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NET ENERGY CONCEPT APPLIED TO RESOURCE UTILIZATION

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ABSTRACT

Development work is reported on a computer program with the capabilities of (1) analyzing preplanned programs for constructing and operating multiple energy conversion or other kinds of processing plants, (2) designing and planning such programs to comply with net energy criteria, (3) computing, for both preplanned and designed programs, current and cumulative energy investments in construction, energy costs of operation, net energy productions, points of energy profitability, and impacts on depletable resources, and (4) compositing computed results for multiple overlapping construction and operating programs, both preplanned and designed.

The computer program in its present state of development is essentially a planning tool. Possible future refinements and extensions could enhance its capabilities.

NET ENERGY CONCEPT APPLIED TO RESOURCE UTILIZATION

It is important that better means be developed to (1) predict long-range impacts of projected energy conversion and new manufacturing operations on rates of resource depletion, and (2) compare the net energy requirements of alternate programs for energy development.

The number of coal conversion plants needed to produce replacement fuels, as natural gas and petroleum are depleted, suggests that an extensive program of plant construction may be in prospect. Also, this might be only one of several resource consuming programs initiated more or less simultaneously to meet our energy needs.

Such programs will entail large energy expenditures or "investments" in activities and facilities that are only indirectly productive of useable energy, including (1) mining ores for manufacture of base metals, (2) fabricating equipment, (3) transporting equipment to construction sites, and (4) erecting and starting-up the plants. Other construction materials, tools, supplies, etc. will also require massive energy investments before coal, or other fossil fuel material can be processed.

Not only are energy investments required to establish energy conversion facilities, but there are also very real "energy costs" applicable to auxiliary materials and energy consumed in routine operations. These must be evaluated in any valid comparison of energy conversion processes. Two processes equal in thermal conversion efficiencies may differ in their overall resource depletion rates due to differences in energy costs associated with auxiliary materials, chemicals, direct energy inputs for processing, energy needed for maintenance, and energy consumptions for replacement equipment and installations to renew the plants.

Energy analysis attempts to quantify and account for all energy flows and for energy potentially available from combustion or conversion of materials transferred into or out of any defined system. The energy cost of a product is the aggregate amount of primary energy (Chapman's [5] "ger" gross energy requirement) necessary for its manufacture, whether supplied as raw or processed resource material, manufactured commodities, fuel or as thermal, electrical, or other forms of energy. It is thus the composite energy expenditure essential for supply of all materials, processes and services entering into the complicated networks that lead to its production.

The relation of energy inputs to energy outputs for a defined system is expressed by the "conservation of energy cost" convention [7] [13] which may be written as follows:

$$\sum_i x_i E_i + \sum_j e_j E_j = \sum_k y_k E_k \qquad (1)$$

The summation of the quantities of materials (x_i) each times its respective unit energy cost (E_i) plus the summation of direct energy inputs (e_j) times appropriate unit energy costs (E_j) equals the summation of exiting material quantities (y_k) each times its unit energy cost (E_k).

Chapman and Mortimer[6] [12] devised a technique for analyzing a program of multi-plant construction. It applies to energy conversion plants of a given size and type, for which construction is initiated at

different times, and for which energy inputs during construction can be aggregated. The cumulative energy investment can be compared with the cumulative energy output, permitting determination of (1) the point of zero net energy, and (2) the point in time at which cumulative energy output first becomes equal to cumulative energy investment. The Chapman-Mortimer technique is analytical, i.e. it computes for any predetermined program the net energy at any time and the requisite time to "energy profitability." It will not design a program to deliver a constant preselected net energy ratio.

Numerous authors have attempted to determine unit "energy costs" for food,[16], [20], [22], [28], [31] manufactured products and commodities,[2], [3], [8], [9], [10], [11], [14], [17], [18], [25], [26], [29], [32], [34], [35] automobiles,[1] electricity,[7], [8] processed fuels,[7], [13] nuclear energy,[36] metals,[15] transportation,[4], [21], [27], [30] and pollution control[19]. Such data are essential to quantitative determination of both energy investments in constructed facilities and energy costs of operation. As Leach[24] pointed out, there are inherent difficulties, however, in determining valid unit energy costs. The key problem is where, practically, to draw the boundary for energy cost inputs to be considered in relation to raw materials, supplies, chemicals, fuels and direct energy consumed. The same boundary problem exists in relation to energy investment in machinery, equipment, buildings, land development, etc., and in relation to the energy costs of replacement machinery and depreciation of capital facilities. Since energy cost contributions extend in seemingly endless chains, quantitative analysis must be truncated at many points. Thus, to apply energy costs in net energy studies, it is necessary in most cases to use the best available approximations.

Other problems with the methodologies have been identified [24]. For example, how should energy cost aggregates be distributed among multiple products? Should differences in energy qualities be taken into account in the analysis? And as Webb and Pearce [33] observed, energy analysis methods do not in themselves provide adequate criteria for establishing long-range energy policy. Energy analysis and economic analysis provide different, but equally valid, and complementary insights and criteria relative to policy formulation.

The work here reported was carried out in the Department of Gas Engineering, Illinois Institute of Technology, as the Master of Science Thesis project of Dominic K. Lai [23].

Objectives of the project were to develop a computer program with the capabilities of:

a) Analyzing preplanned or "arbitrary" programs for constructing and operating multiple energy conversion plants, and/or manufacturing plants, with respect to their overall energy use efficiency and their composite resource consumption, treating inputs of all resources as equivalent to common use of a single resource.

b) Planning and scheduling construction and operation of multiple energy conversion plants in a program to maintain an assigned ratio at all times of net energy to total energy invested. Such programs are called "designed" programs. In this context, net energy is the total rate of energy production at a given time by all operating plants less the amount of energy being used for construction, start-up, and operation of new plants in the program.

c) Identifying the net energy output of each program with respect to the category of refined energy or fuel produced, and developing composite figures for each category.

d) Determining for each plant construction program the cumulative energy investment, the cumulative energy expenditures in the conduct of operations, the cumulative energy output and the point of energy profitability.

e) Determining the composite net energy production and resource consumption at any time for any number (within computer limitations) of arbitrary and/or designed programs, whether for energy conversion or manufacturing, and with any set of assigned starting times for the several programs.

f) Determining, at successive points in time, the cumulative energy investments, consumptions and outputs for such composited programs.

g) Computing for composited programs, the projected pattern of resource utilization and the predicted resource life.

DEFINITIONS

Energy Cost

The unit energy cost of an energy or fuel product from a fossil resource conversion plant is defined as:

$$\frac{\text{total energy consumed or expended in its production}}{\text{energy output or energy content of fuels produced}}$$

The total energy expenditure will include the calorific value of the fossil fuel material, the energy costs of all commodities and supplies consumed, and the energy cost of energy inputs to the operations. For a manufacturing process, the energy cost of the product will include similar contributions but will be expressed in energy amounts per product unit. Energy costs are illustrated in Figures 1, 2, and 3.

Figure 1 shows a representative mining operation; coal is assumed for illustrative purposes. The energy cost of mined coal is the sum of the individual energy cost inputs. To deliver this mined coal to an energy conversion plant entails addition of the energy costs of transportation as shown in Figure 2. The energy cost of the output energy (or fuel) from the conversion plant is the sum of all the individual energy cost inputs to the conversion plant.

Figure 3 illustrates the energy cost contributions of a typical manufacturing plant. The energy cost of the products is again the sum of all energy cost inputs per product element, per unit of mass, or per any conventional reference unit.

Net Energy

For an individual plant construction program, net energy at any time is equal to the total energy production rate of the operating plants

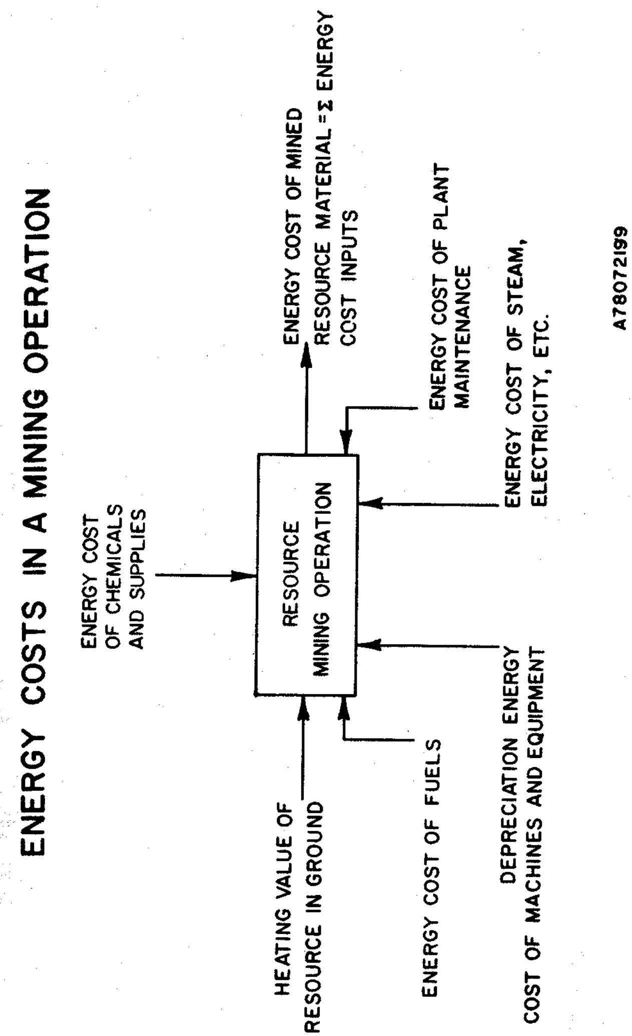

Figure 1.

ENERGY COSTS IN AN ENERGY CONVERSION PLANT

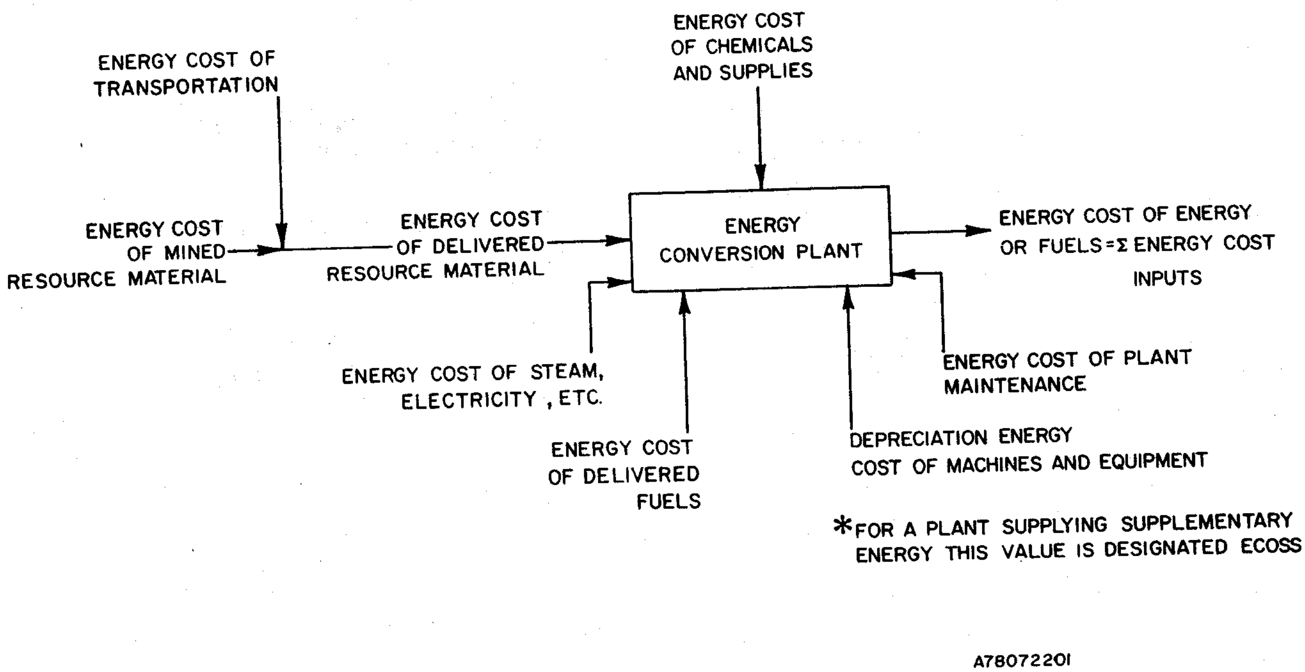

Figure 2.

ENERGY COSTS IN A MANFACTURING PLANT

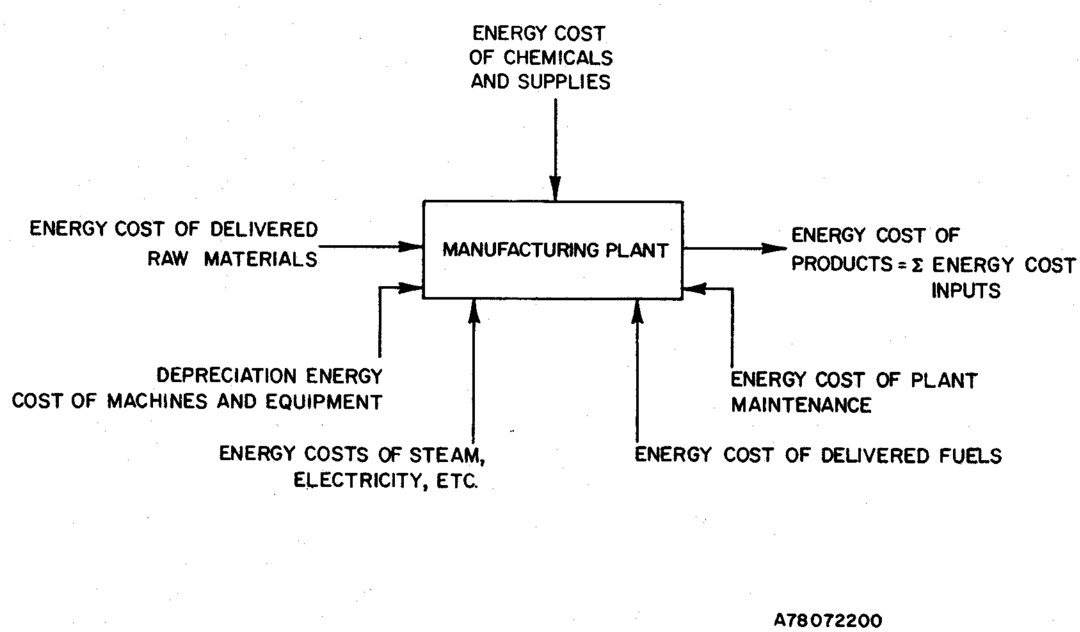

Figure 3.

minus the total energy investment rate for construction of new plants. As here defined, net energy is determined solely by the actual or equivalent disposition and not by the energy cost of the output energy.

For each individual program, and for composited programs, the time to first attainment of net energy is determined. In a procedure similar to Chapman's (8), the computer program finds the point in time at which the cumulative energy output for an individual program first exceeds the cumulative energy investment in plant construction. This is the time to energy profitability. Time to energy profitability is computed similarly for composited programs.

Energy Plowback Multiplier

In a designed program this multiplier is defined as:

$$FR = \frac{\text{rate of energy investment in all plants under construction}}{\text{aggregate energy production rate for all operating plants}}$$

The schedule upon which new plants are initiated will be determined by the value assigned to the plowback multiplier.

Resource Utilization

This value indicates the overall efficiency of the resource use for output energy production. It is defined as:

$$RU = \frac{\text{cumulative useable energy withdrawn}}{\text{calorific value of the total amount of resource consumed}}$$

MATHEMATICAL BASIS

Two types of plant construction programs are considered - "designed" and "arbitrary."

Designed Programs

A designed program exhibits a constant ratio of energy being produced by all operating plants to energy being invested in plant construction. This ratio is a function of the energy plowback multiplier FR. This means that the amounts of energy calculated to be available for investment at successive time intervals govern the initiation of new plant construction. When FR = 1.0, all energy output is utilized for new plant construction and net energy is zero. When FR is less than 1, net energy is positive, and when greater than 1, a constant net energy deficit will be computed. The following equations permit scheduling of plant construction and operations to attain a constant net energy ratio. The number of plants operating at any time is computed by:

$$PLOP = [(FR * RP) + 1]^{\left(\frac{T}{T_c + T_s} - 1\right)} * STP \qquad (2)$$

and the number of plants under construction, operating, or in start-up by:

$$PLCC = [FR * RP) + 1]^{\left(\frac{T}{T_c + T_s}\right)} * STP \qquad (3)$$

The number of plants under construction or in start-up at any time is found by:

$$PLC = PLCC - PLOP \qquad (4)$$

In computing the plants operating and the plants being constructed by equations (2), (3), and (4), the numbers are rounded to integer values. It is assumed that new plants are not started until all those previously initiated have been completed and placed in operation. The procedure is to compute the number of operating plants required at $T = n(T_c - T_s)$ where n is an integer. For each group of plants, it is assumed that construction is initiated at $(n - 1)(T_c + T_s)$. When $T \leq (T_c + T_s)$ the following values are assumed:

PLOP = 0

PLCC = STP

PLC = STP

The number of operating plants when $T < T_c$ is assumed to be zero. During the start-up period, linear increase in energy production and linear decrease in energy investment have been assumed. Thus, a plant is not in full operation until the end of the start-up period. The plant construction time (T_c) and the plant start-up time (T_s) are arbitrary inputs. Construction work may be initiated with one plant only or any number of initial plants (STP) may be specified.

Equations (2), (3), and (4) enable formulation of a construction schedule, in a designed program, that will give any desired net energy ratio over the entire construction period. Example calculations are presented in Table I.

Table I

TYPICAL RESULTS FOR DESIGNED PROGRAM

ASSUMPTIONS:
ENERGY RATIO (RP)=4
$T_c + T_s$ = 5 YEARS
STP=1

	FR = 1.0		FR = 0.5	
END OF YEAR (T)	PLANTS OPERATING	PLANTS CONSTRUCTING	PLANTS OPERATING	PLANTS CONSTRUCTING
0	0	1	0	1
5	1	4	1	2
10	5	20	3	6
15	25	100	9	18
20	125	500	27	54

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Arbitrary Programs

An arbitrary program is one in which construction of any number of plants can be initiated in accordance with any predetermined schedule. Being completely flexible, such programs can be arranged to give (a) an early and large net energy production, (b) no net energy until construction is completed, or (c) no net energy ever if construction should be continued at an accelerating rate until the resource is exhausted.

A variant is a type of program designed not to give a constant net energy but in which the number of plants started is any chosen mathematical function of time. This is "arbitrary" insofar as selection of the mathematical function is concerned but once selected, the construction schedule is predetermined. Chapman referred to linear and exponential programs of this type. The present computer program does not schedule plant construction by accepting an input mathematical function and making the sequencing computations. However, the schedule can be developed in a separate calculation and then input as for any other arbitrary program.

Energy Utilization and Resource Consumptions

General equations are presented below for energy production rates and energy investment rates over any given TT interval for an individual program. Energy outputs for the n^{th} period are given by:

$$(EO1)_n = (PLOP)_n\,(PDC)(TT) + (PLCS)_n(PDC)\ {}^m(XT)(TT) \tag{5}$$

In this equation, the first term on the right is the total energy output of all operating plants in a program. The second term is the energy output of plants in start-up (assuming output to start at zero and rise linearly) to its full value at the end of the start-up period.

The term XT denotes the fraction of the start-up period corresponding to the midpoint of the m^{th} TT interval which ends at time T. Thus, it represents the point in time at which an average value of EO1 for the m^{th} interval can be evaluated. The superscript m is the number of TT intervals in one year.

$${}^m(XT) = \frac{T - (TT/2) - TSS}{T_s} \tag{6}$$

Energy investment in plant construction over the m^{th} interval of T_c is computed by the equation:

$${}^m(EI1) = {}^m(PLC)(CEI)(TT) + {}^m(PLCS)(CEI)(TT)(1 - XT) \tag{7}$$

The final term of equation 7 assumes energy investment to continue through the start-up period starting at its full value and decreasing linearly to zero at the end of the period.

The rate at which resource material is fed to the operating energy conversion plants at time T can be computed by:

$$(RO1M)_n = \frac{(EO1)_n}{(EFO * THVR)} \tag{8}$$

The term ECOST designates the aggregate energy cost of all materials, chemicals, catalysts, supplies, and energy in various forms consumed in the routine operation of a single energy conversion plant. The equivalent resource consumption is:

$$(RCOST)_n = \frac{(ECOST)_n(PLOP)_n(TT)}{(CEF)(THVR)} \tag{9}$$

The resource consumption $(RCOSSM)_n$, equivalent to the energy cost of supplemental energy and materials for mining the resource consumed in plant operations, is computed by the equation:

$$(RCOSSM)_n = \frac{ECOSM(RO1M + RSP)_n}{(EFS)(THVR)} \tag{10}$$

Resource consumed in supplying energy for mining resource materials consumed in the operating plants may be computed as follows:

$$(RSP)_n = \frac{(EM)(RO1M)_n}{(EFS)(THVR) - EM} \tag{11}$$

Summing the resource consumptions related to plant operations, for the n^{th} time interval,

$$(RO1)_n = (RO1M)_n + (RCOST)_n + (RCOSSM)_n + (RSP)_n \tag{12}$$

The interrelation of these energy inputs and resource consumptions is shown in Figure 4.

A similar diagram of energy costs and resource consumptions for the plant construction phase is presented in Figure 5. The terms ${}^m(ECOSS)$, ${}^m(RCOSS)$ and ${}^m(RCOSMS)$ for the m^{th} interval of the construction period are analagous to $(ECOST)_n$, $(RCOST)_n$, and $(RCOSSM)_n$, respectively, and are calculated by similar means.

The aggregate of energy costs of plant equipment and supplies, ECSC1, must be approximated and input. It is used to compute its resource equivalent as follows:

$${}^m(RS1M) = \frac{{}^m(ECSC1)}{(EFS)(THVR)} \tag{13}$$

The following equation aggregates the resource consumptions equivalent to the direct and supplemental energy consumed in plant construction during the m^{th} time interval.

$${}^m(RS1) = {}^m(RS1M) + {}^m(RCOSS) + {}^m(RCOSMS) + {}^m(RSSP) \tag{14}$$

The term ${}^m(RSSP)$ is found by:

$${}^m(RSSP) = \frac{(EM)\ {}^m(RS1M)}{(EFS)(THVR) - EM} \tag{15}$$

ENERGY COSTS AND RESOURCE CONSUMPTIONS FOR OPERATING PLANTS IN A PROGRAM

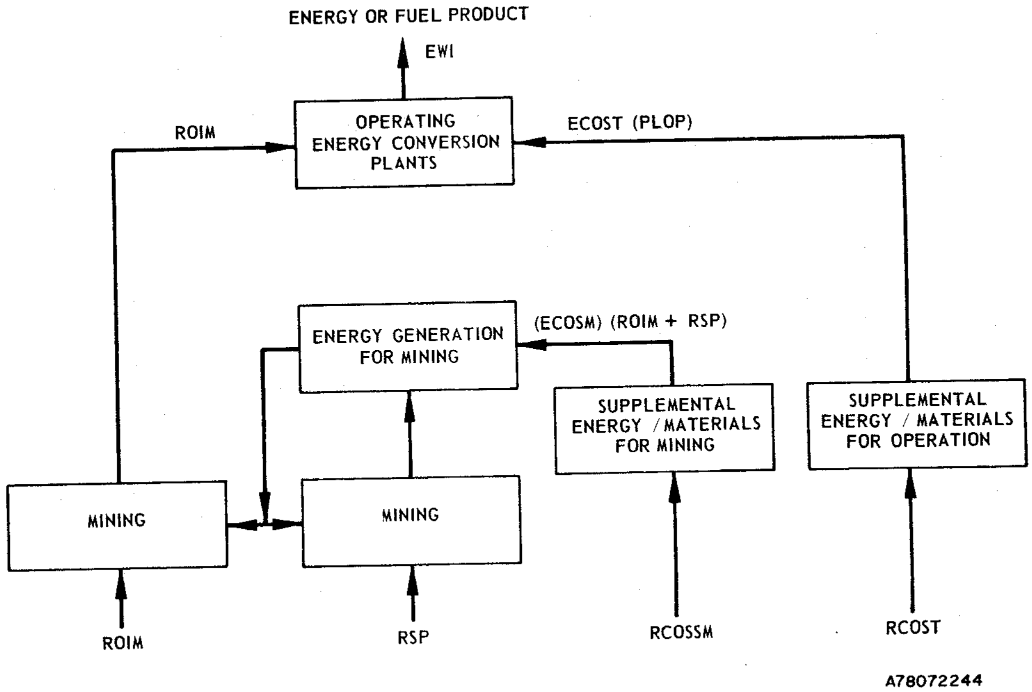

Figure 4.

ENERGY COSTS AND RESOURCE CONSUMPTIONS FOR PLANTS UNDER CONSTRUCTION IN A PROGRAM

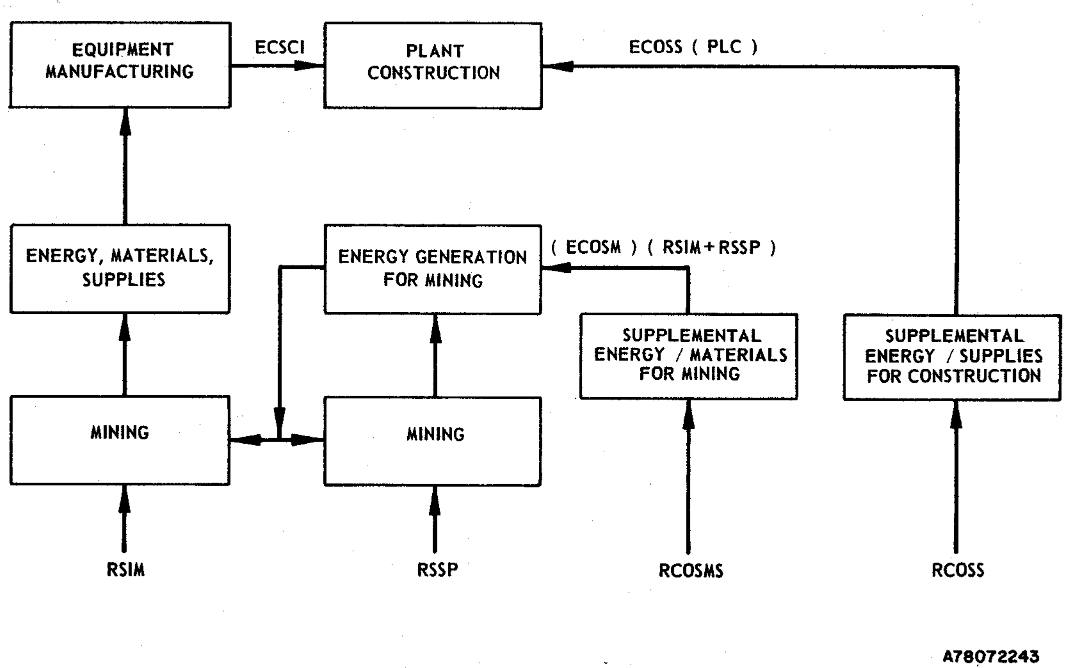

Figure 5.

At each successive time interval, the foregoing computations are made for each of the activated programs. Summation techniques are used to compute current rates and cumulative figures for energy investment, utilization, and output, net energy, and resource utilization for both the individual and the composited programs. Also the status with respect to energy profitability, overall resource depletion are determined. If plants in separate programs produce the same energy, fuel or other product the data are composited and tabulated in appropriate categories.

An entry can be made for the operating life of a plant in each program. If no entry is made, the program will continue until the assigned program production goal is reached or until the total resource is depleted. Once the production goal is attained, construction will stop and all constructed plants will run at design capacity until the resource is depleted.

If an entry with respect to plant operating life is made, replacement of plants is carried out, with the appropriate time lag, in the same sequence as in the original program and with the same energy costs, investments and corresponding resource consumptions. Cycling will continue until resource exhaustion occurs. An original program and a second cycle replacement program is illustrated in Figure 6. In this case, the number of plants under construction at any time is plotted against time for a plant life expectancy of 22 years.

Computer Program Structure

A main program entitled "ENPROAN" (energy program analysis) utilizes three subroutines, PLCON1, PLCON2 and TOPLAN. ENPROAN is diagrammed in Figure 7. It calls PLCON1 and PLCON2 to determine the number of plants in the categories of construction, start-up, and operation at any time for the designed and arbitrary programs, respectively. PLCON1 is diagrammed in Figure 8 and PLCON2 in Figure 9. TOPLAN, a subroutine applicable only to arbitrary programs, is shown diagrammatically in Figure 10. It computes for each program the number of plants under construction, the number in the start-up period, and the number in operation at any time.

Input Data

Input data are tabulated in Table II. Energy cost data are assumed to be available and to represent the best possible determinations or approximations.

Output Data

The printout will:

1. Tabulate general input data and specifications for each program anal

2. Report individual program results including current and cumulative values for energy output, energy investment, energy withdrawn, electrical energy supplied from outside sources for construction and operation, net energy, equivalent resource consumed in construction, equivalent resource consumed in plant operation, number of operating plants and number of plants under construction. These are given for a selected reporting interval which may be any multiple of TT. Usually the multiple is specified to give annual reporting.

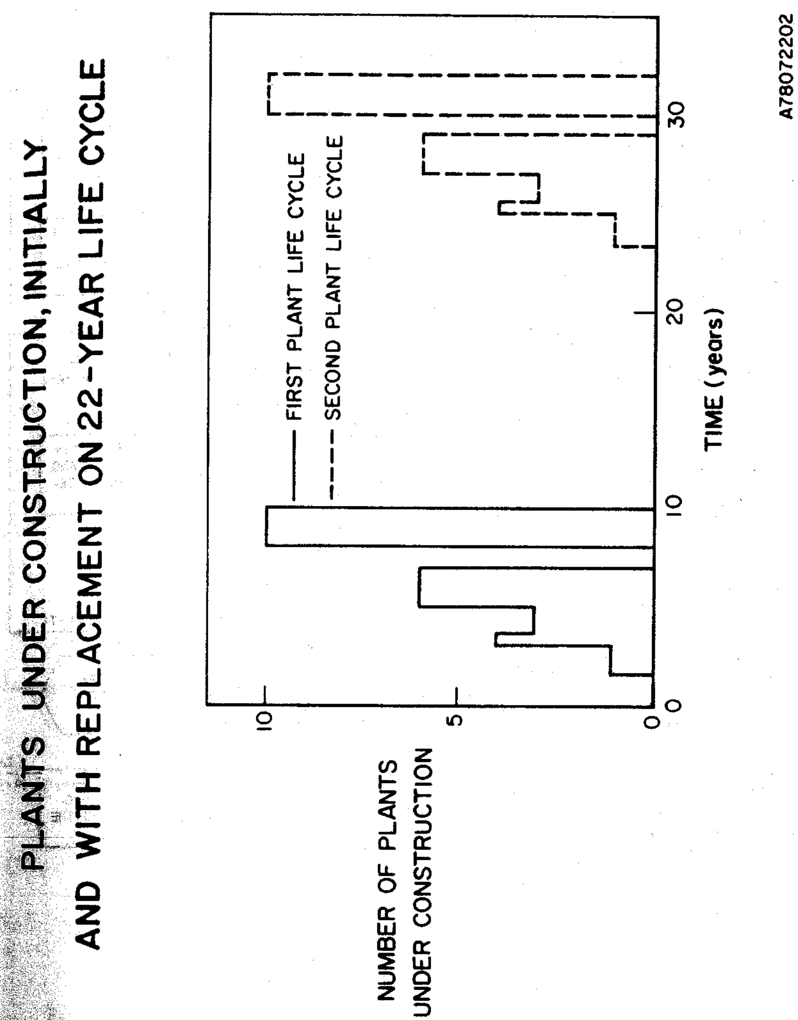

Figure 6.

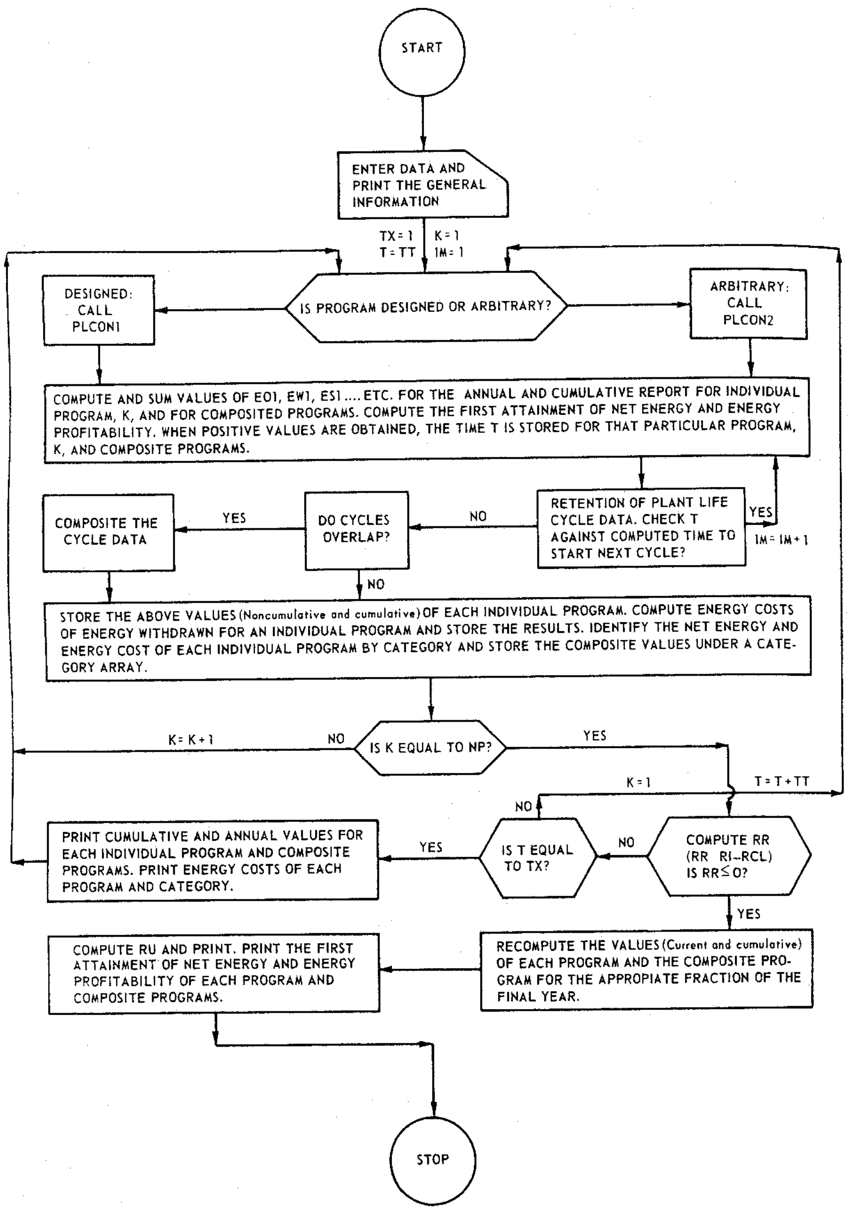

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Figure 7. Diagram of Main Program - ENPROAN

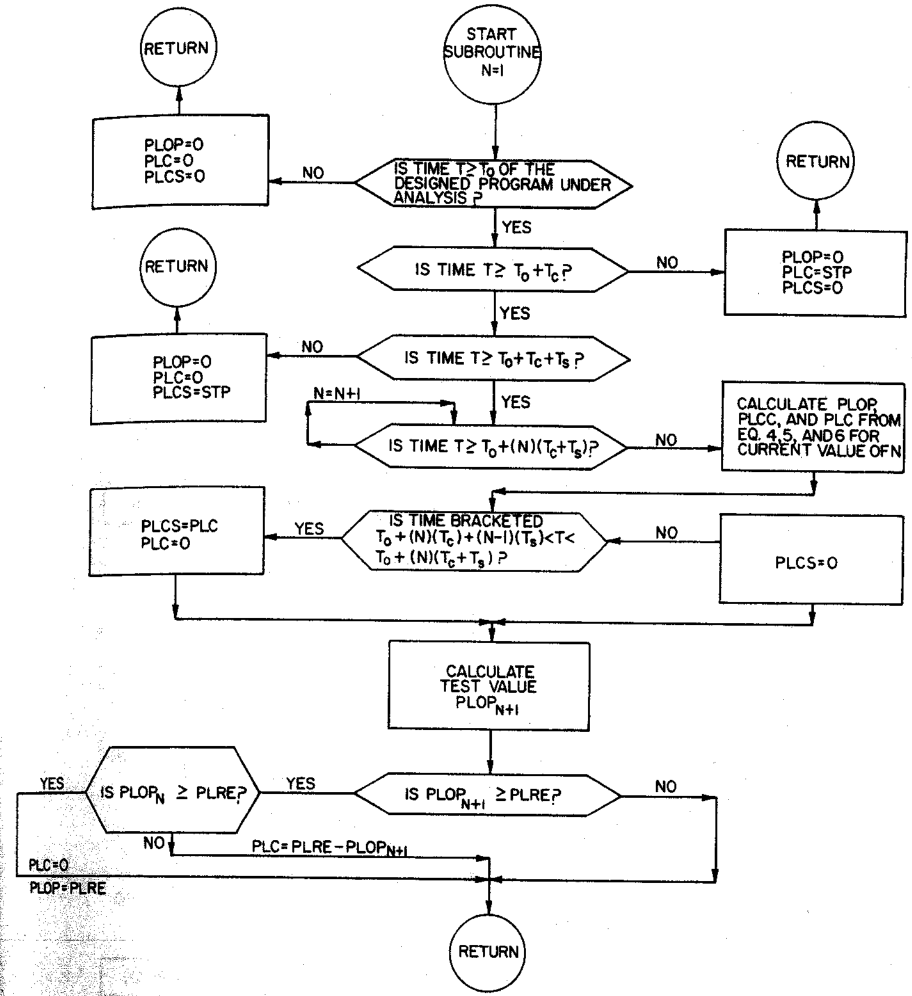

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Figure 8. Sequence of Calculations PLCON 1 - Subroutine

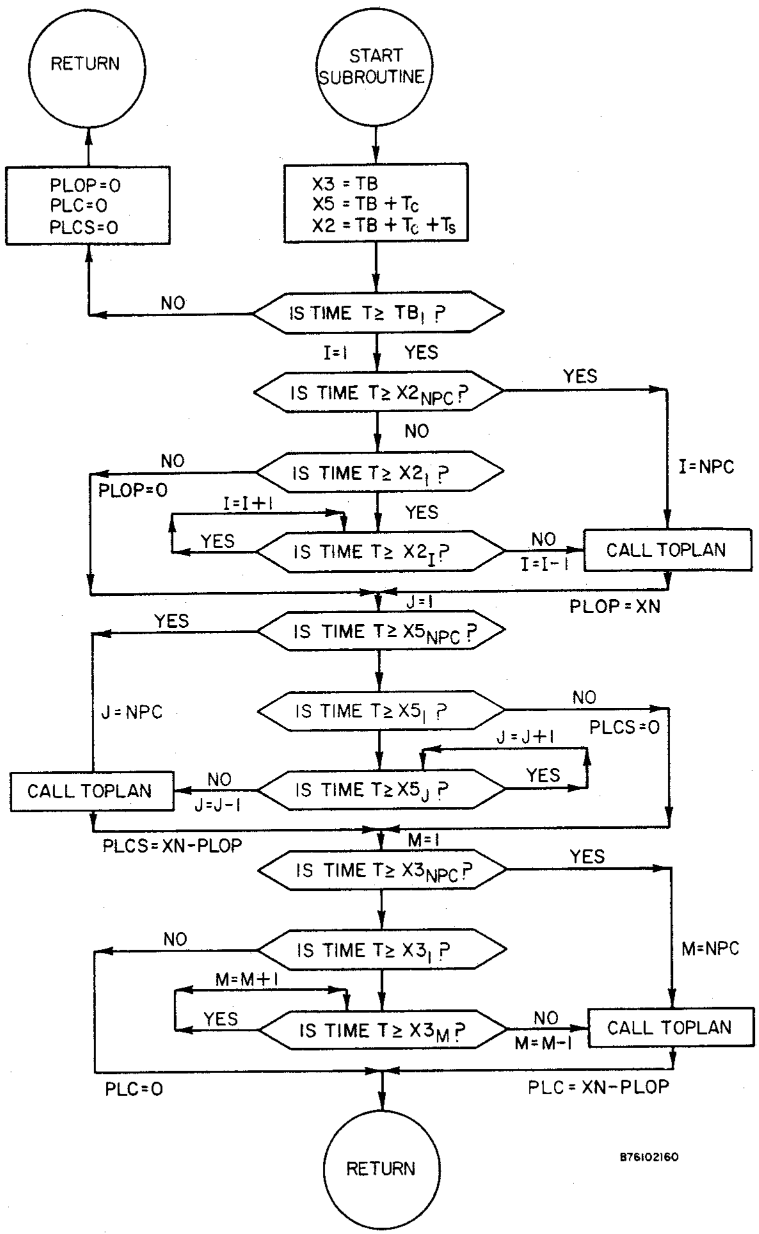

Figure 9. Sequence of Calculations PLCON 2 - Subroutine

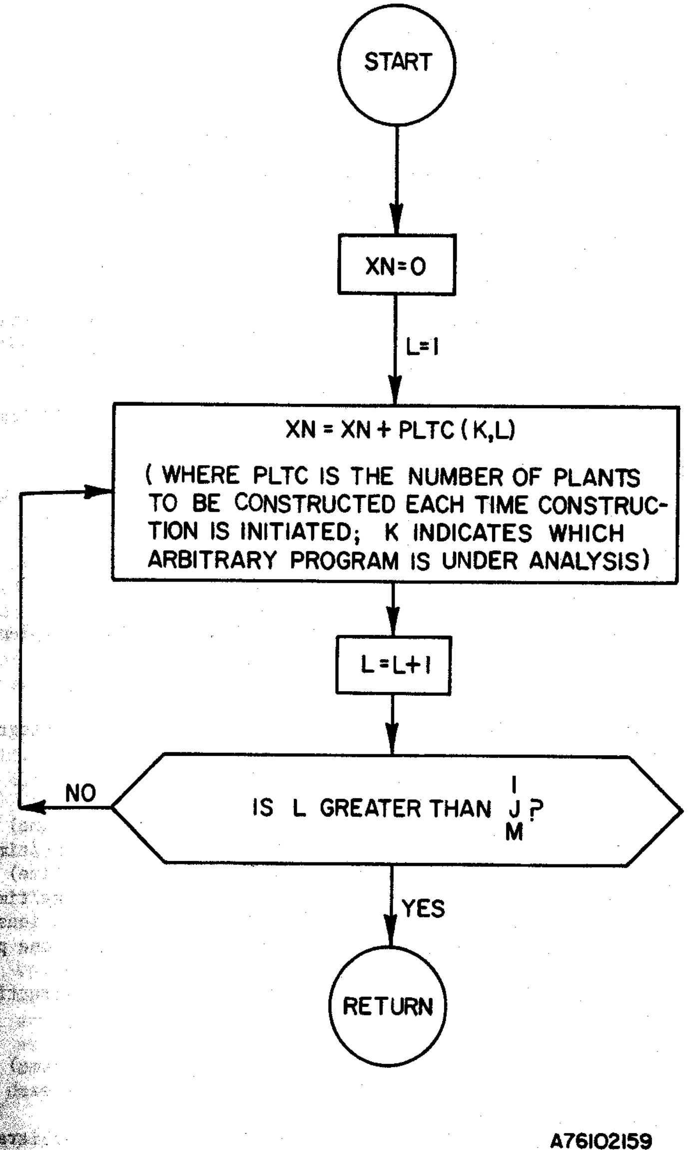

Figure 10. Sequence of Calculations for TOPLAN - Subroutine

TABLE II

Input Data

General

-Name of resource material
-Evaluation interval
-Multiplier of evaluation interval for computing reporting items
-Number of programs under analysis
-Number of program categories under evaluation
-Initial amount of resource (mass)
-Thermal heating value of resource material (energy/mass)
-Energy cost for operating supplemental energy producing plants (energy/time)
-Energy cost for mining or producing resource material (energy/mass)
-Efficiency in converting resource material to supplemental energy
-Efficiency in conversion of resource material to energy costs
-Rate of resource depletion due to pre-existing activities (mass/time)

For Each Program

-Code number of construction program
-Name of program
-Energy plowback multiplier
-Number of plants in initial construction group
-Plant operating efficiency
-Average efficiency of plants producing energy for mining or supplemental energy for plant construction
-Plant construction time (elapsed time)
-Plant start-up time (elapsed time)
-Activation time of program (elapsed time since start of first program)
-Operating life of plants (elapsed time)
-Plant design capacity (energy/time)
-Total energy prodcution goal of program (energy/time)
-Energy investment rate for construction of one plant (energy/time)
-Electrical power required for construction of one plant (energy/time)
-Electrical power required for operation of one plant (energy/time)
-Energy cost of operating one plant ex electrical energy (energy/time)
-Efficiency in converting resource material to energy for operations
-Energy cost of materials, supplies, etc., for construction of one plant (energy/time) Note: direct energy inputs excluded.
-Efficiency in converting resource material to energy for construction
-Specified energy or fuel quantity units
-Conversion factors for energy units
-Number of plant construction initiation times (arbitrary programs)
-Number of plants for which construction is to be initiated at each initiation time (arbitrary programs)
-Specified times for initiation of plant construction (time)(arbitrary programs)

3. Composited results for all activated programs including current and cumulative values for each of the variables reported in (2) except that electrical energy inputs are aggregated, equivalent resource consumptions are totalized and the remaining resource reported.

4. In addition to the composited values, the annual energy cost of energy produced is computed for each program and for composited programs. These annual energy costs are aggregated for each form of energy produced. Computations are continued until resource exhaustion is reached. At this point, the following data are reported:

   a) The elapsed time from initiation of the first program to resource exhaustion.

   b) The overall efficiency of resource utilization.

   c) The time to first attainment of net energy for each program and for the program composite.

   d) The time to attainment of energy profitability.

Scope, Capabilities, and Limitations of the Computer Program

The program is not specific to any particular energy resource. It can evaluate building programs for coal gasification plants, magneto-hydrodynamic plants, nuclear plants or any type of operation in which a resource is converted to energy or fuel. If the predictions are to be accurate, however, with respect to resource utilization, reasonably good input data must be available on energy costs, energy investments, yields, conversion efficiencies and the initial amount of remaining resource.

The computer program can evaluate simultaneously any number of building programs in any number of categories providing limitations of the computer are not exceeded.

Limitations of the computer program in its present state of development include the following:

1. The resource consumed to build and operate installations that supply supplemental energy for mining, construction of new plants, etc. is assumed to be the same resource consumed by the operating plants. Where other resources are obviously used, or energy costs of materials, equipment and supplies from diversified and unknown sources are concerned, the quantities can be converted to equivalent amounts of the reference source. Thus, the total impact of resource consumption is referred to one type of resource although several may be involved.

2. For designed programs, construction of new plants is initiated only when start-up has been completed for all plants previously begun, the number of plants at each initiation time being that computed from equations (5) and (6). This method is continued until the specified maximum power output, fuel production rate, or manufacturing capacity is attained, or until the resource is exhausted.

3. Due to limitations of the computer on which the program was developed it was necessary, with arbitrary programs that all specified plants be initiated in not over fifty construction starts. The program

itself, is not so limited, however, but can utilize the full capacity of any computer in which it is operated.

4. Linear increase of energy output during the start-up period of an energy conversion plant is assumed, together with a proportional increase in resource consumption and a linear decrease in energy use and equivalent resource consumption for construction. These routines could easily be modified to more accurately reflect construction and start-up experience.

5. The energy costs, energy investments, and conversion efficiencies are assumed to be constant or linear functions throughout the years of analysis. Alternate modes of inputting these factors could also be easily developed.

6. The plant construction time and the start-up of an individual program can be reported in either fractional or integer years. Fractional numbers can be specified to one decimal point only.

Typical Results

Printouts of computer program runs are voluminous and no attempt will be made here to present such results in their entirety. However, a graphical representation of computed results will serve to illustrate the utility of the program. Four construction programs are considered as follows:

		Type
Program I	- Manufacturing Plants	Arbitrary
Program II	- High-Btu Gas From Coal	Arbitrary
Program III	- Low-Btu Gas From Coal	Designed
Program IV	- Electricity From Coal	Designed

Figure 11 indicates the number of plants in operation at any time for each of the four programs. Figure 12 shows the computed total energy output, the energy investment, and the net energy withdrawn on a non-cumulative basis for the composited programs. Figure 13 shows a net energy plot for the manufacturing plant program (I) over the life of the resource. Similarly, Figures 14, 15, and 16 show the non-cumulative net energy curves for the arbitrary High-Btu gas program, the designed program to produce Low-Btu gas from coal, and the designed program for electrical power generation, respectively. Figure 17 shows resource consumptions on a non-cumulative basis for the composited programs. In Figure 18 cumulative resource consumptions for the composited programs are plotted against the residual resource.

In addition to information here presented graphically, the following computed information is reported in the full printout:

1. The fuel or energy production from operating energy conversion plants, energy investments and the energy withdrawn from the program. The points indicated for return to zero mark the times calculated for total depletion of the resource.

2. The amounts of electrical energy required for plant construction and operation in each program together with the composite for all programs

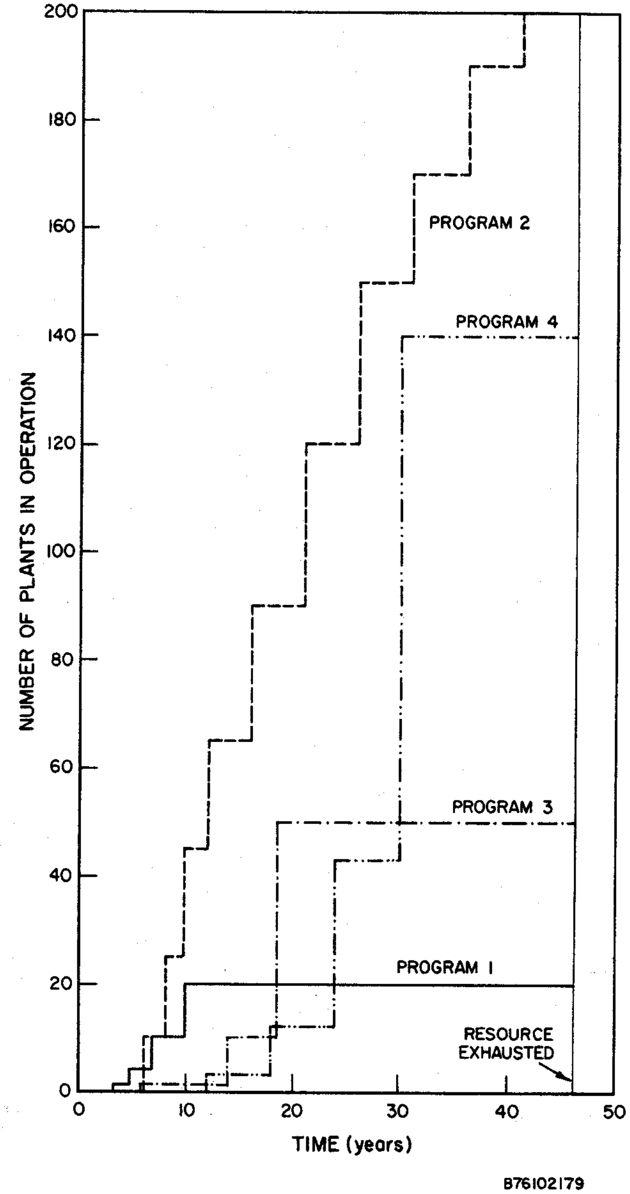

Figure 11. Plants in Operation - Four Programs

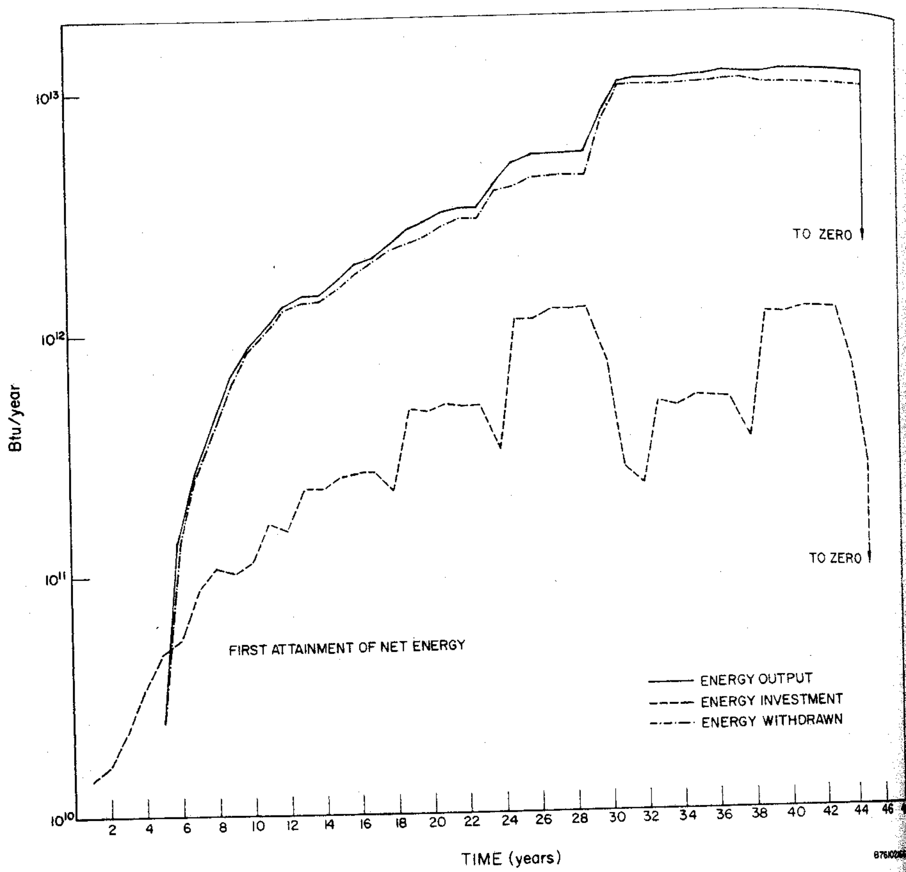

Figure 12. Non-cumulative Energy Output and Energy Investment (Including Energy Costs for Construction) for Composited Programs

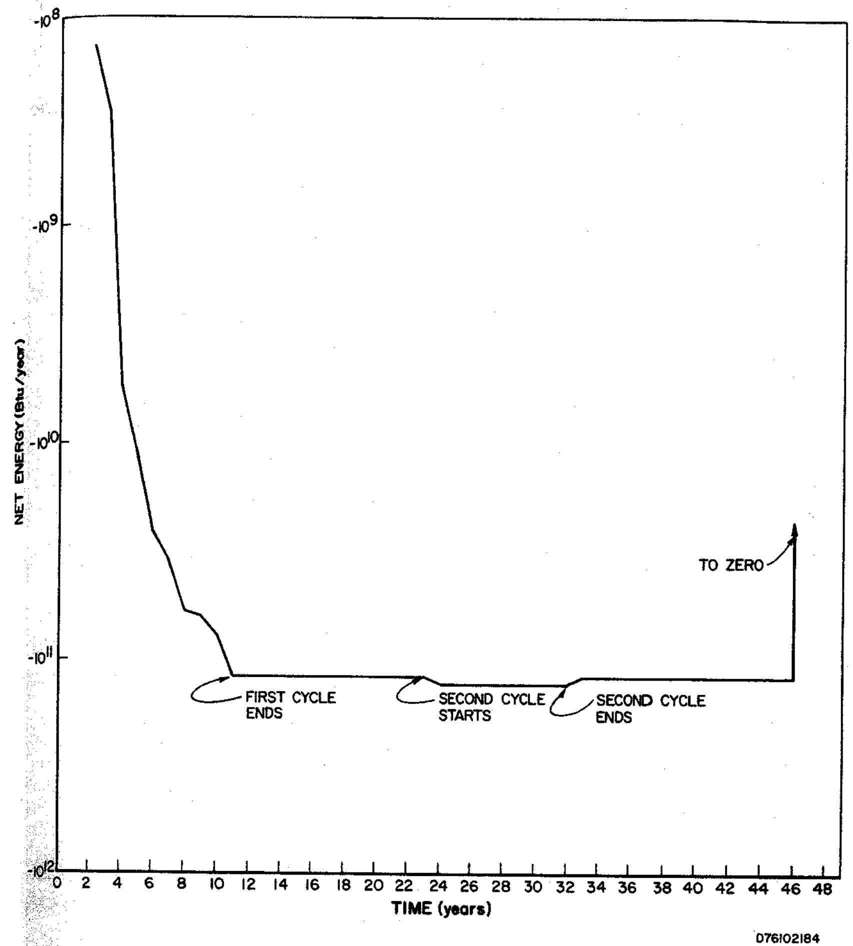

Figure 13. Program I - Net Energy (Non-cumulative) - Manufacturing

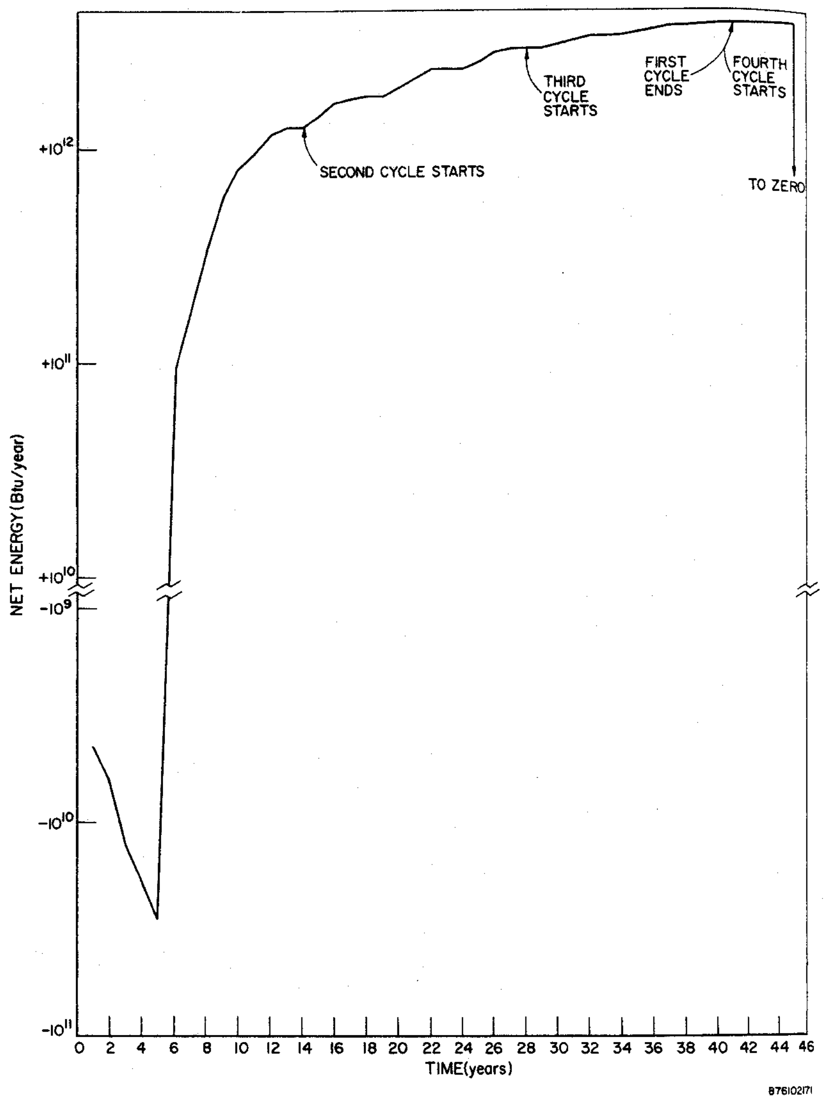

Figure 14. Program II - Net Energy (Non-cumulative) - High Btu Gas

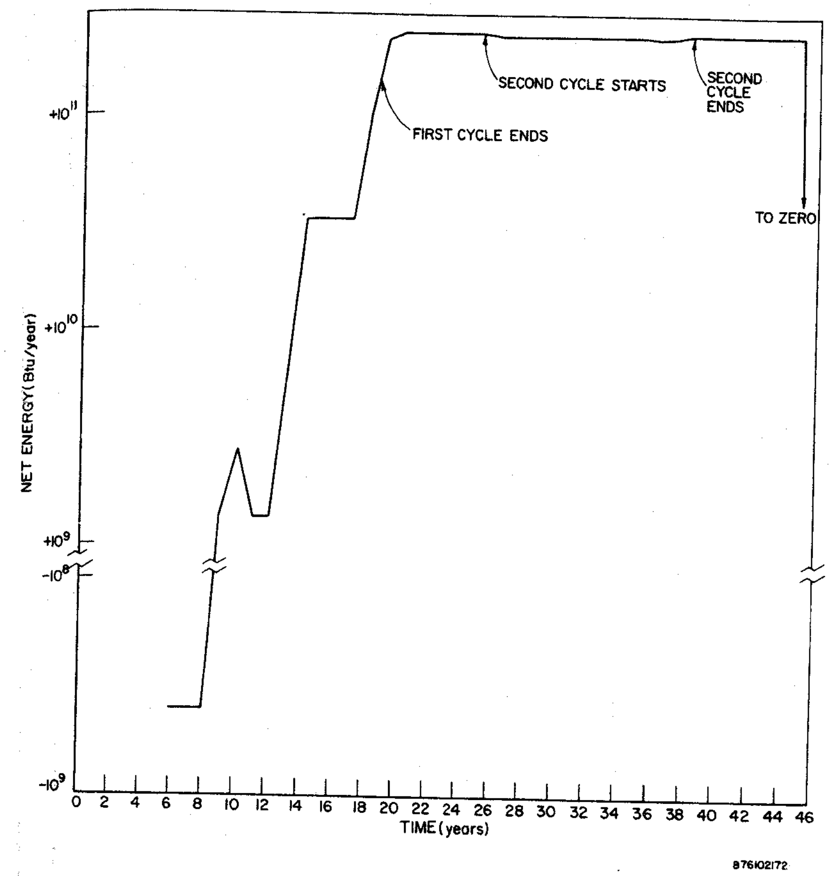

Figure 15. Program III - Net Energy (Non-cumulative) - Low Btu Gas

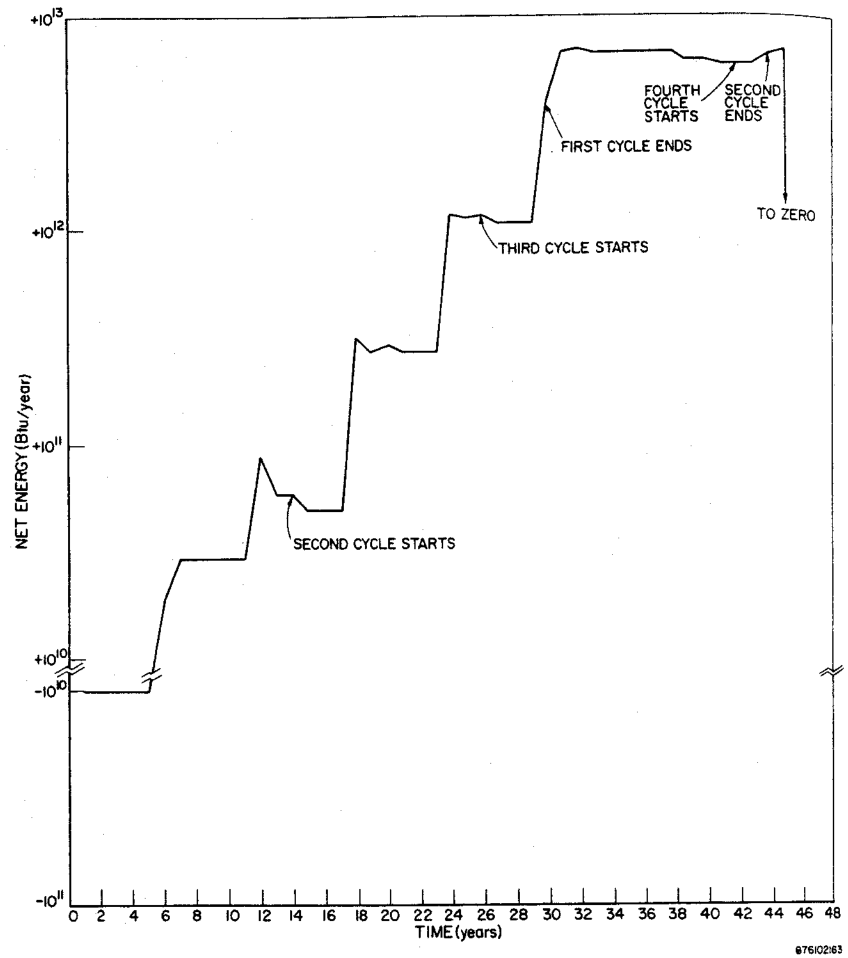

Figure 16. Program IV - Net Energy (Non-cumulative) - Electric Power

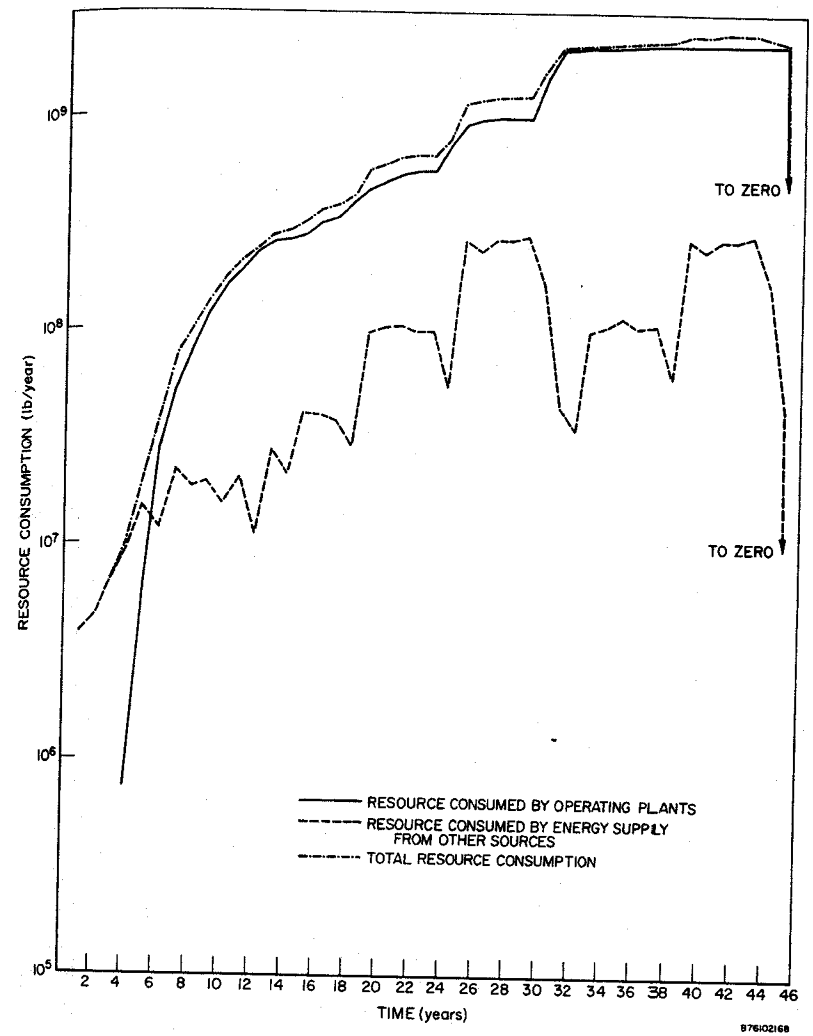

Figure 17. Resource Consumptions (Non-cumulative) - Composited Programs

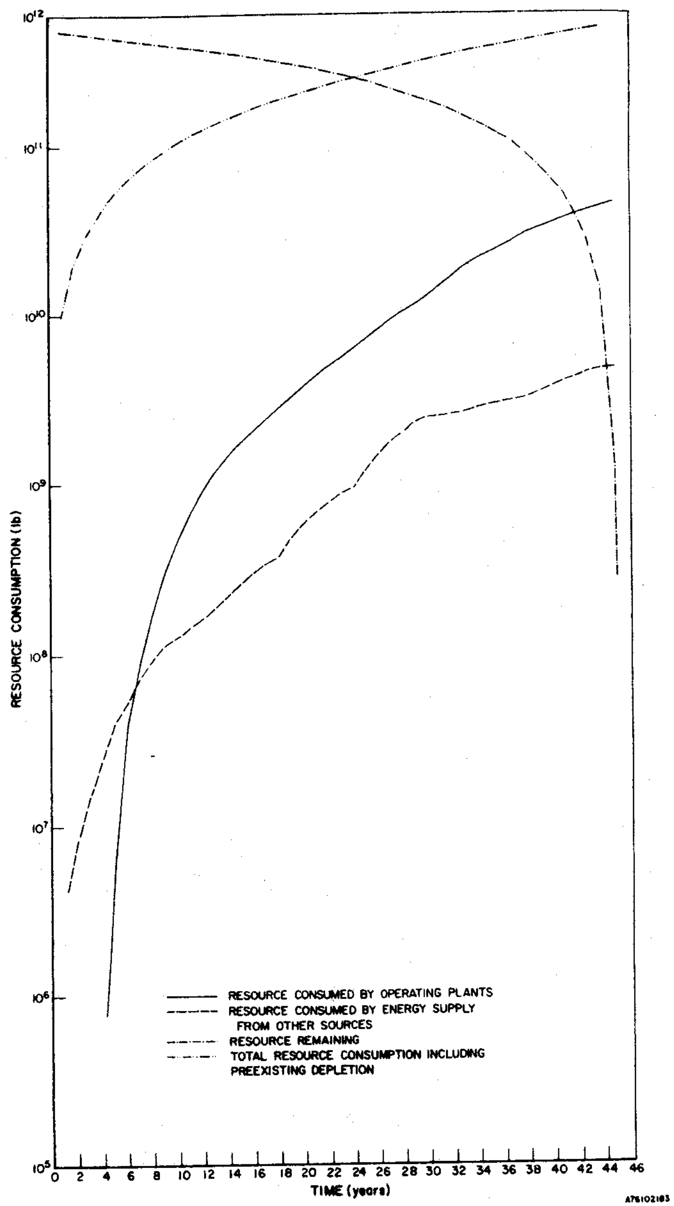

Figure 18. Resource Consumptions (Cumulative) and Residual Resource - Composited Programs

3. The amounts of supplemental energy from extraneous sources for mining of resource materials and for construction in each program and for the composited programs.

4. The net energy figures composited for each category of fuel or energy produced.

5. The energy cost of all energy or fuel withdrawn (all categories) on both current and cumulative bases.

6. The overall composite resource utilization efficiency.

7. The time to resource exhaustion for the composited programs.

8. The time for first attainment of net energy for each program and for the composite of all programs.

9. The time to energy profitability for each program and for the composited programs.

CONCLUSION

The computer program in its present state of development is an essentially simple planning tool.

Many modifications, refinements and extensions can be made to improve its range of applicability, general utility and the quality of computed results.

For example, the program assumes a constant average output from operating plants with no adjustments for shutdowns inadvertent or planned. It would be possible to develop means of introducing data from accumulated experience on operating schedules, service factors, plant efficiencies and updated approximations of unit energy costs to enable better computations.

As presently constituted, the computer program does not accommodate construction program changes at a midpoint in its execution. For example, it might be desired to make arbitrary changes in a designed program. This capability could be easily established in future work.

It is hoped the computer program here described will prove useful in future planning of energy supply and resource utilization.

NOMENCLATURE

ECOSM	supplementary energy costs of mining a resource material. energy/unit mass of resource mined
ECOSS	energy cost of direct and supplemental energy, materials etc. for construction of one individual plant in a program. energy/time
ECOST	energy cost of energy, utilities, supplies, etc. for operation of one plant of an individual program. energy/time
ECSC1	energy cost of equipment installed in all plants under construction in one program. energy/time
EFO	operating efficiency of an energy conversion plant.
EFS	efficiency in conversion of resource to supplemental energy or energy for mining.
EI1	energy investment in plant construction for a program over interval TT. energy
EM	direct energy consumed in mining. energy/unit mass of resource mined
EO1	energy output of operating energy conversion plants of a program. energy/time
EW1	energy, or energy equivalent of fuel products, withdrawn from operating energy conversion plants of one program.
CEI	energy investment rate for construction of one plant of a program. energy/time
FR	energy plowback multiplier. The fraction of energy produced that is equivalent to the energy invested in new plant construction.
PDC	design capacity of a plant in a program.
PLC	number of plants being constructed or started-up at a given time in one program.
PLCC	number of plants operating, being constructed or started-up at a given time in one program.
PLCS	number of plants being started at any time in a program.
PLOP	number of plants operating at a given time in a program.

RCOSMS	resource equivalent to (ECOSM)(RS1M + RSSP). mass/time
RCOSS	resource consumed equivalent to (ECOSS). mass/time
RCOSSM	resource equivalent to (ECOSM)(RO1M + RSP). mass/time
RCOST	resource consumed equivalent to ECOST. mass/time
RO1M	resource consumed by energy conversion plants of a program. mass/time
RP	ratio of the energy output rate for one plant of a program to the energy investment rate for construction of one similar plant.
RS1M	resource consumption corresponding to ECSC1. mass/time
RSP	resource mined to provide the energy needed to mine RO1M.
RSSP	resource mined to provide the energy needed to mine RS1M.
RU	resource utilization of the composite program carried to resource exhaustion. net energy produced overall/original heating value of resource
STP	number of plants started simultaneously as the first step in a program.
T	time.
T_c	elapsed time required for construction of one plant.
THVR	unit thermal heating value of resource material. energy/mass
T_s	time required to start-up one plant.
TSS	most recent time in a program when plant start-ups were initiated.
TT	specified interval between reporting times.
XT	fraction of start-up period $=(T - \frac{TT}{2} - TSS)/TS$

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NET ENERGY ANALYSIS OF FOSSIL FUELS AND A MATERIALS PROCESSING APPLICATION

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ABSTRACT

Two studies on net energy are discussed in this paper. The first, "Net Energy Analysis: An Energy Balance Study of Fossil Fuels", developed a methodology and net energy data for twenty trajectories of fossil fuel production systems. The systems include resources in the ground and all process steps up to energy delivery to end use.

The second study deals with net energy required to produce various materials, fabricate and distribute products from those materials, and recycle the products or materials back into the production system. The methodology and general findings are presented.