to be an alternative to electricity. The separation or conversion process most commonly used today to produce hydrogen is the reaction of high-temperature steam with a hydrocarbon, which is an open-cycle chemical process. Today, methane is the most common hydrocarbon used to produce hydrogen. Hydrogen can also be produced by electrolysis, closed-cycle thermo-chemical separation from water, and open-cycle chemical-separation. The open-cycle separation of hydrogen utilizes the input of carbon or a hydrocarbon as well as thermal energy and water to produce free hydrogen. The closed-cycle has water and thermal energy inputs only. Chemicals utilized in the closed-cycle processes are continuously recycled to their original form.

B. <u>Energy Conversion Trajectories</u>

Figure 1 is a generalized schematic of the energy flow as controlled by man for his beneficial use. The energy resources are shown on the left as they exist in nature. All of these are energy sources because they are not in equilibrium with the environment, and will naturally decay in time to equilibrium with the environment. Man can intercept the energy and control this degradation process for his benefit and then return the energy to nature as indicated on the right hand side of the chart where it tends toward equilibrium with the environment. Finally, the energy is radiated to space.

The total-energy chain-efficiency as used here only includes the energy flow from the time that man intervenes until he completes his use and the energy is again free in nature. The coal left in the mine, the oil left in the ground, and the solar energy remaining untapped (land utilization efficiency) are not considered. The chain efficiency, then, is the energy beneficially used divided by the resource energy required to produce the work, or heat, for any specific energy trajectory.

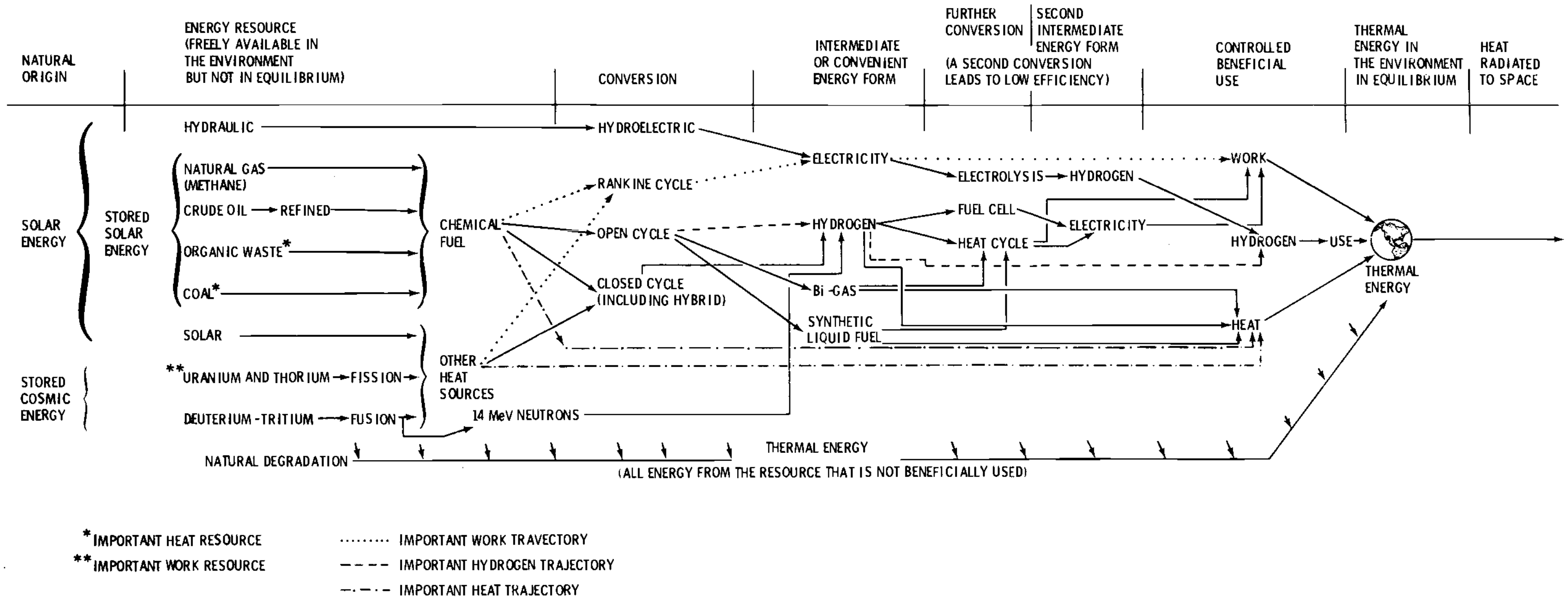

Figure 1. Generalized Energy Flow Schematic

Displayed in Figure 1 are eight energy sources and three beneficial end-uses. Hydrogen is included as an end-use along with work-energy and thermal-energy only to evaluate the best production chain to that point. Hydrogen represents a new energy carrier and thus was given special emphasis for evaluation in this study.

Among the eight energy sources and the three end-uses there are hundreds of possible trajectories. For this study, the conversion processes are generalized to four types: Rankine-cycle generation of electricity, open-cycle production of hydrogen and other synthetic fuels, closed-cycle production of hydrogen, and direct heating. Ninety trajectories were used in this evaluation.

The intermediate or convenient energy forms given most emphasis in this study were hydrogen and electricity, but Bi-gas and liquified synthetic fuel were also considered. Not considered here but worthy of evaluation are methanol, methane, and ammonia.

C. The first law of Thermodynamics

The energy-balance procedure using the first-law-of-thermodynamics is an established method for determining the resource required to produce a unit of usable energy. Varied energy-conversion plants can be compared by this method if they use the same input energy and produce the same output. However, the following considerations indicated that the traditional method for evaluating energy systems may not have been totally applicable for comparing future power plants.

1). The second-law availability has been shown in some cases to provide a better evaluation of energy systems than the first-law.

2). The evaluation of the energy cost to produce energy (i.e., net energy analysis), has been proposed as an important method of evaluation for future power plants.

3). Attempts to equate electricity and hydrogen at equal availabilities or equal calorific values in order to use the first law have not been successful. This is because electricity can be used for work energy more efficiently than hydrogen; either electricity or hydrogen can be produced from each other; either can be used for some of the same applications and for yet other applications only one can be used; and, they both can be produced from the same resource, but at different efficiencies.

4). Historically, economics has determined power plant preference more than thermodynamics.

These four considerations are discussed in more detail throughout the chapter.

D. The Second Law of Thermodynamics

1. Availability

The second law provides the basis for evaluating the potential of energy in any form to provide useful work for man. Availability is the measure of the work that can be controlled and usefully utilized by man if the material or process (system) containing this available energy could be reversibly (no inefficiencies or losses) converted from its existing energy form to that desired by man while being reduced to equilibrium. It is measured in the same units as work energy, but is not the same as first-law conserved-energy. Rather, it is a potential energy which is not in equilibrium with the environment. It is the driving force that causes the process to progress, and, as the process progresses, available energy is consumed. When the material, process, or system is in complete equilibrium with the environment, usable energy is zero and has no potential for use or conversion to other forms of energy.

In the energy chains discussed in this thesis, the input and output of each link or node is usually fuel (chemical energy) or electricity and is roughly 100% available. For fuels, the availability is not equal to either the high or low heating value but is close enough to the typically used higher heating values that are used in the nodal efficiencies, that are taken from the literature, that the difference can be neglected. The fuel availability is determined by calculating the minimum amount of work-energy that is needed to synthesize the fuel, into what ever state it is to be used, out of materials in the environment and in equilibrium with the environment. This minimum work is, of course, equal to the maximum work that can be accomplished by the fuel.

2. Cascading

The second law provides many valuable insights that must be understood to truly evaluate power plants. Energy cascading is an example. Many of man's energy requirements are for essentially low-grade heat. However, his fuels are high grade; if they are used in low-grade applications, a significant amount of availability has been lost (unused).

Electric heat is an example, since electric energy is high grade (essentially 100% available). When electricity is used to heat a home where the temperature desired is 294°K (70°F), there is a big loss of availability. High grade electricity could have been utilized to do work and still have had enough heat left over to heat the house.

Using the same energy to perform several different tasks as the energy degrades is called cascading. The use of topping and bottoming cycles on a power plant is an example. In this case, the high-temperature combustion drives one heat-cycle; the exhaust heat from that cycle drives the main cycle; and the waste heat from the main cycle drives the bottoming cycle. However, this improved efficiency is achieved only if the combination approaches a Carnot cycle (the thermal cycle that will yield the maximum efficiency for a given maximum temperature) better than a single cycle, or better utilizes the temperature range.

It may be noted that, since it is the practice to convert fuels to work energy in heat cycles, the node efficiencies in these cases are controlled by material considerations, not the fuel availability. The materials of construction limit maximum cycle temperatures to well below combustion temperatures. The availability, in a way, determines the combustion temperature which in turn can potentially yield a highly efficient conversion process. The materials, however, limit the energy-conversion cycle to a lower temperature and thus a lower efficiency.

3. The Use Of The Second Law

This thesis uses the first law as the basic method of evaluation. However, the second law is valuable in understanding the actual process efficiencies and the maximum possible efficiencies of power plants. Such thermal energy processes can only be properly evaluated by using the second law.

In this thesis, however, the power plant is represented as a node and the node efficiency is taken from the literature. Therefore, the thermal cycle and thus the second law considerations are already contained in the node. By using this nodal approach, the energy input and output to each node is essentially 100% available (as noted in Section D.1 above). In other words, for purposes of this study, the first and the second laws will produce essentially the same results.

E. Net Energy Analysis

1. Definition

In evaluating future energy-conversion systems, all energy inputs must be considered. Net-energy analysis is an analytical technique that was developed in recent years and was written into the Energy Act of 1974 (Public Law 93-577), the same law created the Energy Research and Development Administration. The technique tries to identify and quantify the energy that is in materials, the energy that is used to fabricate equipment and construct conversion plants and equipment, and all other energy inputs that are normally not part of the traditional steady-state input-output energy balance. These are called energy subsidies.

Energy inputs are related to the costs of the items. Three methods, and combinations of the three, have been used to determine the values. The first is to assume that, for power plants, the energy per dollar is the same as the Gross National Product (GNP) divided into the national yearly energy consumption. The second method is to analyze all of the processes and total the costs and energies. The third method uses input/output information from the 357 major sectors of the U. S. economy.

It is unfortunate that much of the analysis that has been completed to date is confusing, misleading, and contradictory. This is not because of the methods, but because many interpretations are required; it is not clear what to include and what form to include it in. Further, since input energy is the desired information, large differences in results are generated by the location of the boundary of the calculation. This is because the energy for an operation can come from inside the boundary and thus not be counted or it can come across the boundary and become part of the subsidy; therefore, the results of net-energy calculations can be significantly affected by arbitrary calculational boundaries. There is also some confusion in handling the calorific value of electricity as compared to resource energy.

2. Estimation of the Energy Subsidy

The results of energy subsidy calculations for power plants and energy trajectories, as reported in literature, vary considerably from analyst to analyst. Frabetti[4] has reconciled the results of the significant reports. He concludes that the energy subsidies for power systems are less than 10% today. Thus, the results of net-energy analysis may not significantly affect the conclusions reached using only the first law.

Rohmbough and Koen[5] have shown that the average subsidy per dollar invested in power plant equipment and materials is roughly equal to the U.S. energy consumption divided by the gross national product (GNP). Frabetti,[6] in evaluating the subsidy for heating systems in New England, produced the same result. Baron[7] observed, from studies of many present and proposed power plants, that the capital, plus interest, invested in a 1000 MWe plant and its fuel is inversely proportional to the net cycle efficiency. As a convenient approximation, it is assumed that these relationships will hold for the systems evaluated in this thesis.

Combining these two relationships cancels the cost and yields:

$$\text{The Energy Subsidy As A Percentage Of The Resource Energy Input} = \frac{0.014}{\text{Total Energy Chain Efficiency}}$$

A conservative constant of 0.02 will be used.

Assuming that the relationship is applicable, it is noted that, if the total chain efficiency is 20%, the subsidy is 10% of the resource energy input. In other words, for one joule of output, five joules of resource are required, plus an energy subsidy of 0.5 joules of resource energy or the equivalent (which is equal to 0.1 joules of output energy or the equivalent). This is in agreement with Frabetti's findings that today's subsidy is below 10%. Present plants have chain efficiencies above 20%. If this relationship applies, the energy subsidy is not only small but a function of the first law efficiency. Appendix B derives the above energy subsidy relationship and discusses it further. For purposes of illustration, the net energy efficiencies are calculated along with the first-law efficiencies.

F. Method of Analysis

1. Scope of Study

As discussed under II.D. "The Second Law Of Thermodynamics", and II.E. "Net Energy Analysis", neither the second law availability considerations nor net-energy inputs will affect the results of power-plant evaluations derived by using the first law when second law effects are internal to the nodes and reflected in the node efficiency. Economic considerations will be discussed under II.G. "Other Considerations".

The traditional technique for evaluating power-producing plants, based on the first law of thermodynamics, will therefore be the technique used in this study. The evaluation is defined so as to rank the systems by the amount of energy resource required to produce a unit of beneficially used energy. As noted in Figure 1, the trajectories are varied, have eight potential energy resources, and have three beneficial end-uses of the energy. Since a relationship between work-energy, thermal-energy, and hydrogen as to their relative benefits to man is not obvious, the energy trajectories are separated into these three end-use groupings.

This thesis is based on an assumption that the best policy is one that would utilize the least amount, in terms of joules of energy, of the total earthly resource of abundant energy sources. In other words, the abundant resource that should be used is the one that provides the highest total-energy trajectory-efficiency.

This is roughly what is happening in the free market today, and will likely continue into the 50-year period discussed. Continued use of such policies would conserve the abundant but finite energy resource. A policy favoring a resource which could not be as efficiently used would be more consumptive.

On the other hand, the results of this analysis provide a means of comparison that can be used to determine the social or political factors required to preferentially select renewable energy resources. This is discussed in more detail under II. G. "Other Considerations". However, if two resources provide about the same efficiency, this study gives preference to the renewable source. Likewise, it is desired that the convenient, stored, chemical-energy sources (fossil fuels) be conserved as much as possible.

2. Trajectory Computations

The trajectories have been schematically displayed for data collection and computations. Figure 2, "Trajectory Key" and Figure 3, "Typical Trajectories" illustrate the display and identify the information shown. All of the data displays that have been used in this thesis are included in Appendix A.

To avoid repeating the same energy chain information for each end-use evaluated, two types of chains are considered (Figure 3). The chains that have electricity as the convenient energy form have two end-use nodes, work-energy and thermal-energy, as shown in the top chain of Figure 3. Therefore, the displayed chain is really two trajectories identified by the number in the middle of the end-use node. And, the chains that have hydrogen as the convenient energy have four end-use nodes: hydrogen itself; work-energy produced by a heat engine; work-energy produced by a fuel cell; and thermal-energy (the bottom chain of Figure 3). The chain nodes are then the information that is coupled with each end-node to make a complete trajectory. Hydrogen is considered as an end-use node and a chain node.

Figure 2 illustrates the two types of nodes used and identifies the information displayed. As stated earlier, the node efficiencies are taken from the literature. The trajectory first-law efficiency is determined by multiplying the efficiencies of all of the nodes of the trajectories together. The first-law

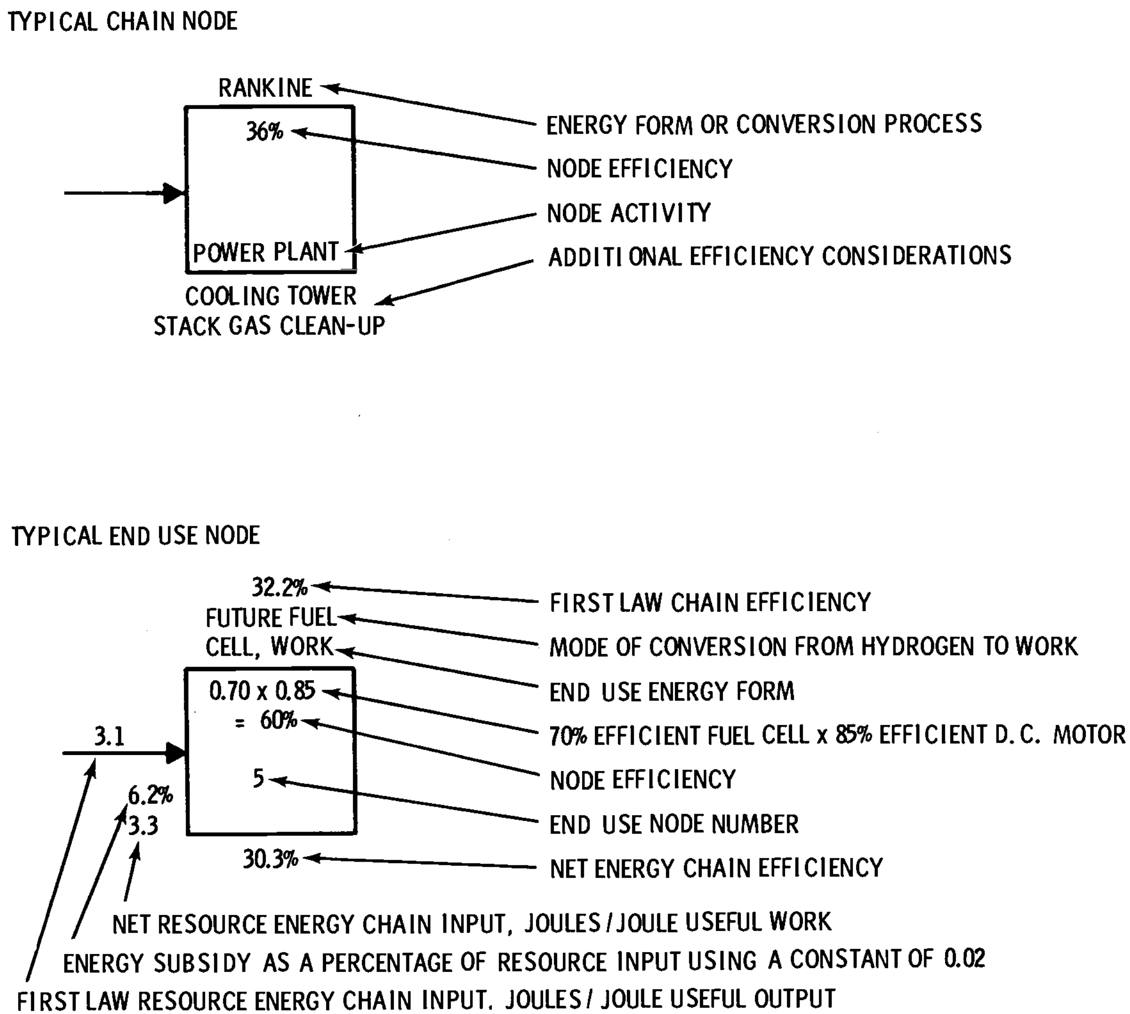

Figure 2. Trajectory Key

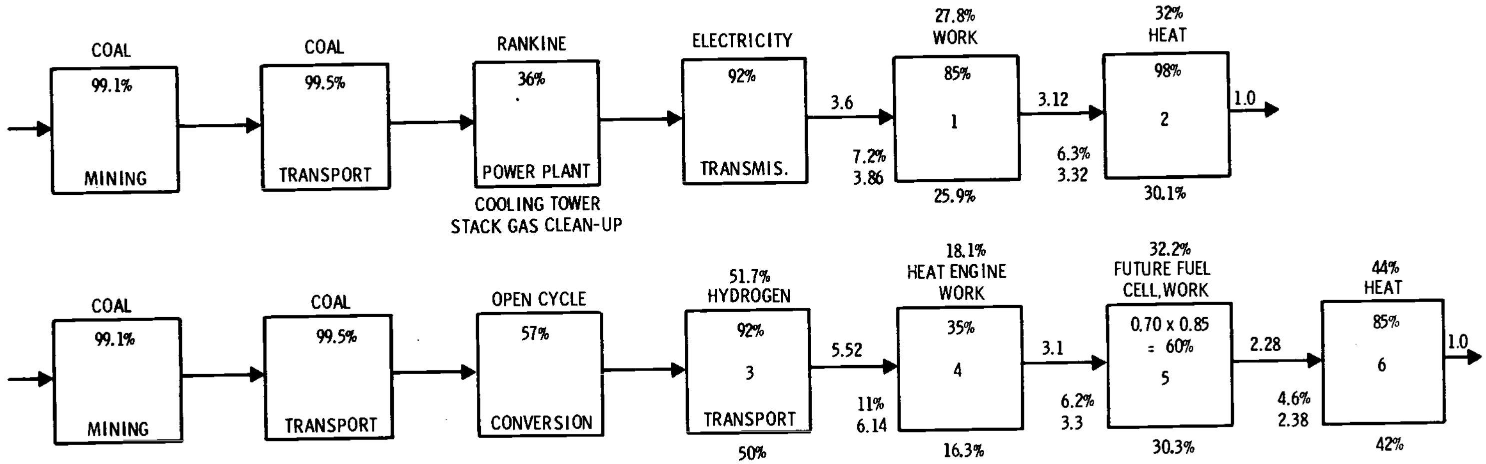

Figure 3. Typical Trajectory

resource-energy input to produce a joule of useful energy is the inverse of the trajectory first-law efficiency.

The net-energy-subsidy percentage is calculated from the relationship determined from II.E.2. "Estimation of the Energy Subsidy", using a factor of 0.02. The energy subsidy is then calculated by multiplying this percentage by the first-law input. The net trajectory-input energy is then the sum of the subsidy and the first-law input energy (joules per joule of useful energy). Finally, the net trajectory-efficiency is the inverse of the net trajectory-input energy (joules per joule of useful energy). The input energies are in terms of joules input per joule of beneficially used energy.

3. Node Efficiencies

Many of the efficiencies used were from Baron[7], although they were modified to remove the net energies that he used. The Baron efficiencies for nuclear reactors were further modified so that the energy cost of the first core fuel was part of the fuel node efficiency. The electric power plants were all assumed to have cooling towers for heat removal and the coal plants had stack gas clean-up. Baron's efficiency for his solar collectors included a land utilization efficiency. As defined for this study, until man has control of the energy free in nature there are no inefficiencies. Thus, the sun that falls between reflectors is not counted as input; therefore, a collector efficiency for current solar tower design of 70% was used.

The Rankine-cycle efficiency for solar power plants was assumed to be 27% to include a minimum amount of storage. Additional (adequate) storage would further reduce the efficiency. The solar electrical-transmission efficiency was assumed to be 88% to account for probable long transmission distances. In a similar manner, the minemouth coal-plant electrical-transmission efficiency was assumed to be 87.5%.

The node-efficiency assumptions are all listed in the trajectory schematics in Appendix A. In all cases covered, it was assumed that the electrical-to-work energy-efficiency was 85%. This number represents the typical electric motor efficiencies as found in Mark's Handbook[9] for either AC or DC motors.

The hydrogen-to-work efficiency was assumed to be 35% if a heat engine were used and 60% if a fuel cell were used (85% DC motor X 70% fuel cell). The electrolysis efficiency was assumed to be 70%.

Coal conversion to heat was assumed to be 60% efficient and solar conversion to heat was assumed to be 85%. Electricity to heat was assumed to be 98% efficient and hydrogen to heat 85% efficient; the lower percentage for hydrogen heating accounts for moisture removal, which may be required in many applications.Nuclear fission for heating may well be the most efficient and should be studied further but because of the lack of data and since a better evaluation was beyond the scope of this study, a very conservative efficiency of 50% is used.

Straw was used as an example of an organic waste; however, straw may not be typical in that, as harvested, it is dry and does not require the heat of vaporization of water as an added inefficiency. Straw is also a clean fuel. The straw transportation efficiency of 93% was calculated assuming modern efficient collection and transportation[10]. A 300-mile transportation distance was assumed. The open-cycle conversion of straw to hydrogen was assumed to be 60% efficient. The low density of straw and storage considerations could reduce these efficiencies.

Hundreds of thermochemical cycles have been proposed for separating hydrogen from water. All of these cycles utilize thermal energy conversion. Thus, these cycles have unavailable energy (a portion of the energy that cannot be converted) determined by temperature-limited materials as do the heat engines. In short, these cycles have maximum theoretical efficiencies equal to that of the Carnot cycle. The thermochemical cycle that quite possibly may have the highest efficiency is a hybrid cycle, in that, one step of the cycle includes the electrolytic separation of sulfurous acid. This cycle is assumed to have an efficiency of 45% and is assumed to be the most efficient of the closed-cycles. To bracket the closed-cycle efficiencies, it is assumed that, in the period discussed, no closed cycle with an efficiency less than 20% will be considered. A 40% cycle is also included.

It must be recognized that using one efficiency for the end use of energy can be misleading. For example, the electrical-to-work efficiency of 85% applies to an electric motor operating at an efficient load. On the other hand, an incandescent electric light operating where heat is not desired is 5% efficient[11]. The end-use efficiencies used in this thesis are expected to represent the national average.

G. Other Considerations

1. Economics

Baron[7] has made an interesting observation (This has been noted previously but is repeated here to make a different point.) relating total trajectory efficiency and power plant cost including the cost of money and the cost of fuel for the plant life. He observed that the product of the cost and efficiency is a constant for all present day power plants and for most proposed for the future.

It is not clear how universal this observation is or even if it is accurate. However, if it is even somewhat true, it implies that the rankings as determined in this thesis using thermodynamic considerations would be similar to economic rankings today and the trend could continue through the period considered here. Further, decisions to utilize less efficient energy sources could result in equivalent increased costs.

2. Socio-Political Considerations

The efficiencies as calculated for the energy trajectories can be used to determine what weighting should be applied to less efficient, but more socially acceptable, energy sources to make them preferentially used. This can be determined by the ratio of the total-trajectory efficiency of the more efficient resource energy divided by the total efficiency of the preferred resource energy trajectory. Any weighting larger than this ratio would favor the socially-preferred energy-trajectory.

III. RESULTS

A. Illustrations

The results of the first-law efficiency calculations for the total trajectories were segregated as to the beneficial use of the energy. The results were then further divided as to the type of conversion (e.g. Rankine-electric, solar, etc.) and finally the results were plotted as Figures 4, 5, and 6. The trajectories are identified on the plots by the end-use node numbers from Appendix A. The generalized groupings are positioned within a closed line for convenience and with no relevance to horizontal position. The vertical position is the calculated trajectory first-law efficiency.

B. Work As The End Use Of Energy

Figure 4 is the plot of the trajectory efficiencies for those trajectories that have work as the end-use. Hydroelectric, with an efficiency of 67%, utilizes the least resource energy; however, hydraulic energy is no longer considered an abundant source. The hydroelectric trajectory has three characteristics that lend themselves to high efficiencies. The trajectory is short, with only three nodes. The resource energy is work-energy, as is the end-use of the energy. Finally, there are no heat cycles in the trajectory.

In contrast to the hydroelectric chain are the trajectories that use heat cycles to produce hydrogen, which is then utilized in a heat engine. These are illustrated in Figure 4 by the closed-cycle-hydrogen-heat engine trajectories and the Rankine-electric-electrolysis-hydrogen-heat engine trajectories. Two heat cycles in series with efficiencies of 35% will limit the trajectory efficiency to 12% as a maximum. Either system using a 70% efficient fuel cell instead of a heat engine could be as efficient as some of the Rankine electric trajectories.

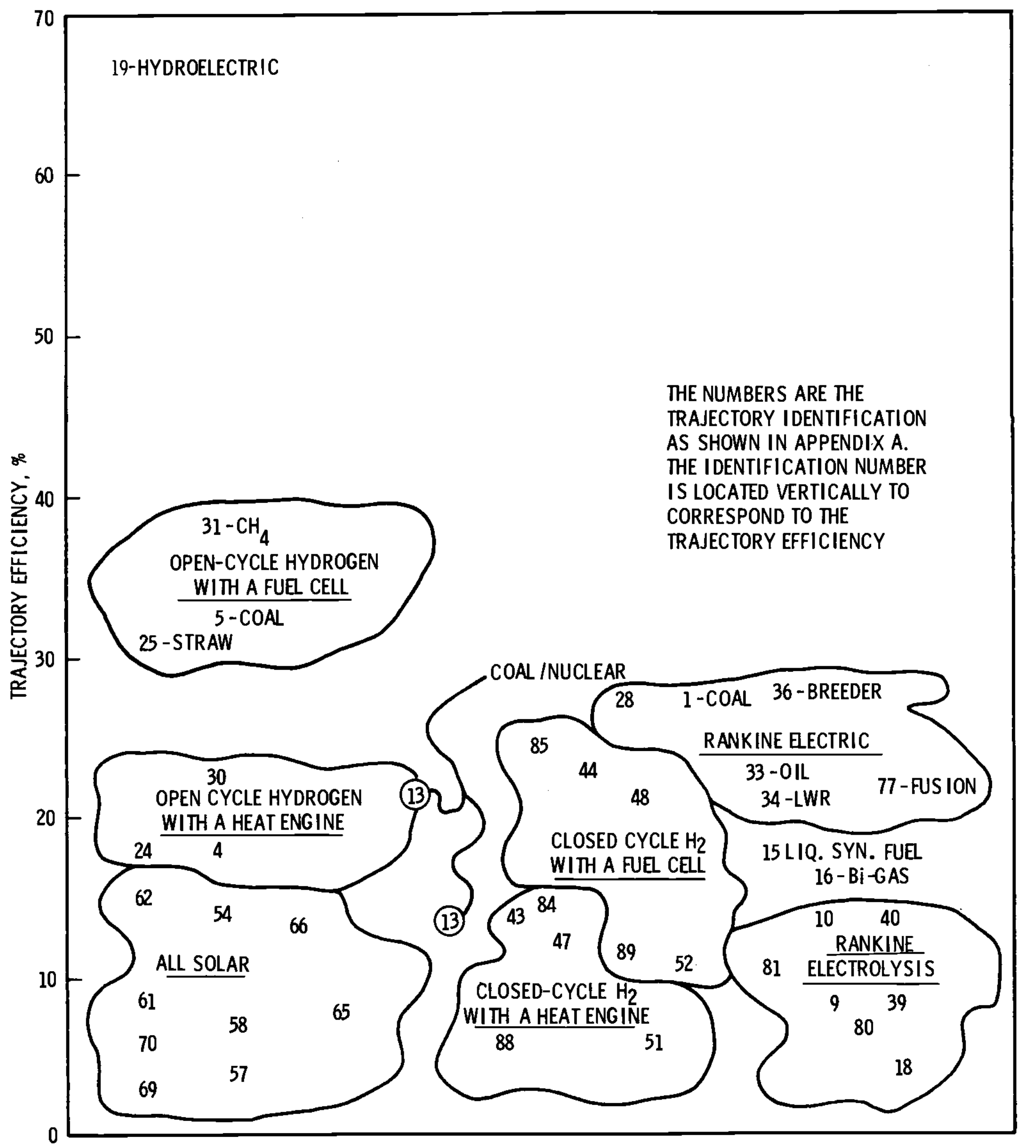

Figure 4. Energy Trajectory Efficiencies For Work Energy As The Beneficial Use For Man

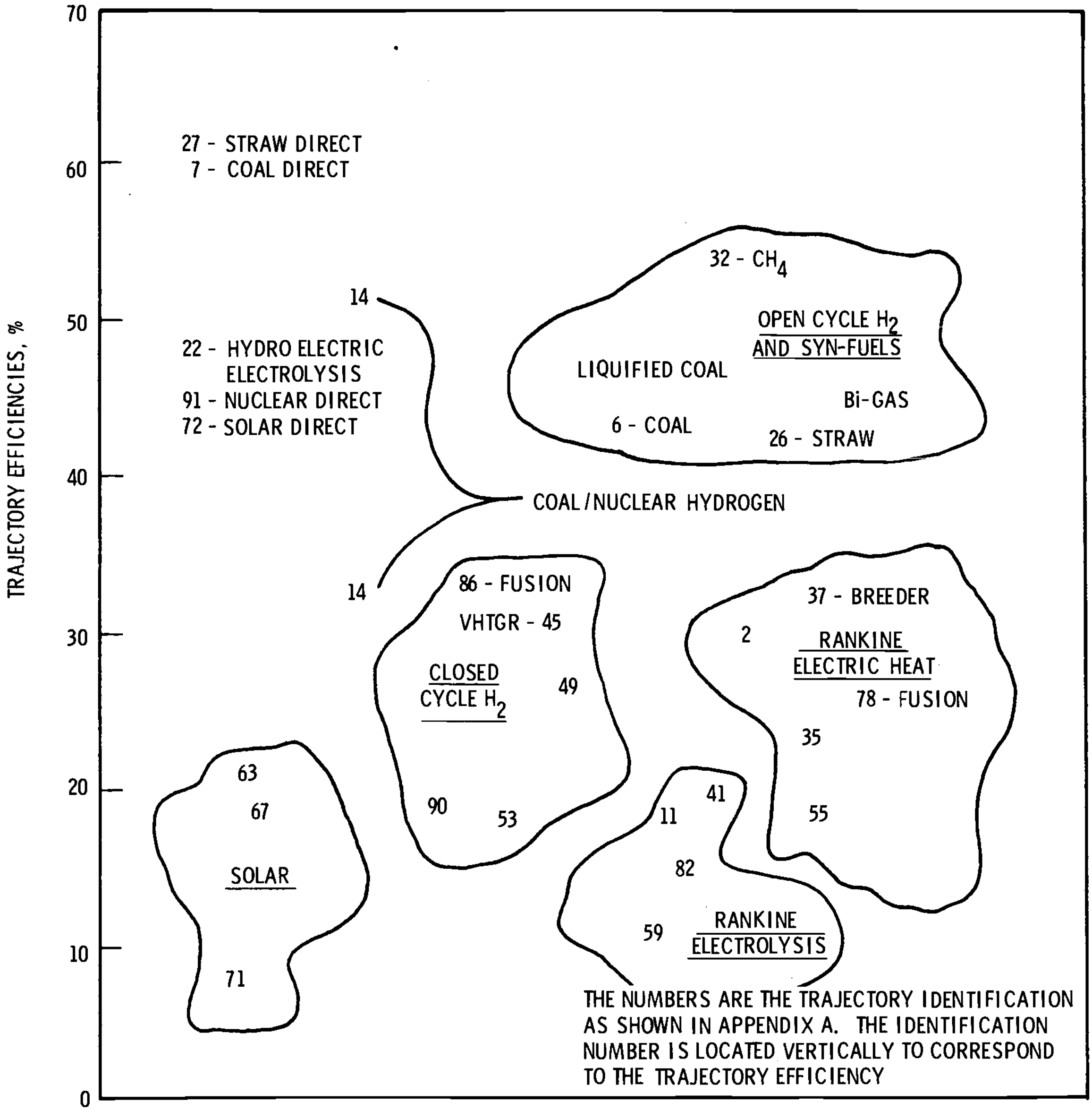

Figure 5. Energy Trajectory Efficiencies For Thermal Energy As The Beneficial Use For Man

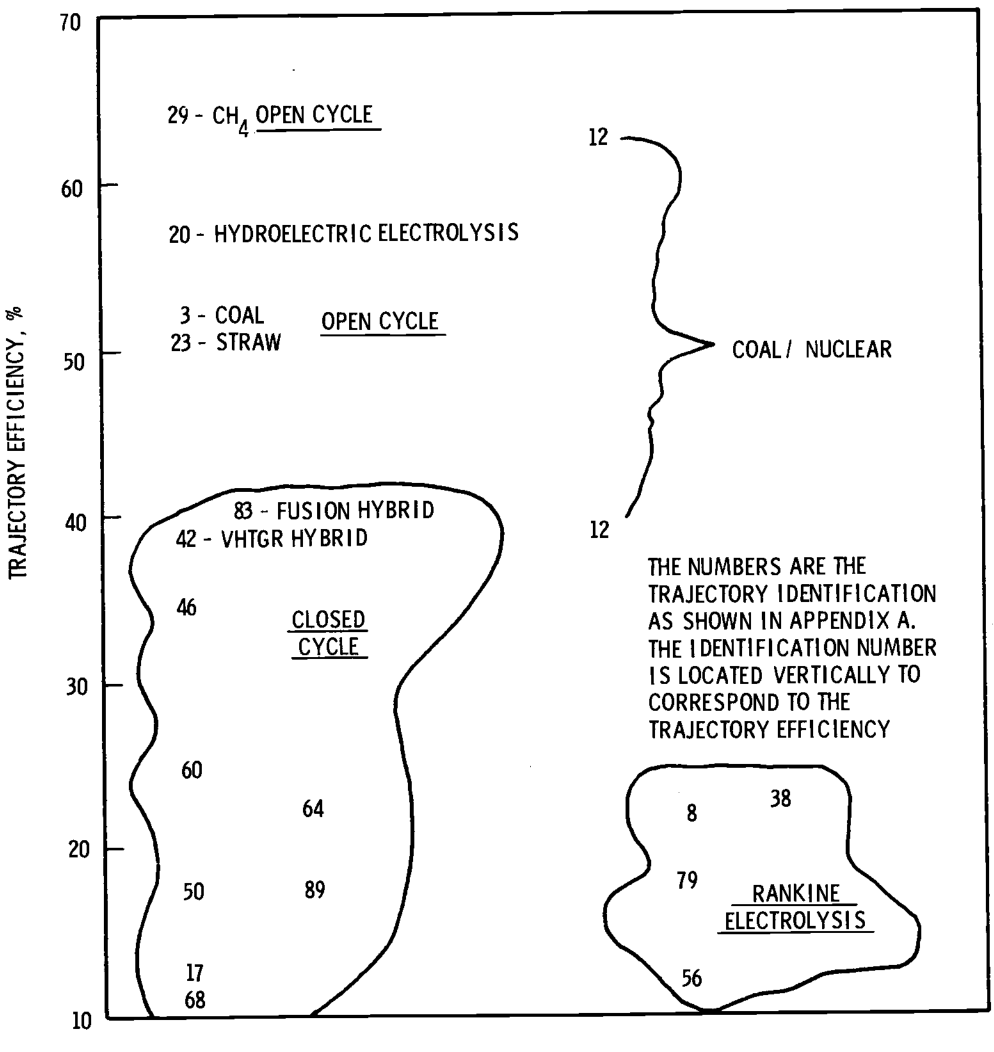

Figure 6. Energy Trajectory Efficiencies For Hydrogen As The Beneficial Product For Man

Hydrogen produced from natural gas by an open-cycle process driving a heat-engine would be on parity with the Rankine-electric trajectories, but natural gas is not an abundant resource. Other open-cycle trajectories, including liquified synthetic fuel and Bi-gas, do not provide the optimum utilization of energy resources for work-energy. If an economical, 70% efficient fuel-cell were available, open-cycle hydrogen would be a preferred trajectory for work-energy when the total energy-resource is to be conserved. On this basis, research and development now devoted to electrolysis and closed-cycles could better be applied to fuel-cell development.

The highest efficiency for solar plants producing work-energy (as evaluated here) was a trajectory of 15%; even this did not include adequate storage. A preferred resource weighting factor of at least two is required to make large solar-power plants competitive for work-energy.

If conservation of the total energy-resource is desired, if hydroelectric power is not available, if large economic-fuel-cells (70%) efficient) are not available, and if the energy trajectories and efficiencies evaluated here represent large power-plants for the next 50 years, then the energy required for work-energy applications will continue to be produced by the Rankine-cycle. Oil, natural gas, and fusion are energy resources not expected to be utilized with the Rankine-cycle for new large-power-plants within the period of this study, since both oil and natural gas may not be abundant and fusion is not expected to be significantly deployed in the next 50 years. Coal, as a unique valuable source of stored chemical-energy, should be conserved, since coal and nuclear fission have about the same total trajectory efficiency. This leaves nuclear fission as the preferred source of energy when work-energy is the desired end-use. The breeder, with a trajectory-efficiency of 28%, is the best utilization of the resources as defined for this study for work-energy. The breeder also makes available an additional energy resource which, in effect, increases the fissionable energy resource by a factor of approximately 60 at the minimum and at least that much more by also utilizing thorium.

C. Thermal Energy As The End Use Of Energy

This study evaluated all of the trajectories for thermal-energy use at the same temperature and all of those considered here are capable of achieving high temperatures. The user's temperature requirements can significantly affect the results of comparisons of energy systems. Low temperature requirements allow the inclusion of abundant, thermal-energy sources that would otherwise not be considered because of the low quality of the energy (low temperature). For example, waste heat and geothermal energy sources can have high trajectory efficiencies.

Figure 5 is the plot of the energy trajectory efficiencies for those trajectories that have thermal-energy as the beneficial end-use. Coal directly fired (and straw if the efficiency assumptions used here for straw are realistic) provide the best utilization of resources at 60% efficiency. As before, the other natural chemical-energies, natural gas and oil, are not considered to be abundantly available. The open-cycle synthetic-fuels and hydrogen provide relatively good use of the resources at 40 to 50%. However, if chemical energy is available for producing open-cycle fuels, it would be more efficient to directly fire the chemical-energy for the thermal-energy. If straw or other organic wastes prove to be abundantly and economically available, and the efficiencies used here apply, then the renewable energy-resource should be used in preference to coal.

There may be few applications for interruptable thermal-energy, that is solar energy without heat storage; however, when it can be used, it provides a respectable efficiency of 45%. All other solar trajectories are less than 21%.

A high temperature nuclear plant used for thermal-energy has a trajectory efficiency of 47% and possibly considerably higher (An adequate efficiency was not available for this study but merits further consideration.) and should be considered in preference to coal, as coal should be conserved for energy storage* needs. A hybrid coal/nuclear plant will use the coal more efficiently (53%) when producing hydrogen for thermal-energy uses, but at a lower overall efficiency of 33%. Thus, the nuclear plant by itself for direct heat would have been better.

Thermal-energy converted from closed-cycle or electrolytic-hydrogen or from electric-resistance heat is at best 33% efficient and does not represent a good utilization of the resource. It should be noted, however, that had the beneficial thermal-energy been provided by an electric heat pump with a COP = 2, then the Rankine-electric thermal-energy would have provided good resource utilization.

In summary, when thermal-energy is desired, coal and possibly organic waste provide the best utilization of resources when directly-fired. Solar direct-heating without storage provides good utilization of a renewable energy source. Nuclear heat, provides an option for conserving stored-chemical energy.

D. Hydrogen As The End Use Of Energy

As noted before, hydrogen is not truly the end-use of energy; however, for comparing conversion trajectories that all produce hydrogen, it can be treated as an end-use node.

* Energy storage is generally considered as energy converted from one form to another for temporary storage such as in pumped storage, electric batteries, or energy converted to a synthetic fuel. It is also used in this thesis to include the fossil fuels; i.e., chemical stored-energy available in nature. Methane produced synthetically is identical to methane found in nature except that to produce the synthetic methane energy was consumed that was already under the control of man.

The two energy sources that provide the highest efficiencies for hydrogen production, natural gas and hydroelectric, are not considered abundant energy-sources. This leaves the open-cycle production of hydrogen from coal or an abundant, efficient, economic organic-waste as the preferred method. A technique of supplying nuclear heat to the coal/steam process could conserve coal, yielding a coal-only efficiency of 64% and an overall efficiency (coal plus nuclear) of 40%.

Hydrogen should be produced by an open cycle from coal or organic-waste for the maximum utilization of resources. Nuclear heat could be supplied to the process in order to conserve some of the chemical energy-resource.

E. Hydrogen As An Energy Carrier

Hydrogen has been proposed as an alternate to electricity as an energy carrier. Electricity is generally thought of as a producer of work-energy. As shown by Figure 4, unless a 70% efficient fuel-cell is available, hydrogen-to-work energy is not as efficient as electricity-to-work energy and would consume stored chemical-energy, as well. The stored chemical-energy should be conserved for those applications where stored energy is required to produce hydrogen for applications where hydrogen's unique characteristics are required; i.e., as a chemical and as a fuel for air and space vehicles.

Hydrogen and other synthetic fuels as energy carriers to produce thermal-energy are more efficient than electricity, except where a heat pump with a COP of 2 is usable. However, the hydrogen and synthetic fuels would be most efficiently produced by an open-cycle process using coal or organic-wastes. These same chemical fuels could be used directly and more efficiently than hydrogen for thermal-energy. Since hydrogen does not provide the best utilization of the resources as an energy-carrier for either work-energy or thermal-energy, it is not likely, as some have predicted[1], to become 10% of the total energy supply in the time period studied. Nor is hydrogen a more efficient carrier for long-distance energy-transport for work-energy than electricity.

Massive quantities of stored energy may be required if large solar power plants are built. Chemical energies provide high-density energy-storage and hydrogen in particular has been proposed. As long as there is abundant chemical-energy already available, it should be used instead of producing hydrogen or other fuel by a closed thermal-cycle at 30 to 40% efficiencies. Using existing chemical-energy will provide for the maximum utilization of the resources for those times that synthetic stored-energy would otherwise be used.

The results of this thesis, with the assumptions and qualifications noted, indicate that, for the maximum utilization of the energy-resource, hydrogen should be produced for use as a high-density-energy fuel for vehicular propulsion, but not as an energy-supply carrier as an alternate to electricity. Further, hydrogen should be produced by open-cycle processes, rather than by electrolysis or closed-cycle methods.

IV. CONCLUSIONS

The conclusions are divided into three parts. Part A contains the conclusions relating to the analytical techniques. Part B summarizes the assumptions and highlights the main study conclusions. Part C lists some unexpected results relating to hydrogen energy.

A. Analysis Technique

The long used technique for comparing energy systems, the first-law-of-thermodynamics energy-balance method, was expected to be somewhat inadequate for this study; however, it provided strong positive results. Net-energy analysis and second-law availability considerations do not significantly alter the conclusions.

It was not anticipated that the end-use of energy could so significantly affect the results. The total chain must be used when evaluating systems that have different end-uses, contain no common energy form in the chain, or use different energy inputs. Power plants cannot be compared without evaluating the entire energy trajectories.

B. Conserving The Energy Resources

The conclusions of this study are based on the following premises for large power plants over the next 50 years:

1) Only abundant energy sources are to be utilized.
2) The least amount of all of the energy resources is to be used.
3) Renewable energy sources are to be preferentially used when trajectories from different resources have near equal efficiencies.
4) Nuclear energy should be used in preference to non-renewable stored chemical energy sources when the trajectories are near equal.

1. Work Energy

When the beneficial energy use is to be work-energy, Rankine-cycle conversion of coal and nuclear fission to electricity are equally efficient. Because of coal's value as a stored chemical-energy, nuclear energy should be used and coal conserved.

2. Thermal Energy

When the beneficial energy use is to be thermal-energy, the direct firing of organic waste (whenever it is abundantly and economically available) should be used. Coal will provide an equal chain efficiency, but should be conserved if organic wastes are adequately available. If solar energy can be directly applied without requiring storage, it should be used where possible.

3. Energy Storage

When energy storage is desired, the use of organic-waste is preferred; coal is the next most desirable. When stored-energy is already abundantly available, it is not prudent to convert one abundant-energy-source (e.g., solar) into another abundant source (e.g., hydrogen) at a large loss of energy.

4. Energy Transport

When work-energy is required, electricity will provide a more efficient energy transport medium than hydrogen. When energy is to be transported for thermal application, stored chemical-energy (coal or organic waste) should be transported for direct firing. An open-cycle product (e.g., hydrogen or another synthetic fuel) should be used if direct firing is not a possibility.

5. Solar Energy

Solar energy should be utilized for direct thermal-energy applications when energy can be used without storage.

All of these conclusions are contingent on the applicability of the energy trajectories considered and the nodal efficiencies used.

C. Hydrogen Energy

Because of the large volume of literature[1,2,3,12,13] extolling the use of hydrogen-energy, most of the results of this study specific to hydrogen were not expected. The results are summarized below. (These results only apply if the assumptions listed under IV.B. "Conserving The Energy Resources" are valid.)

1) Hydrogen will not be competitive with electricity, even for distant transport.
2) Hydrogen will probably not become 10% of the energy supply.
3) Hydrogen used for energy-storage is not good utilization of resources.
4) Synthetic fuels, including hydrogen, are poor utilization of the resources for work-energy, but are reasonably good for thermal-energy.
5) Hydrogen should only be produced for use where its unique characteristics are needed (e.g., as a chemical or an aircraft or spacecraft fuel).
6) Closed-cycle production of hydrogen and electrolytic production of hydrogen are both poor utilization of resources. Research and development now devoted to these two processes could better be spent on fuel-cells.
7) For the best resource utilization, hydrogen should be produced by an open-cycle process.

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APPENDIX A

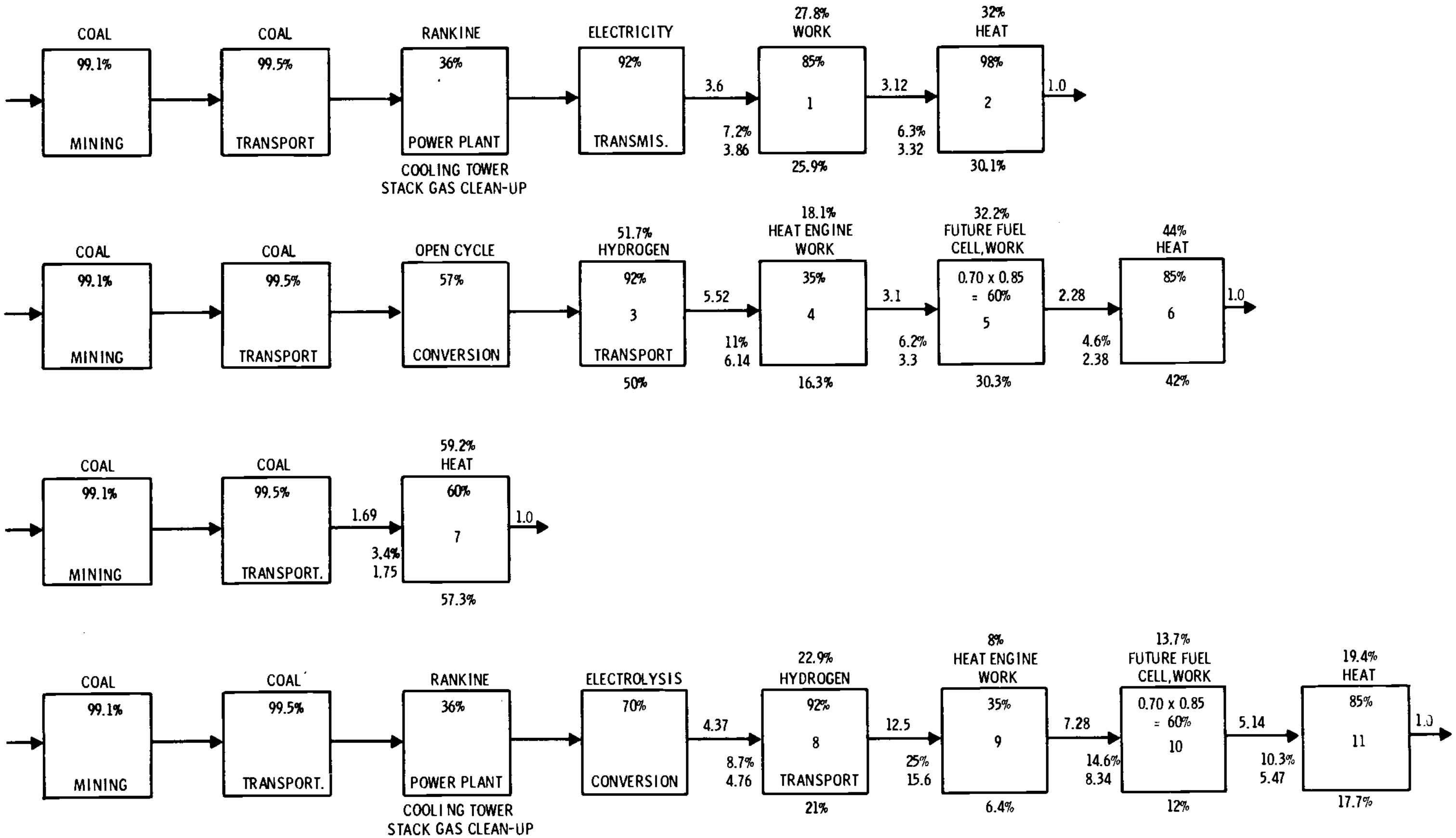

Figure 7. Coal Trajectories -1

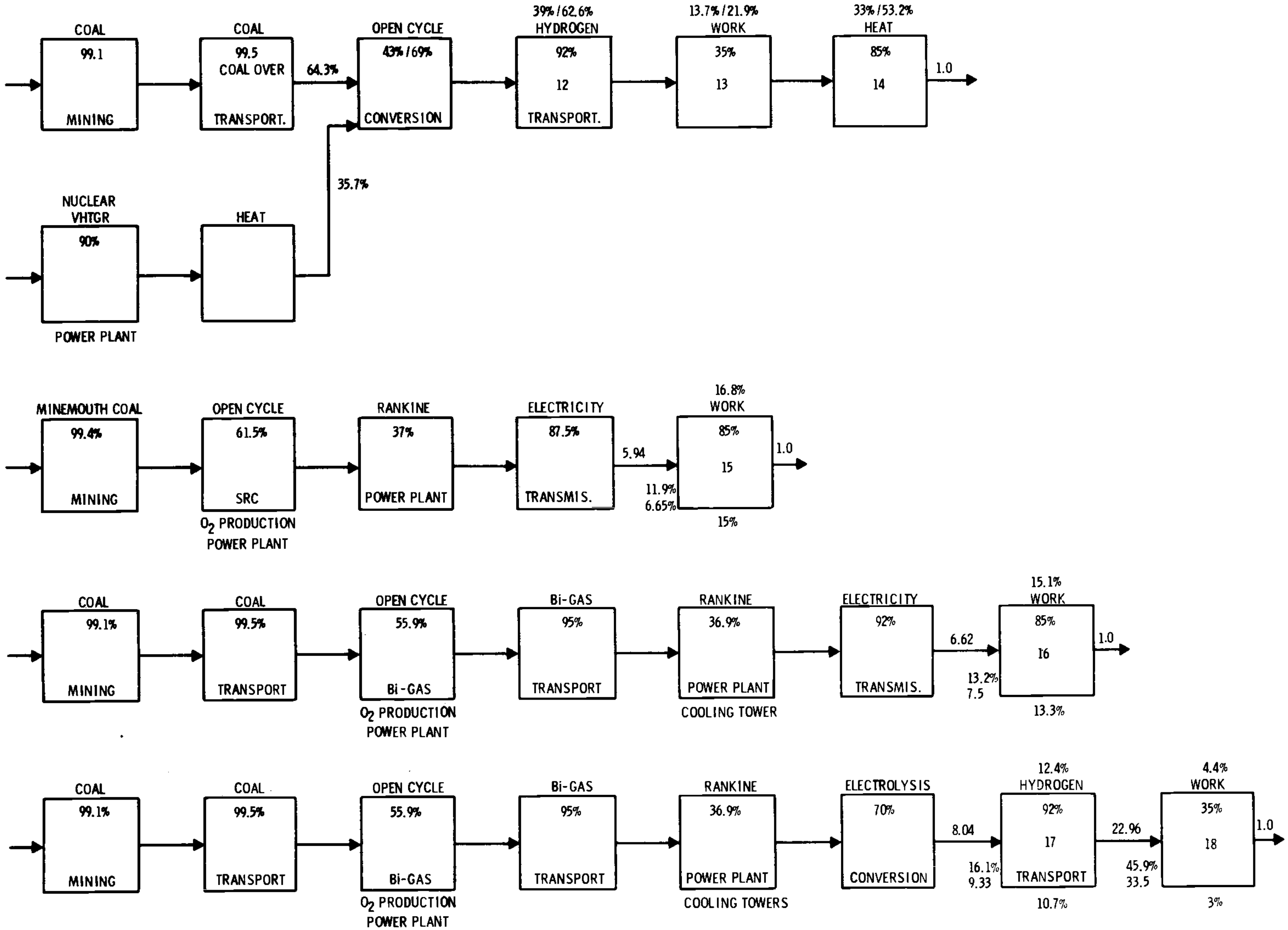

Figure 8. Coal Trajectories -2

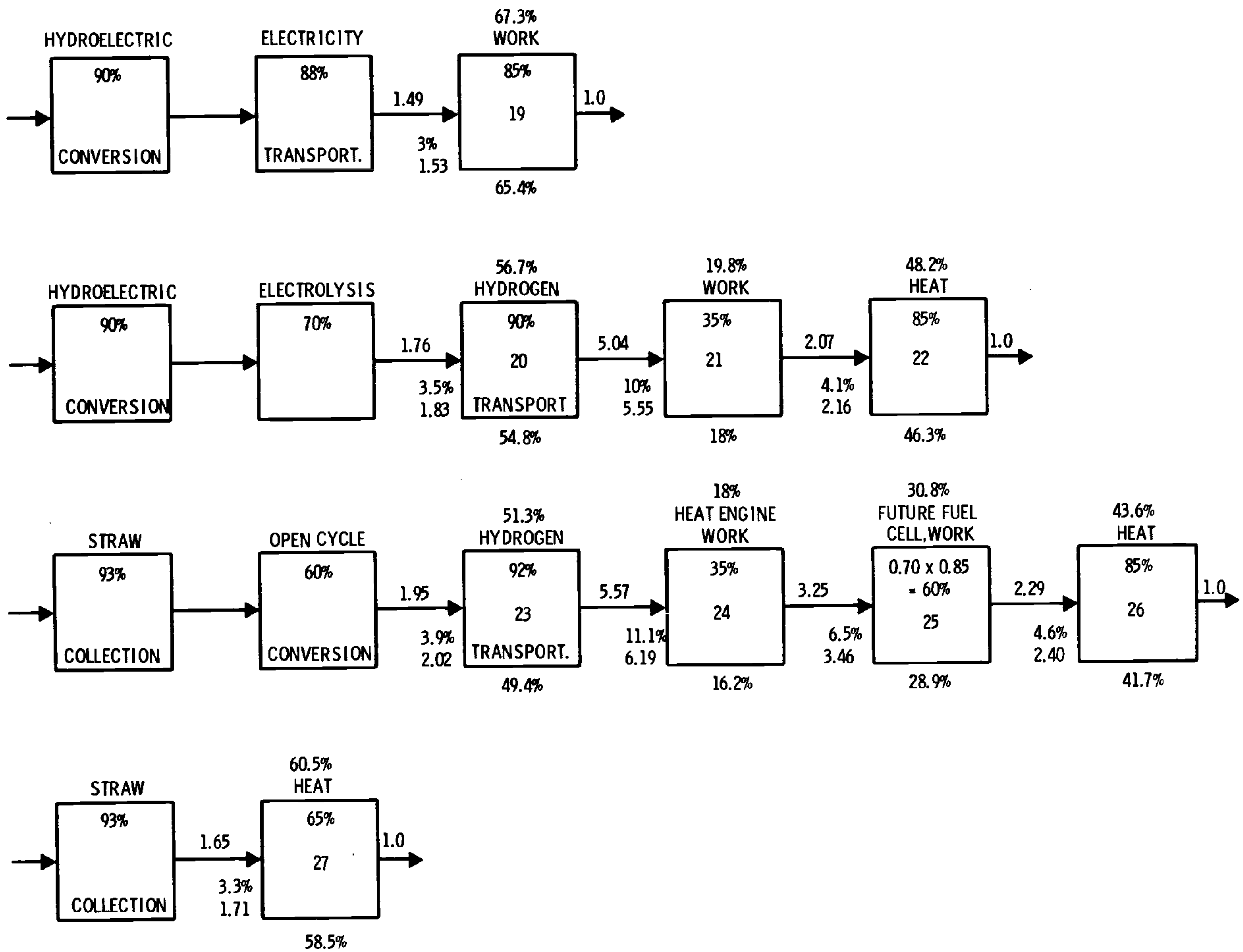

Figure 9. Hydroelectric And Straw Trajectories

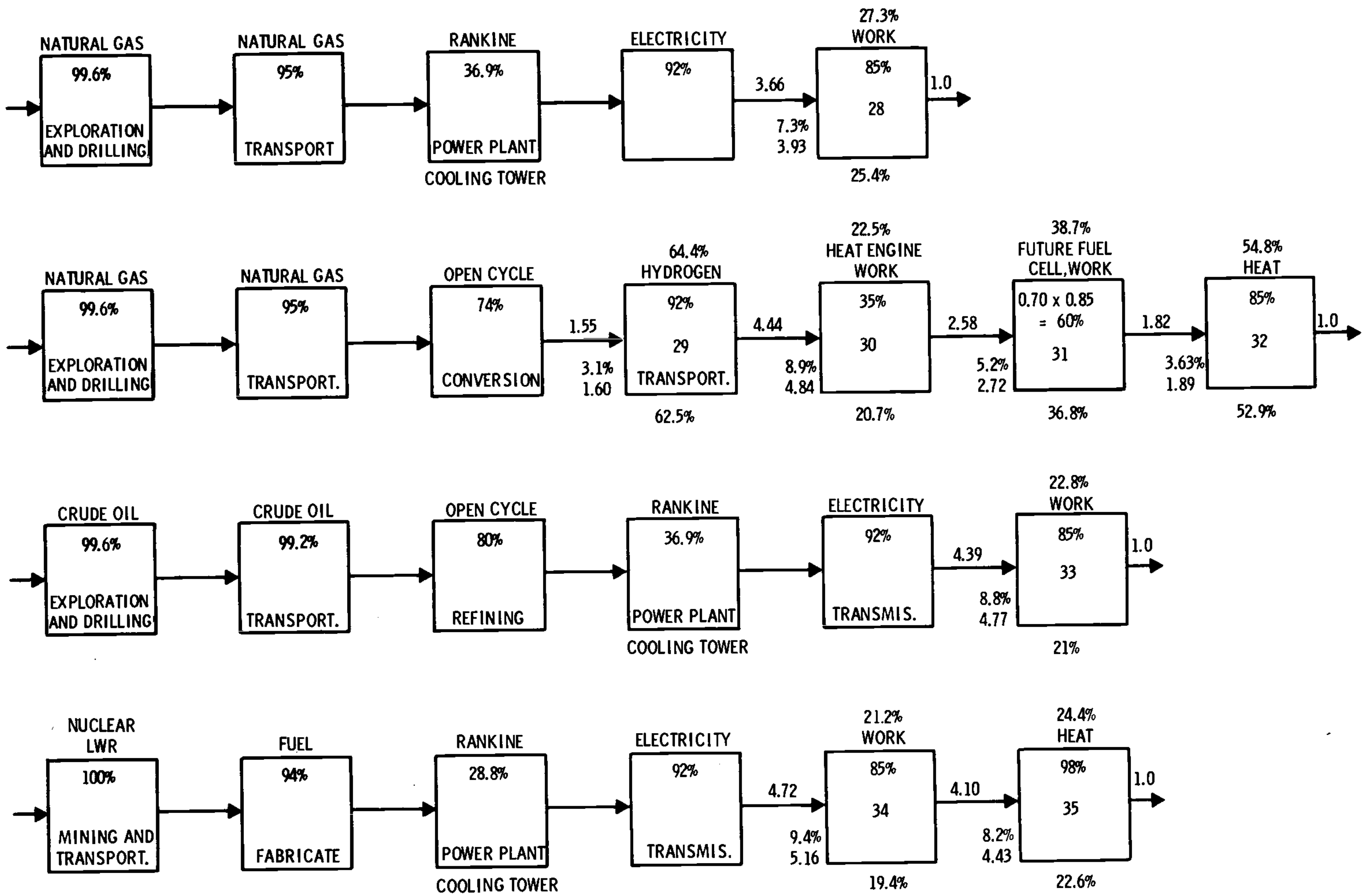

Figure 10. Existing Conversion Trajectories

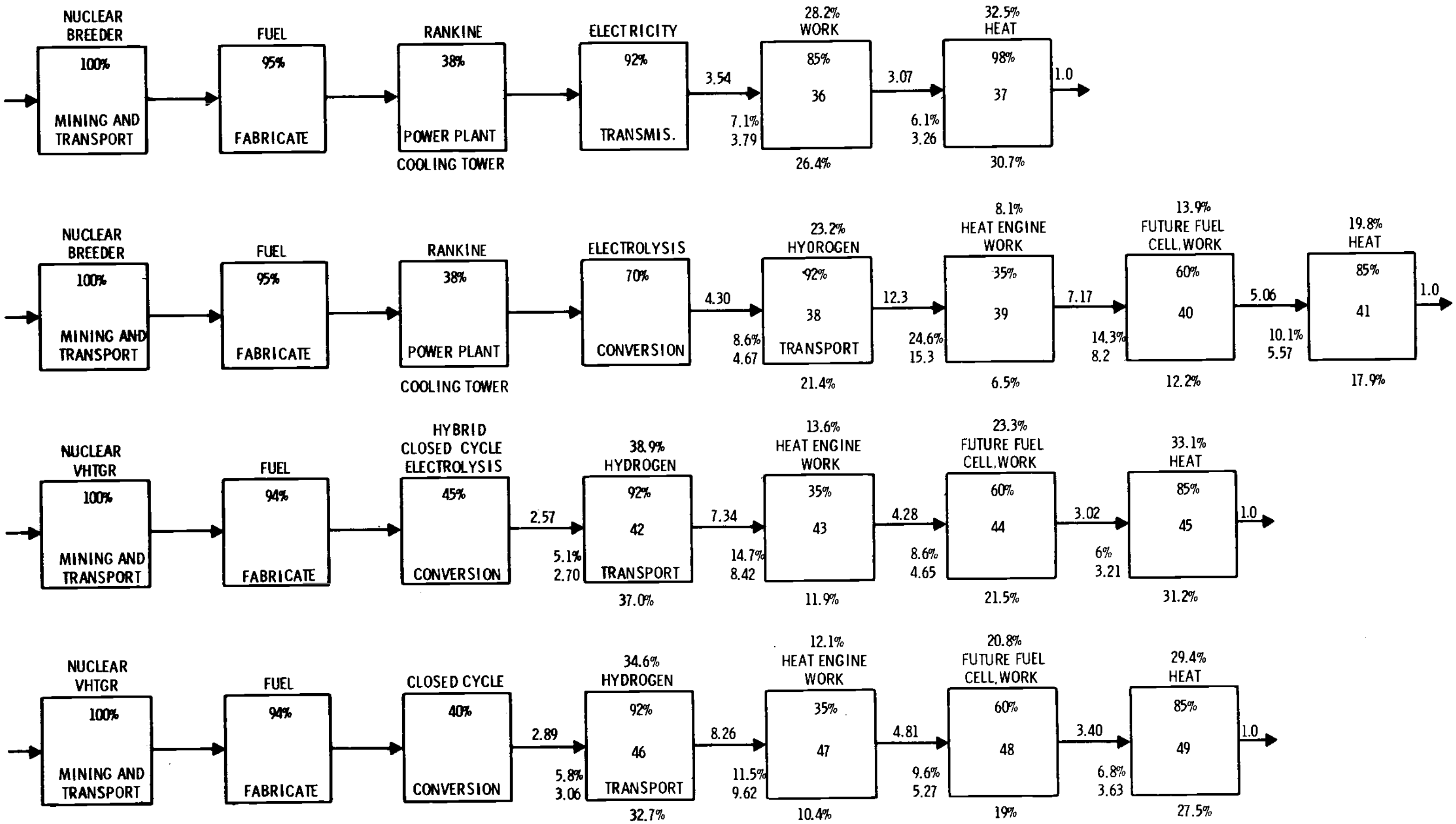

Figure 11. Nuclear Trajectories

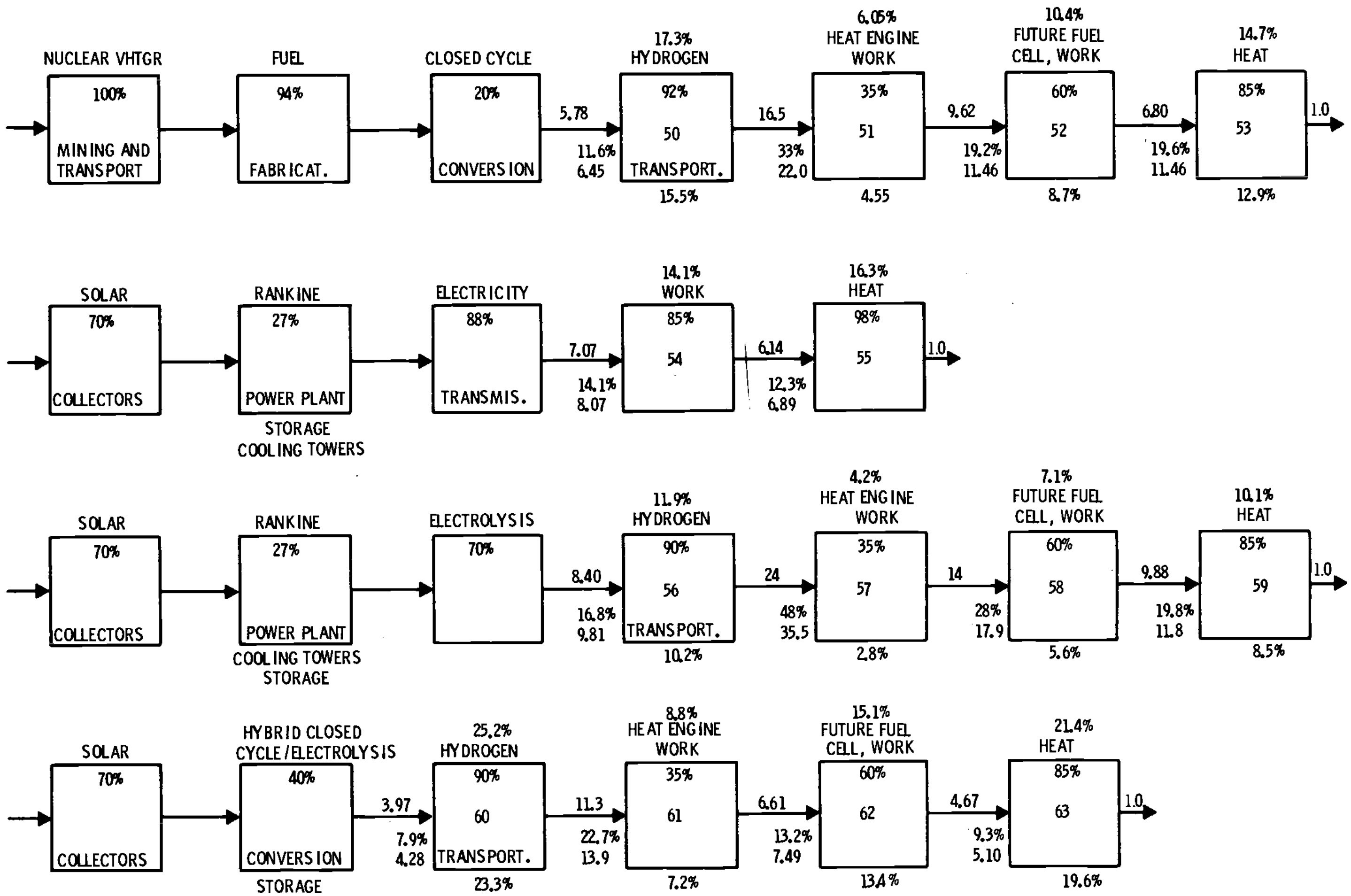

Figure 12. Solar Trajectories -1

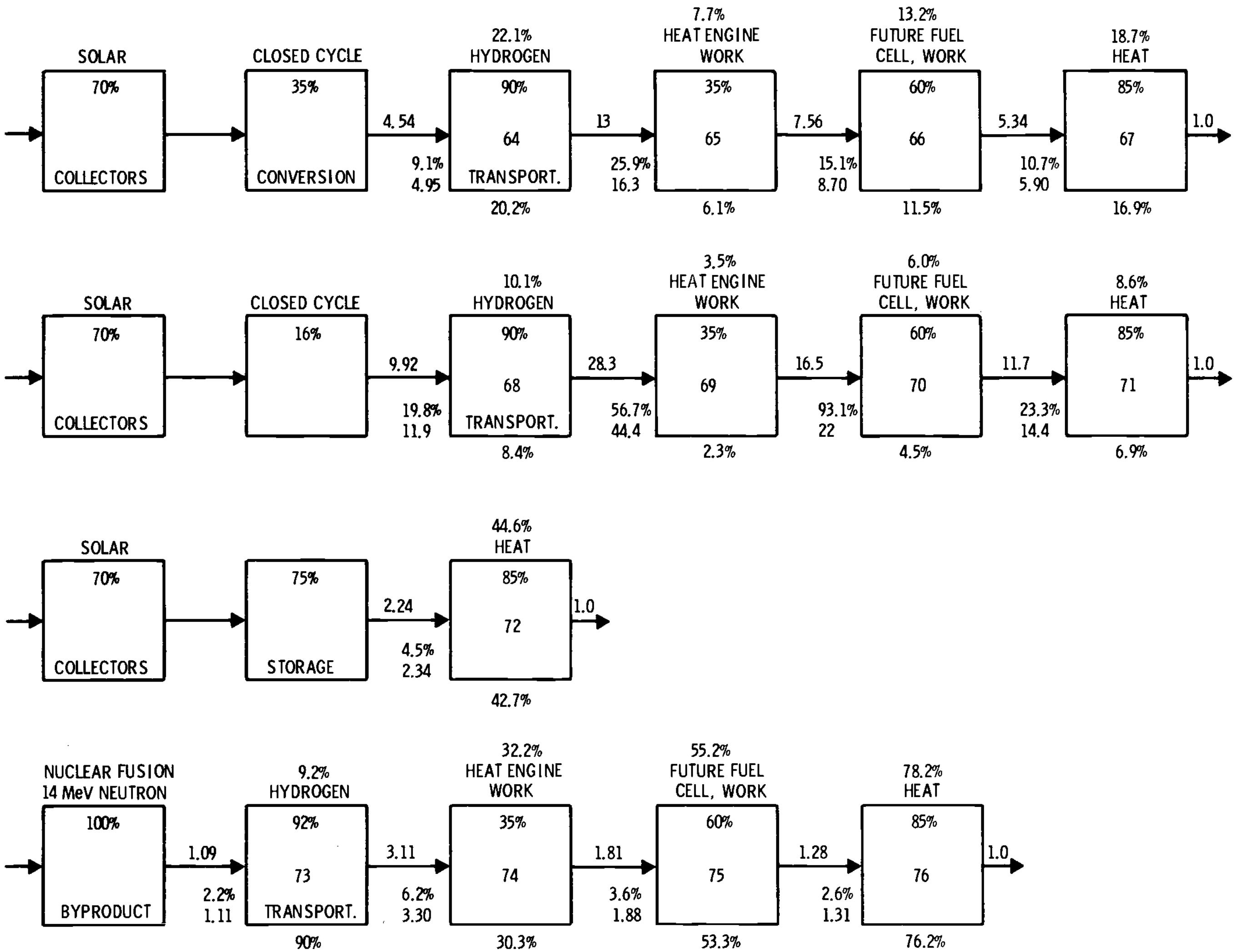

Figure 13. Solar Trajectories -2

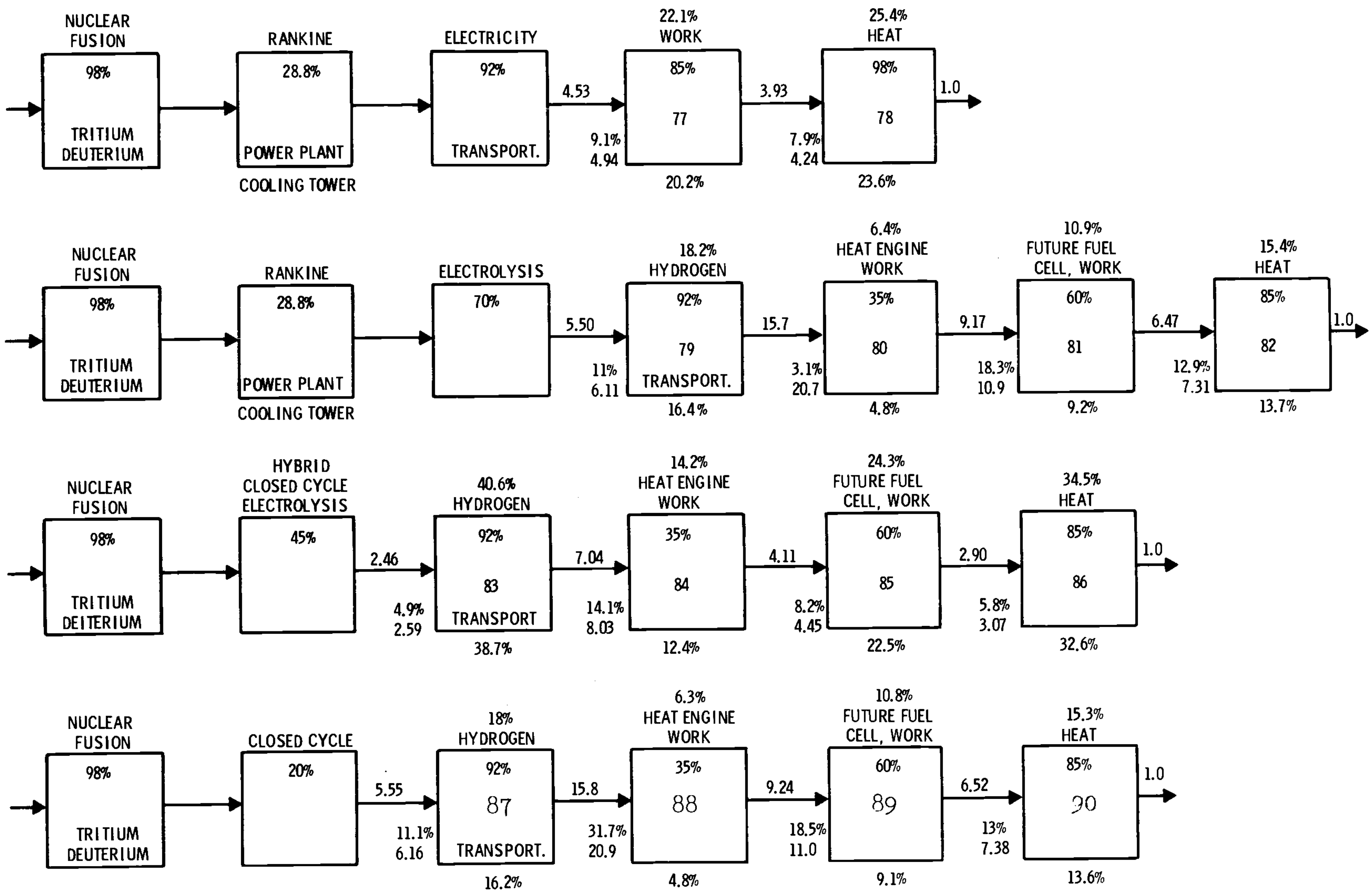

Figure 14. Fusion Trajectories

APPENDIX B

APPENDIX B

NET ENERGY

The evaluation of data from various recent net-energy analyses[5,7,14,15,16,17,18] that have been performed for large power plants over the last several years resulted in a conclusion that significant differences in the calculations or the implications of the calculations can be made because of an arbitrary design decision between one plant and another. Such things as whether the energy used in a process was derived internal to the plant or was procurred from off-site can make a large difference in the quantity of subsidy energy.

Likewise, considerations as to whether the resource form of energy or the final product energy, electricity or hydrogen, are used to supply energy to the process, or refine the materials, or to build the plants can have a significant effect on the results. However, the interest is still very high to develop a measure of the amount of energy that is supplied indirectly as energy inputs; e.g. the energy that makes the materials, reduces the ore, the energy that runs the metal fabricating equipment, and the energy that goes into the construction of the plant and equipment. All should be accounted for as true inputs to an overall energy study; this is the basis of the net-energy analysis interest today.

Evaluating the results and taking into account the differences as noted above, it becomes apparent that the total subsidy in terms of resource energy today and in the near term future is less than 10%. As noted by Frabetti,[19] "... all subsidies indirectly reflect the relatively low energy to produce energy characteristic of the 1967 U.S. economy."

It is considered that as plants get less efficient, as the energy chain from resource energy to product energy get longer, as there are more steps or nodes in these chains, it will most likely mean that the energy subsidies will get larger. It is proposed that a generalized curve could be plotted using the results of calculations that have been generated to date and that the data will show subsidies increasing with total energy chain efficiency decreasing.

It is noted that the energy required per dollar invested for various items relating to power plants and for power plants,[7,19] does not scatter as much as the net-energy calculations themselves. In fact, Rohmbough & Koen[5] have simply taken the U.S. energy consumption divided by the gross national product as a constant to use for subsidy energy divided by the capital investment of the power plant.

Secondly, Sy Baron pointed out that the total capital invested in the energy chain, including fuel, multiplied times the efficiency of the entire chain is essentially constant. Indirectly this is saying that for any plant with a specified energy output, the cost of the plant will relate to the resource energy input required. The cost is an inverse function of the energy chain efficiency or in other words the cost times the trajectory efficiency equals a constant. Combining these two relationships results in an equation that relates the subsidy energy to the overall chain efficiency.

Starting with the relationship that equates the energy subsidy for a power plant, BTU, divided by the capital investment in the plant; to, the U.S. energy consumption, BTU, divided by the gross national product. Or:

$$\frac{\text{Energy Subsidy}}{\text{Capital Investment}}, \frac{\text{BTU}}{\$} = \frac{\text{U.S. Energy Consumption}}{\text{GNP}}, \frac{\text{BTU}}{\$}$$

$$= \frac{68{,}000 \times 10^{12}, (1975)}{1.5 \times 10^{12}, (1975)}, \frac{\text{BTU}}{\$} = 45{,}333 \text{ BTU/\$}$$

Since Baron included the costs of money in his cost and the above figure does not include it, it is reduced by a factor of two and rounded to equal 25,000 BTU/$. Or:

$$\frac{\text{Energy Subsidy}}{\text{Capital Investment, Including Interest, Etc.}} = 25{,}000 \text{ BTU/\$}$$

The energy subsidy, BTU, is equal to the subsidy as a percent of the output energy times the output energy, BTU. Which yields:

$$\frac{\text{Energy Subsidy, \% X Output Energy, BTU}}{\text{Capital Investment, Including Interest, Etc.}} = 25{,}000 \text{ BTU/\$}$$

Taking Baron's observation[7]:

$$\text{Capital Investment, Including Interest, Etc.} \times \text{Net Cycle Efficiency} = 0.40 \times 10^9, \text{\$}$$

Putting these two equations together, eliminating the capital investment and rearranging yields:

$$\text{Energy Subsidy,\%} \times \text{Net Cycle Efficiency} = \frac{.40 \times 10^9 \ (25{,}000)}{\text{Output Energy}}$$

A 30 year plant life, operating 7,000 hours per year gives an output energy = 0.717×10^{15} BTU, so:

$$\text{Energy Subsidy,\%} \times \text{Net Cycle Efficiency} = \frac{0.40 \times 10^9 \ (25{,}000)}{0.717 \times 10^{15}} = \underline{\underline{0.0139}}$$

(A constant of 0.02 is conservatively used in this study.)

It should be noted that the energy-subsidy percentage applies as a percentage to either the input or output energy. If it takes 3 joules of resource energy to make 1 joule of electricity, it also takes 3 joules of resource energy subsidy to make 1 joule of electricity subsidy.

It is recognized that the above derived relationship has several approximations and also generalizes some considerations that are important power plant differences. These differences should thus merit separate consideration when comparing plants. However, the relationship appears to confirm that the subsidy is below 10% today.

It is not clear how far this curve should be extrapolated; however, for this thesis it should be satisfactory because it is only 10% or less of the total energy supply and thus even a large error will not affect the results very much. As Frabetti stated,[6]

> "Much effort has been spent in this analysis as well as in other studies to determine the correct size of energy subsidies. It appears ...that several levels of approximation would have sufficed to obtain adequate subsidy effects. ...there seems to be little benefit in precisely determining energy subsidies.".

So far this paper has not discussed whether the subsidy energy is supplied as resource energy or output energy (hydrogen or electricity). In the U. S. energy economy today the subsidy energy is almost totally process heat from resource energy (fossil fuels). Nuclear energy represents a slight variation from the norm in that uranium enriching energy is electrical and is 3 to 4%. For the needs of this thesis it is assumed that the subsidy energy could have been either electrical or resource energy without much effect on the conclusions.

For instructive reasons, extrapolate the curve to 100% subsidy, 2% total chain efficiency, to evaluate the implications of this situation. At that point an equal amount of resource energy is required for the subsidy as is required for input to the energy chain. If this subsidy had been all electrical or hydrogen energy, that is the same as the output energy, it can be seen that no beneficial energy would be available to society. However, if this subsidy had been totally resource energy, then the only effect is that the net efficiency would be 1/2 the first law efficiency. Twice as much resource energy is required to achieve the same output. In the case of 100% electrical subsidy, twice as much resource produced no output.

The same zero net-energy effect with a high electrical subsidy can be achieved at less than 100% electrical subsidy if the electrical subsidy precedes in time the plant operation and the growth curve is exponential.[20]

It is clear, that whenever possible, resource energy should be used. It should be noted that most of the subsidy is resource energy today and the total subsidy is 10% or less.