DOE/PE/70143-02 Volume 1
Volume 1 of 3 Volumes

UC-90

Dc. 2111

#1

30 to Stock

25 cop to NTIS
Balance for Stock

11/16/80

MASTER

Fossil 2 Energy Policy Model Documentation

Generic Structures of the Fossil 2 Model

October 1980

Prepared for:
U.S. Department of Energy
Assistant Secretary for Policy and Evaluation
Office of Analytical Services
Under Contract No. AC01-79PE 70143

DISCLAIMER

Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price:	Printed Copy:	$7.00
	Microfiche:	$4.00

Master

DOE/PE/70143-02 Volume 1
Volume 1 of 3 Volumes

Fossil 2 Energy Policy Model Documentation

Generic Structures of the Fossil 2 Model

October 1980

Prepared for:
U.S. Department of Energy
Assistant Secretary for Policy and Evaluation
Office of Analytical Services
Washington, DC 20585

Prepared by:
Energy and Environmental Analysis, Inc.
Arlington, Virginia 22209
Under Contract No. AC01-79PE 70143

VOLUME I:

GENERIC STRUCTURES OF THE FOSSIL2 MODEL

Page

1. INTRODUCTION

This report discusses the structure, derivations, assumptions, and mathematical formulation of the FOSSIL2 model. Each major facet of the model -- supply/demand interactions, industry financing, and production -- has been designed to parallel closely the actual cause/effect relationships determining the behavior of the United States energy system.

The data base for the FOSSIL2 program is large, as is appropriate for a system dynamics simulation model. When possible, all data were obtained from sources well known to experts in the energy field. Cost and resource estimates are based on DOE data whenever possible.

This report presents the FOSSIL2 model at several levels. In Volume I, an overview of the basic structures, assumptions, and behavior of the FOSSIL2 model is presented so that the reader can understand the results of various policy tests. The discussion covers the three major building blocks, or generic structures, used to construct the model:

- Supply/demand balance
- Finance and capital formation
- Energy production.

These structures reflect the components and interactions of the major processes within each energy industry that directly affect the dynamics of fuel supply, demand, and price within the energy system as a whole.

Volumes II and III of this report list the equations that comprise the FOSSIL2 model, along with variable definitions and a cross-reference list of the model variables. Volume II provides the model equations with each of their variables defined, while Volume III lists the equations, and a one line definition for equations, in a shorter, more readable format.

FOSSIL2 is based on earlier work related to the FOSSIL1 model.* A complete set of documentation for the FOSSIL1 model is available from the Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire.

---

* The format of the FOSSIL2 documentation is taken from Backus, G., et al. FOSSIL 79 Introduction to the Model. Thayer School of Engineering, Dartmouth College, DSD #165, Hanover, NH, 1979. Backus, G., et al. FOSSIL 79 Documentation, Thayer School of Engineering, Dartmouth College, DSD #166, Hanover, NH, 1979.

ACKNOWLEDGEMENTS

The FOSSIL2 model was developed by Anthony Masevice under guidance provided by Roger Naill and others within the Office of Analytical Services. Thanks go to Lee Rogge of EEA Inc. for her extensive work in documenting the model, and George Backus of Purdue Univeristy for his analytical support in model development.

2. MODEL OVERVIEW

2.1 MODEL METHODOLOGY

A computer simulation model should be designed to enhance the user's understanding of a particular problem, its origins, and its potential solutions. To achieve this objective, the model must meet two criteria: its structure must represent adequately the relevant processes in the real-world system, and its organization and output must be clear and consistent. If the policy-maker using the model can identify the major components of the model, understand its output, and use the model to test and evaluate alternative policies, then the model is serving its purpose well.

The FOSSIL2 model uses the system dynamics modeling technique to capture the important aspects of the United States' energy problems. System dynamics has several advantages over other modeling methods for this application, the primary advantage being its ability to capture complex feedback interactions in large systems. These interactions are largely responsible for unforeseen counterproductive impacts that might result from some of the implemented policies.*

2.2 MODEL ORGANIZATION

The FOSSIL2 model is a highly aggregated representation of the national energy supply/demand balance. On the simplest level the model can be divided into two parts, one determining the demand for various fuels and the other representing their production. These two parts interact by exchanging information on fuel demand, availability, and price and use this information to balance supply and demand (Figure 1).

---

* For a more detailed explanation of system dynamics modeling, see Forrester, J. Principles of Systems. Cambridge, MA: Wright-Allen Press, 1968; and Goodman, M. Study Notes in System Dynamics, Cambridge, MA: Wright-Allen Press, 1974.

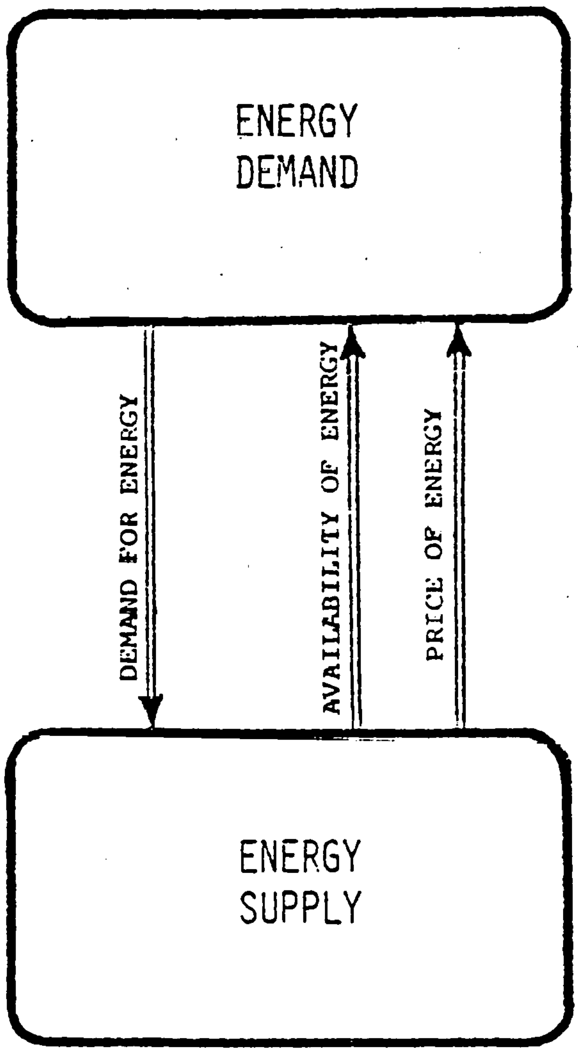


FIGURE 1

Basic FOSSIL2 Structure

Adjustments in demand occur largely in response to price, higher fuel prices causing both an overall reduction in demand and a shift to other, less expensive fuels whenever possible. Supply changes in response to price are a result of short-term and long-term adjustment mechanisms. Short-term production adjustments occur in response to changing demand and are achieved by changes in production capacity utilization. Long-term changes are effected by increasing (decreasing) production capacity through profit-induced investments.

Supply or production is disaggregated by fuel type into four sectors - oil, gas, coal, and, electricity. The sectors all have the same basic or generic structure, however, specific differences attributable to each sector are fully incorporated. Each of the supply sectors can be further subdivided into a fuel supply/demand balance subsector, a financial subsector, and a fuel production subsector which includes a representation of each proven or new production technology. Interactions between the fuel supply sectors exist when a production technology demands another fuel as either a feedstock or an energy input, e.g. electric utilities' demand for coal. The information exchange is then similar to that occurring between the demand and production sectors. Figure 2 presents a generalized view of sector organization and interaction in the FOSSIL2 model.

2.3 DEMAND SECTOR

The demand sector specifies both total net energy demand and fuel-specific net demands. Total demand is determined as a function of Gross National Product (GNP), the average energy price, and average energy availability. The nominal GNP is generated using a predetermined growth rate path derived using the outputs of macroeconomic equilibrium models. It is then modified by the impacts of increasing average energy price and fuel availability to estimate expected realized GNP values. The average price is weighted by relative fuel consumption, and energy availability

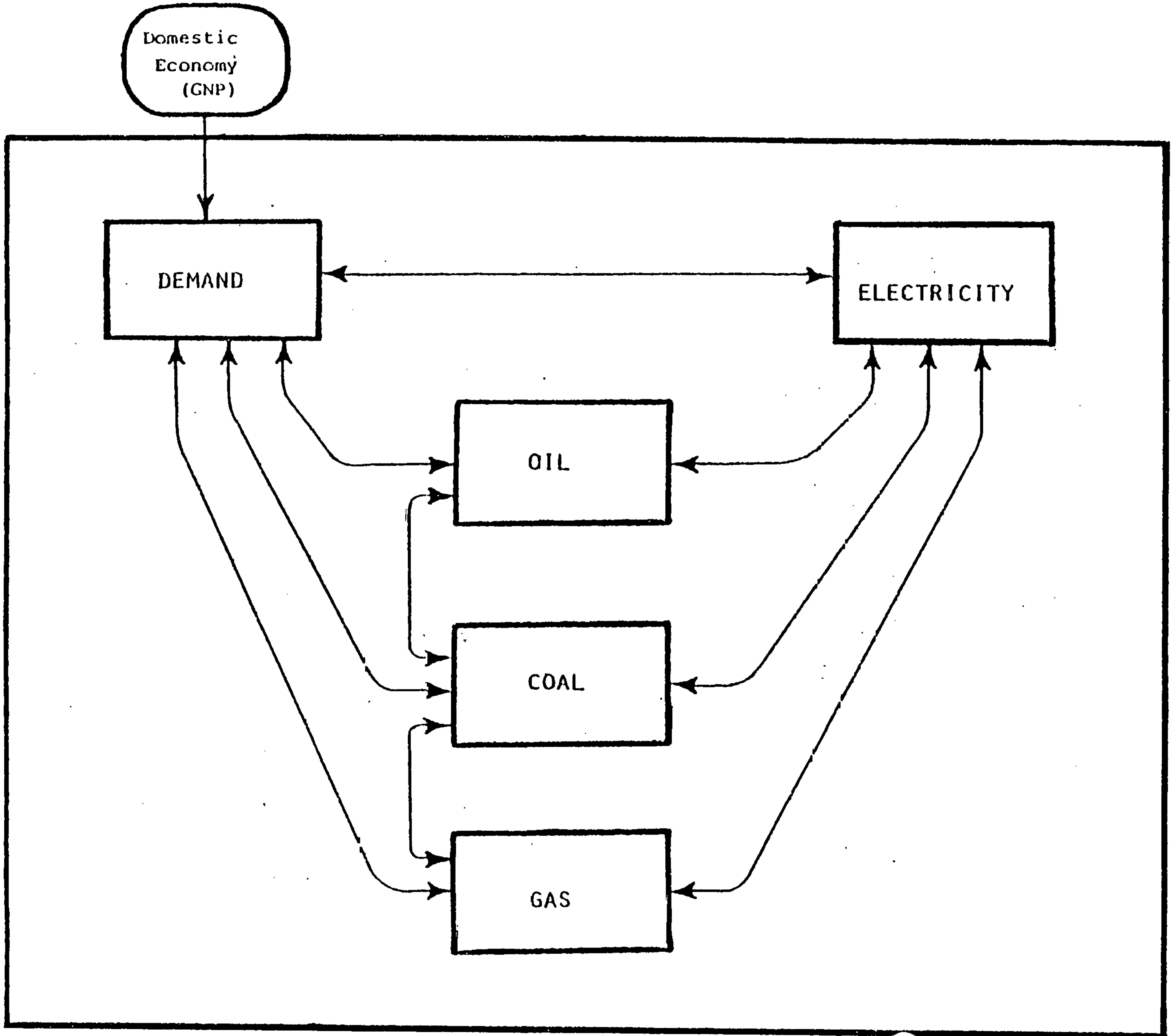


FIGURE 2
Sector Organization of FOSSIL2

is measured by a five-year moving average of the consumption/demand ratio.

Interfuel substitution occurs among five energy sources: oil, gas, coal, electricity and decentralized sources. The relative cost of each source to the consumer, its relative convenience, and its match to end-use activities determine the share of the total demand each fuel can meet. The four fuel production sectors for oil, gas, coal and electricity are designed to estimate the fuels' production levels and prices. Decentralized energy sources are not represented as a full-scale energy production sector but rather as a section within the demand sector. Consumer demand for decentralized sources is represented as a percentage of total energy demand and varies according to the cost of decentralized energy relative to centralized sources.

2.4 SUPPLY SECTORS

2.4.1 Supply/Demand Balance Subsector

After the demand sector allocates centralized energy demand among the four fuels, this information is passed to the fuels' respective production sectors. Within the supply/demand balance subsectors, each fuel's demand is compared with available production capacity to determine a free-market wellhead price and an average delivered price. Depending on the fuel and its degree of price regulation, the free market price may be further modified to yield the actual price and profit margin used in determining industry revenues. Demand also is compared to production capacity to determine the industry's capacity utilization factor.

2.4.2 Financial Subsector

The funds available to each industry to invest in new production capacity are estimated in the financing subsector. The size of the investment is projected using the price realized for a fuel, its production costs, and the size of the industry's capital assets. Funds available are compared with funds needed to meet current and future operation and expansion costs, and the lesser value is taken to be the funds actually used for those purposes. Each industry's available investments are then allocated among the industry's various production technologies on the basis of the marginal costs using a logistic allocation function (a modified logit model). Those technologies with the least marginal costs receive a greater portion of the available investment funds, e.g., electric utilities burning coal start receiving greater investments than utilities burning oil or gas as oil and gas costs become increasingly higher than coal costs. Investments allocated to the various production subsectors add to the production capacity of the subsector after typical capacity construction delays.

2.4.3 Production Subsectors

The production subsectors deal with two types of production technologies: extraction and conversion. The extraction technologies are those which involve removing a fuel from the ground, e.g., coal mining, all oil production exclusive of coal liquefaction, and conventional and unconventional natural gas recovery. Conversion technologies change one form of energy into another more desirable or useful form. Conversion processes include all forms of electricity generation, coal liquefaction, coal gasification and synthetic natural gas production.

Production from each subsector is a function of demand and production capacity. Capacity utilization changes are used to make short-term adjustments in output when projected demand does not correspond to actual demand. The electric industry, for example, customarily changes its capacity utilization in response to seasonal peaking. Conventional oil and natural gas production are constrained by geological limits relating output to the size of the reserves rather than by their production capacity utilization factors.

For all production processes that extract a resource, the least expensive, most easily accessible portion of the resource is assumed to be discovered and extracted first. This leads to increasing costs as a function of cumulative production, e.g. as thinner seams of coal are mined and more arctic and offshore oil wells need to be drilled. Conversion technologies which use fuels as feedstocks or fuel inputs are subject to depletion costs indirectly as they are reflected in the price of the primary fuels.

3. GENERIC STRUCTURES*

The behavior of a complex socioeconomic system generally can be understood by examining the behavior of the system's underlying component relationships. The mathematical description of these relationships, which often recur throughout the system, is referred to as a generic or fundamental structure. The FOSSIL2 model is composed of three such structures -- the supply/demand balance, financing, and production generic structures -- that appear in slightly modified form in all four fuel industry sectors. To understand these three structural building blocks, they are presented here in their simplest, most idealized form. In practice, the generic structures are modified to suit each specific energy industry application. The dynamics and framework of each of these structures are discussed below.

3.1 SUPPLY/DEMAND BALANCE

The supply/demand generic structure simulates the market-clearing process, i.e., the dynamic adjustments in both the price and quantity of a product produced in response to the relative balance between the product's supply and demand. As demand changes, both the utilization of existing production capacity and the fuel price react to equalize supply and demand. Increased demand increases utilization and price and, therefore, supply; reduced demand reduces utilization and price and, therefore, reduces supply. The assumption behind this structure is that, over the short run, producers can adjust supply through capacity utilization changes; over the long run, supply can be adjusted through changes in production capacity financed by varying price and, therefore, profit levels.

* This chapter is based on: Masevice, A., A Review and Assessment of the FOSSIL1 Supply Structures, DSD #125, Thayer School of Engineering, Dartmouth College, Hanover, NH, 1978.

Figure 3 shows the connection between the production and financing structures and the supply/demand structure within a given fuel sector (also shown at the bottom of Figure 4). Figure 4 shows important information flows within the boundaries of the supply/demand balancing structure. Information generated by the two key variables in the structure -- capacity utilization and price -- is exchanged with sources outside the structure.

The prices determined by the supply/demand structure are used in the financing generic structure to calculate funds available for capital investment. The capacity utilization factor is used to determine production rates. Other sectors of the model use information about the price and availability of a fuel to determine both end-use and feedstock demand.

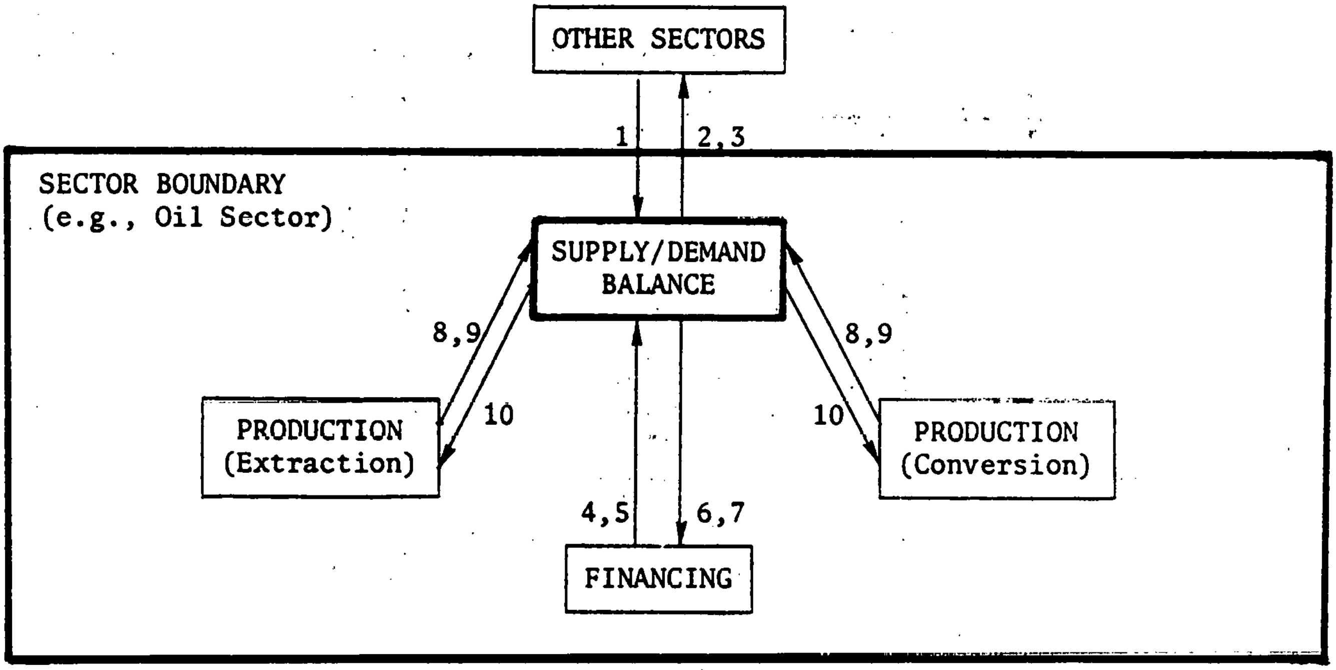
3.1.1 Capacity Utilization

The capacity utilization relationship uses demand and production capacity (the FOSSIL2 measure of supply potential) as inputs to yield the capacity utilization factor. These relationships are shown graphically in Figure 4.

Determining a capacity utilization factor is equivalent to determining a balance between supply and demand for a resource in accord with classical economic theory. Total production capacity is calculated as the sum of individual production capacities, yielding the maximum possible supply of the energy product. (The individual production capacities are determined in the generic production structures.) Next, a ratio of the total demand for the fuel (gas, oil, coal, or electricity) divided by this total production capacity is formed. The ratio indicates the percentage of capacity utilization needed to balance supply and demand. For example, a ratio of 0.4 would indicate that only 40 percent of capacity would need be utilized to meet demand. The actual capacity utilization factor is a nonlinear function of this ratio and therefore is specified in a

FIGURE 3

GENERIC SUPPLY/DEMAND BALANCE SUBSECTOR EXTERNAL INFORMATION FLOWS



	INPUT	OUTPUT
OTHER SECTORS (Industries)	1. DEMAND (for feed-stocks and/or end use	2. (Market) PRICE 3. AVAILABILITY (for entire industry)
FINANCING	4. TOTAL INDUSTRY EQUITY 5. TOTAL INDUSTRY COST	6. TOTAL INDUSTRY PRODUCTION RATE 7. (Market) PRICE
PRODUCTION	8. PRODUCTION RATES 9. PRODUCTION CAPACITIES	10. CAPACITY UTILIZATION FACTOR (for entire industry)

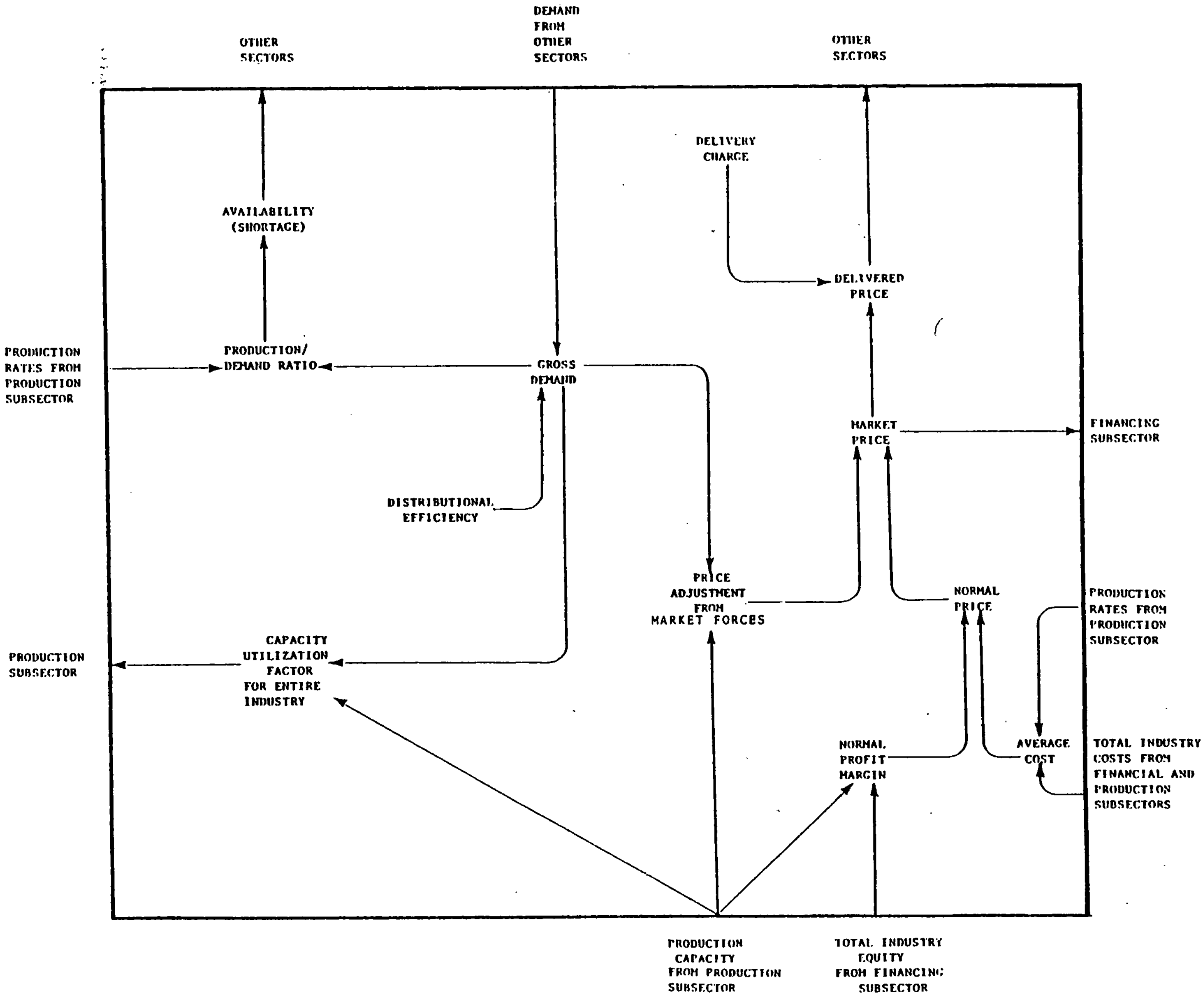


FIGURE 4

Generic Supply-Demand Subsector Structure table function that plots the capacity utilization factor against the demand/capacity ratio. The capacity factor is equivalent to the ratio (the slope of the table is one) for lower ranges of the table because producers are able to meet demand easily at lower capacity factors.

The capacity factor drops below the demand/supply ratio, however, for values in the upper ranges of the table, usually when the demand/capacity ratio exceeds 0.9. This difference in values develops from the increased difficulties and costs incurred when operating existing capital above its normal utilization factor. The capacity utilization factor gradually approaches 100 percent as the demand/capacity ratio exceeds 0.9. Typical equations describing the capacity utilization of Figure 4 might include the following:

CUF = TABLE* (CUFT, TD/TPC, 0, 1.0, 0.1)
CUFT = 0/0.1/0.2/0.3/0.4/0.5/0.6/0.7/0.8/0.90/0.92
TPC = PC1 + PC2 + ...
TD = D1 + D2 + ...

where:

CUF	=	capacity utilization factor (fraction)
CUFT	=	capacity utilization factor table
TPC	=	total production capacity of sector (Btu/year)
TD	=	total demand from other sectors (Btu/year)
PC<n>	=	production capacity of one of the production subsectors within the sector (Btu/year)
D<n>	=	demand from one of the other sectors (Btu/year).

In the linear range of the table supply equals demand. Above the linear range of the table (i.e., above 0.9 for the previous example), a domestic energy shortage occurs since supply, equivalent to capacity utilization

---

* TABLE signifies a functional relationship represented by a table. Table values are given for CUF for each 0.1 change in TD/TPC (the demand/supply ratio) as TD/TPC varies from 0 to 1.0.

as determined above times production capacity, begins to drop below demand. Shortages are reflected in the production/demand ratio, which serves as the index of availability in the model. This ratio is calculated as the ratio of total production to demand and is represented in Figure 4 by the following:

PDR = TPR/TD

TPR = PR1 + PR2 + ...

where:

PDR = production/demand ratio (fraction)

TPR = total production rate (Btu/year), or total supply

PR<n> = production rate of one of the production subsectors within the sector (Btu/year)

A ratio of one indicates full availability, while a ratio of less than one indicates a shortage. This shortage can be mitigated in the short run only through increased imports. When this is impossible, the shortage becomes a measure of economic loss through curtailment of needed energy to the energy-dependent sectors of the economy. The long-run solution is either to increase production capacity through new capital investment or to shift demand away from the scarce fuel through interfuel substitution. New investment is generated through accrued profits, and profits are increased as the price responds to the relative scarcity of supply, as defined in the pricing relationships of the supply/demand generic structure. Thus, the long-term responses to energy shortages are initiated through an increase in energy price (unless blocked by government regulatory actions).

Under regulated conditions, determining capacity utilization becomes slightly more complicated. As an industry increases its capacity utilization beyond the normal level (0.80), added costs are incurred by labor overtime and increased equipment breakdown due to heavier use. Since regulations set the absolute price, it is not in the economic interests of the company to increase the capacity utilization unless the regulated price is sufficiently high to cover the added cost of increased output. This situation is seen in both the oil and gas industry sectors of the model.

3.1.2 Pricing Relationships

The pricing relationships calculate the wellhead and delivered prices of each of the four energy forms from average costs, total capital, and total production capacity. Prices may be set in one of two ways: by a regulated pricing rule or by market forces as typically described in conventional economic theory.

The normal price of a product is computed as the average cost plus a profit margin. The industry average cost is computed as a weighted average of the costs of the different methods of production (for example, conventional oil, shale oil, and synthetic oil from coal). This weighting is accomplished by adding individual production rates multiplied by their unit cost of production and dividing by the total amount of production (see the following ACST equation).

The equations in the model are formulated so that a profit margin is computed based on a normal business return-on-equity (ROE) [usually 10 percent per year (real), after taxes]. Given a normal ROE, the FOSSIL2 model calculates normal profit margin before taxes as follows:

- ROEN = normal ROE
- Profit = ROEN x equity
- Total Btu produced = normal capacity utilization factor (CUFN) x total production capacity (TPC)
- Profit/Btu = profit/total Btu produced = (ROEN x equity)/(TPC x CUFN).

The actual industry profit margin (and, therefore, price) will fluctuate in response to changing market forces. An elasticity factor (the price multiplier), determined by production capacity and demand (see Figure 4), is multiplied by the normal industry price to yield the actual price for each fuel. Therefore, as demand increases relative to supply, profit margin will increase, and price - the sum of that industry's average cost and the actual profit margin -- also will increase.

The supply/demand generic structure also accounts for losses in the transmission or distribution of fuel supplies to end-use markets. These losses are accomplished by dividing the net demand for the fuel type by its processing efficiency, yielding gross demand. In other words, the actual demand for the product is increased by the amount of distributional loss. In this manner the model properly accounts for the full demand that the industry must meet.

Typical equations for the complete supply/demand structure are listed below:

CUF = TABLE (CUFT, GD/TPC, 0, 1, 0.1)

CUFT = 0/0.1/0.2/0.3/0.4/0.5/0.6/0.7/0.8/0.9/0.92

ND = D1 + D2 + ...

GD = ND/DE

DE = 0.97

TPC = PC1 + PC2 + ...

TPR = PR1 + PR2 + ...

PDR = TPR/GD

DP = MP + DCHG

MP = (PMN + ACST) x PMM

PMN = (ROEN x EQ)/(TPC x CUFN x (1-TR))

PMM = TABLE (PMMT, GD/(TPC x CUFN), 0.8, 1.25, .05)

PMMT = 0.8/0.85/0.9/0.95/1/1.15/1.3/1.5/1.7/1.9

CUFN = 0.8

ROEN = ROER + INF

ROER = 0.10

ACST = TCST/TPR

*TCST = CST1 + CST2 + ... + DEP + INT

where:

CUF = capacity utilization factor (fraction)
CUFT = capacity utilization factor table
ND = net demand (Btu/year)
D<n> = demand from one of the sectors (Btu/year)
GD = gross demand (Btu/year)
DE = distribution efficiency (fraction)
TPC = total production capacity (Btu/year)
PC<n> = production capacity of production option <n> (Btu/year)
PR<n> = production rate of production option <n> (Btu/year)
TPR = total production rate (Btu/year)
PDR = production demand ratio (fraction)
DP = delivered price ($/Btu)
DCHG = delivery charge ($/Btu)

MP = market price ($/Btu)
ACST = average cost ($/Btu)
PMN = profit margin normal ($/Btu)
PMM = price multiplier (dimensionless)
PMMT = price multiplier table
CUFN = normal capacity utilization factor (fraction)
ROEN = normal return on equity (fraction/year)
EQ = total industry equity ($)
INF = inflation rate (fraction/year)
TR = tax rate (fraction)
ROER = real rate of return on equity (fraction/year)
TCST = total cost ($/year)
DEP = depreciation ($/year)

---

* Equation actually found in financial structures.

INT = interest ($/year)

CST<n>= cost of production option <n> ($/year)

The corresponding DYNAMO flow diagrams are found in Figures 5 and 6.

3.2 FINANCING

The FOSSIL2 financing generic structure determines the amount of funds to be invested in capital equipment and allocates these funds among the different methods of energy production. This structure serves as the long-term link between the supply/demand and production structures of each sector. As prices and profits increase, more funds are available for allocation to the various production alternatives. Industry allocates the largest proportion of funds to those alternatives estimated to be most profitable. The financing generic structure of FOSSIL2 simulates both the generation and the allocation of funds.

Figure 7 shows the input-output characteristics of the financing generic structure within a single sector of FOSSIL2 as it relates to the other two generic structures (supply/demand and production) within that sector. The main output of the financial generic structure is the investment flow to the various production alternatives. The only other output is capital, used by the supply/demand balance to determine normal profit margin. All inputs to the financial structure are used to determine these variables. The financial structure, unlike the supply/demand and production structures, acts separately within each model sector; no input or output passes from one sector to another.

3.2.1 Source of Funds

The generic financing structure consists of two parts, the source-of-funds relationships and use-of-funds relationships. Funds used in capital investment consider both the funds available to the industry and the funds actually needed by the industry. Funds needed for investment are determined from forecasted demand and production capacity (supply).

GENERIC SUPPLY-DEMAND BALANCE STRUCTURE

DYNAMO FLOW DIAGRAM

CAPACITY UTILIZATION SUBSECTOR FOR INDUSTRY WITH 2 TECHNOLOGIES

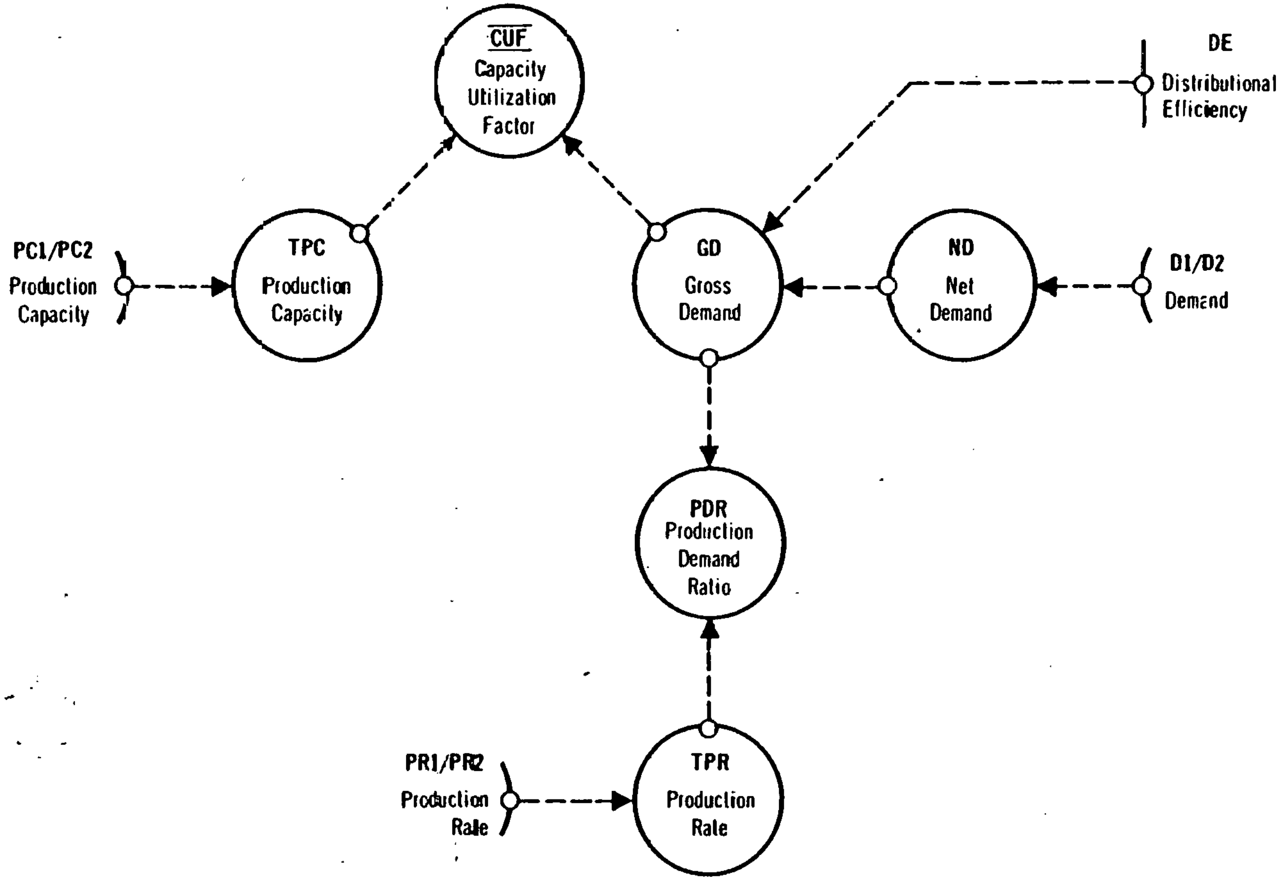


FIGURE 6

Generic Supply-Demand Balance Structure
(Dynamo Flow Diagram)

Pricing Subsector for Industry with Two Technologies

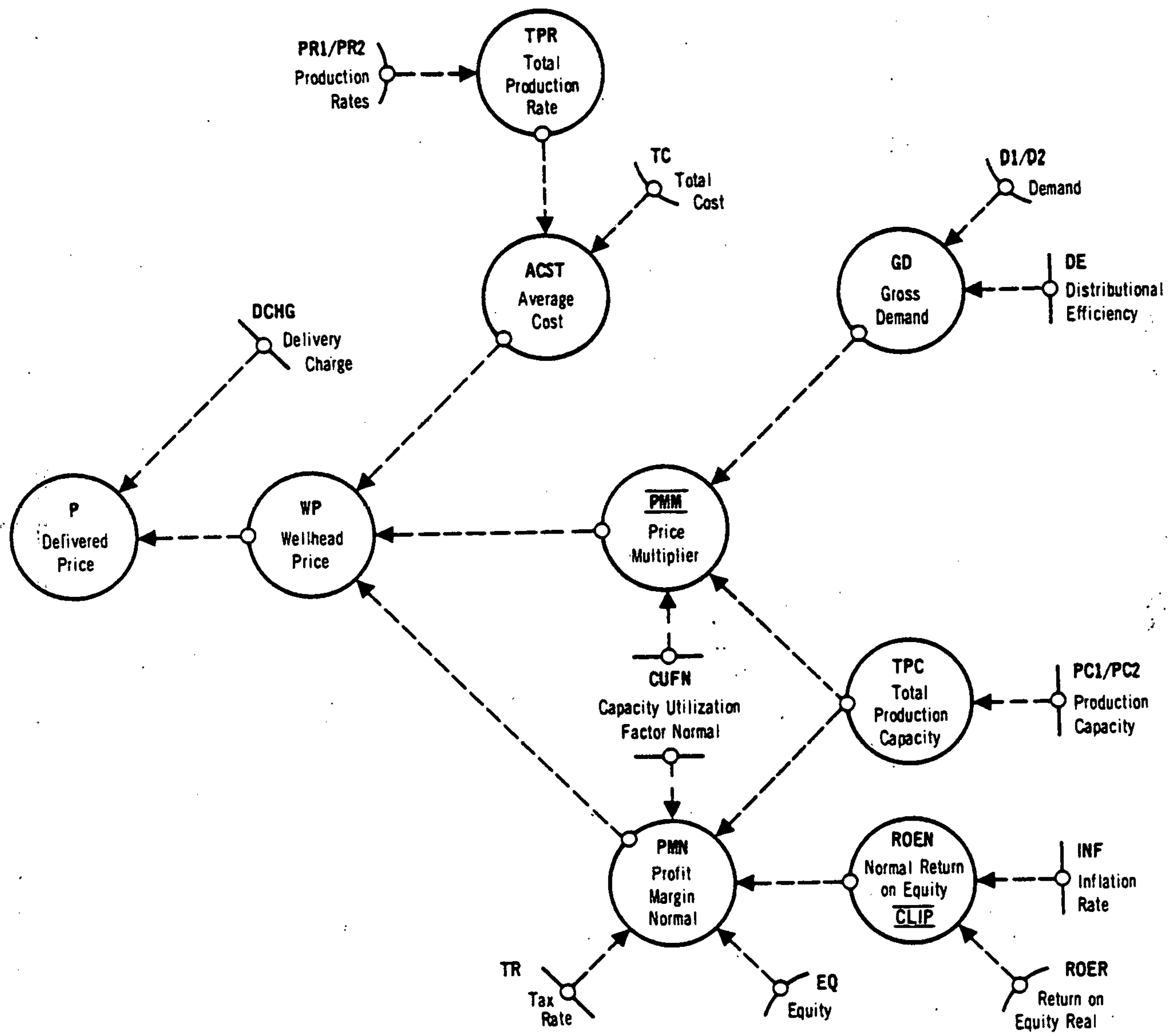
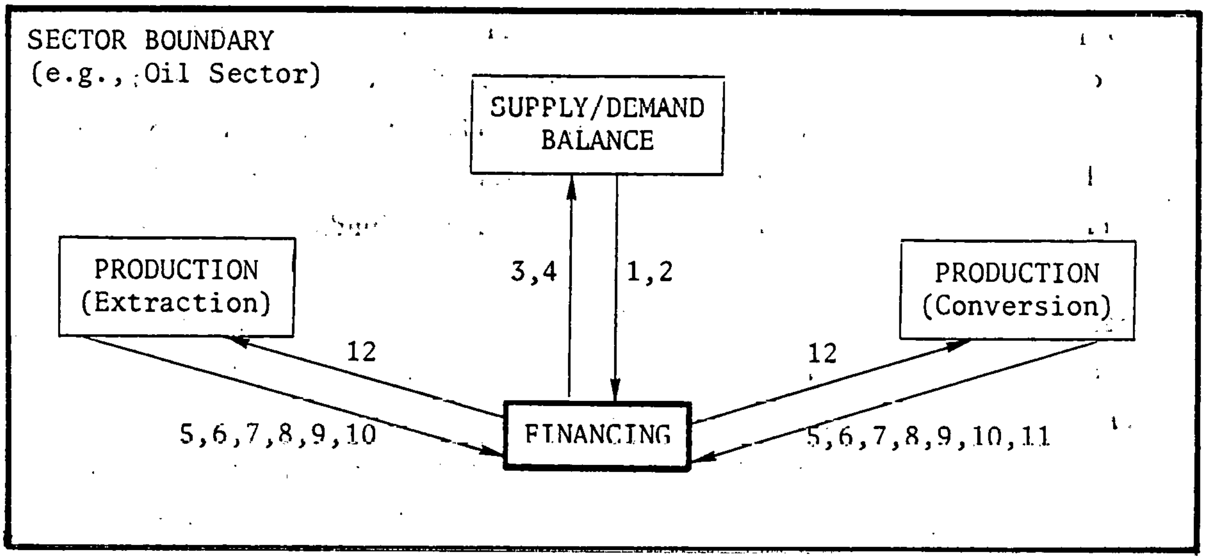


FIGURE 7

GENERIC FINANCING SUBSECTOR: EXTERNAL INFORMATION FLOWS



	INPUT	OUTPUT
SUPPLY/DEMAND BALANCE	1. TOTAL INDUSTRY PRODUCTION RATE 2. (Market) PRICE	3. TOTAL INDUSTRY EQUITY 4. TOTAL INDUSTRY COST
PRODUCTION	5. PLANTS UNDER CONSTRUCTION 6. FACILITY COMPLETION RATES 7. PHYSICAL ASSETS 8. CAPITAL COSTS 9. OPERATING AND MAINTENANCE COSTS 10. PRODUCTION COSTS 11. FEEDSTOCK COSTS	12. INVESTMENT FUNDS

Funds available are those funds generated by internal operations (internal funds) plus the funds which the industry can command in external markets based on its size (assets) and profitability (ROI). If the industry has available more funds than are needed, the industry will invest only what is needed. However, if the funds desired exceed the amount available, the industry is constrained to invest only those funds that are available.

Inherent in the source-of-funds relationships is the inclusion of an asset stock in the financial structure. Gross assets allow for proper accounting of depreciation and funds flow. Book assets (net assets) enable the direct calculation of debt and equity and thereby include determination of dividends, interest costs, and debt repayment explicitly in the structure. The incorporation of gross and net assets into the financial accounting structure allows financial variables to be adjusted for inflation and the proper industry price and return on investment to be determined. Accounting for physical assets remains a distinct part of the production process.

All calculations use constant dollars with 1975 as the base year since constant dollars allow easy comparison of financial statistics for different years in real terms. For example, if the value for domestic oil production assets in constant dollars is stated at $50 billion in 1975 and $200 billion in 2025, it is clear that assets are four times as large in real terms and have grown at a rate of 2.8 percent over the period. If current dollars are used instead of constant dollars and a five percent inflation rate is assumed, the value of assets in 2025 would be reported as almost $2300 billion. Assets would appear to have grown at a rate of 7.8 percent and would be 46 times as large in monetary value. However, to compare the asset growth in real terms, the $2300 billion figure for assets in 2025 would have to be deflated into 1975 dollars. The calculations using current dollars become even more cumbersome when the inflation rate fluctuates.

There are two major drawbacks to using current dollars. First, an inflation rate for the future must be assumed to report monetary figures in future dollars (i.e., current dollars of the future). Model results will be in error to the degree that future inflation does not match this assumed value. Second, growth in real terms cannot be determined easily when current dollars are used, as illustrated in the above example.

Although constant rather than current dollars are used in the model to avoid these drawbacks, inflation still must be taken into account. Specifically, the varied effects of inflation on different variables must be considered. For example, high inflation has a relatively minor effect on depreciation allowances since assets never are adjusted for inflation on accounting balance sheets, but a very significant effect on net income, new capacity costs, and capital expenditure requirements.

Since the model does adjust for these differences, inaccuracies are prevented. First, the depreciation allowance, as a source of internal funds, does not allow the same amount of new capacity purchases as the amount of assets depreciated in any given year. It is impossible to recycle funds perfectly since inflation makes new capacity costs much higher. One dollar of depreciated capacity may be enough to purchase only $0.60-0.70 of new capacity, depending on the inflation rate and the elapsed time between purchases.

Second, ignoring the effects of inflation leads to understating the constant dollar return on investment as compared to the current dollar return commonly reported in industry financial statements. To correct these limitations, the effect of inflation on financial variables is included in the FOSSIL2 financial structures.

The details of the financial flows are not totally apparent in Figure 8 but can be seen by examining the actual equations. A typical set of equations used in the source-of-funds section of an industry's financial structure is listed below:

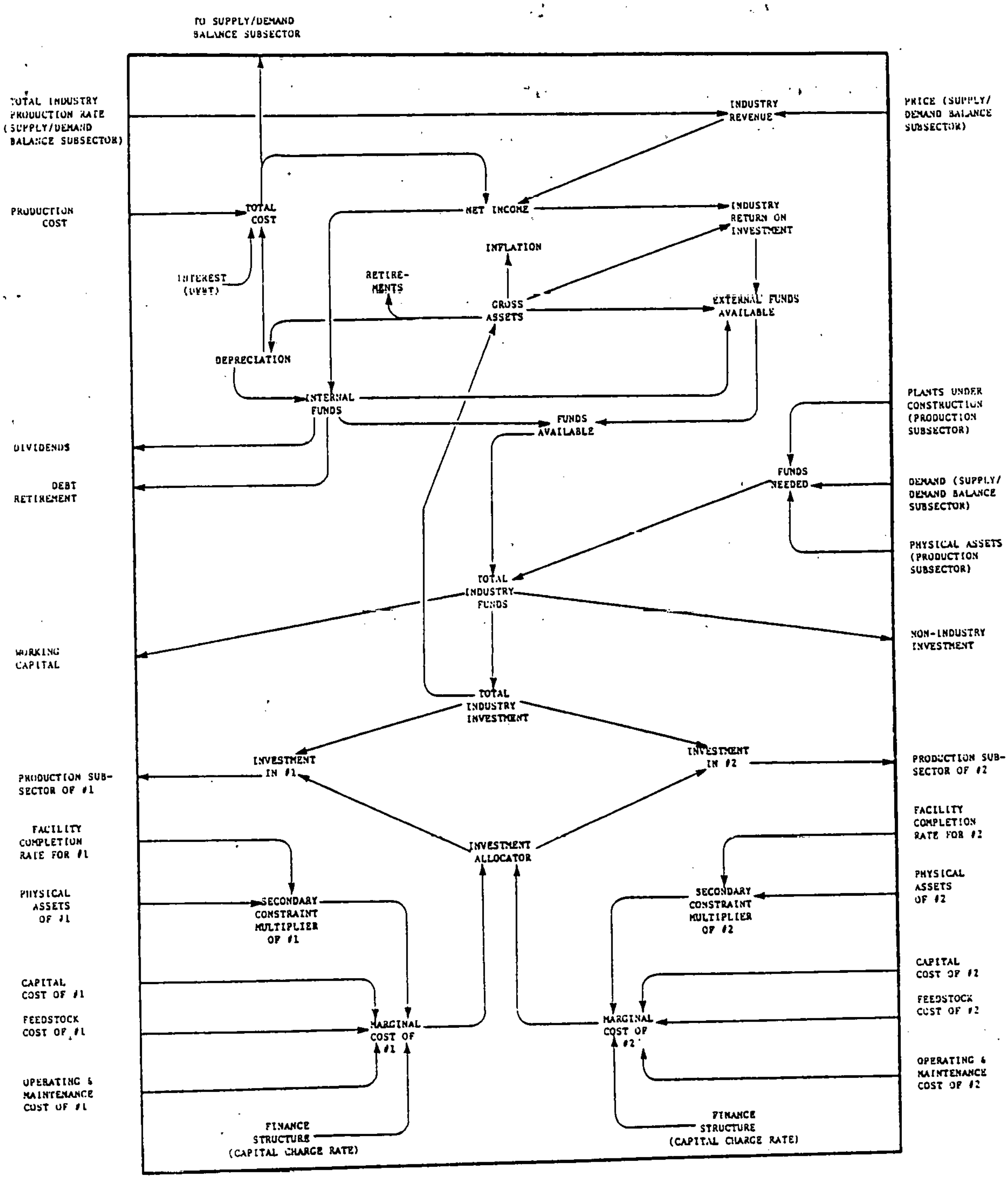


FIGURE 8

Generic Financing Subsector Structure for Two Technologies

NI = (1-TR)(REV-TCST) + (ITC x NPC)

TR = 0.35

ITC = 0.07

REV = P x TPR

TCST = DEP + INT + CST1 + CST2 + ...

GA.K = GA.J + (DT)(INV-GAR-VLI)

GAR = GA x ARF

ARF = 0.033

VLI = GA x INF

INF = 0.055

DEP = GA/BLC

BLC = 17

NA = GA x ADF

ADF = 0.50

EQ = NA x EF

EF = 0.95

DEBT = NA x DF

DF = (30/70) x EF

INT = IR x DEBT

IR = IRN + INF

IRN = 0.025

DRMT = DEBT/DL

DL = 10

IF = NI + DEP - DIV - DRMT

DIV = TABLE (DEPOT, ROI/ROIN, 0.8, 2, 0.4) x NI

DPOT = 0.6/0.5/0.35/0.2

ROIX = SMOOTH (ROI/ROIN, EAT)

ROIN = ROIR + INF

ROIR = 0.08

ROI = (NI + INT)/(DEBT + EQ)

```
FA     = IF + EFA
EFA    = GA x GR
GR     = TABLE (GRT, ROIX, 0, 3, 0.5)
GRT    = 0/0.04/0.07/0.09/0.11/0.12/0.13

FN     = MAX (0, (FPA - TPA - TPUC + AFCT x ARF x (PA + FPA)/2)/FCEN)
FPA    = NPA x EXP(NPA/SPA-1)
NPA    = (GD/CUFN) x ACC
SPA.K  = SPA.J + (DT)(NPA - SPA)/AFCT
AFCT   = (FCT1 x FCR1 + FCT2 x FCR2 + ...)/NPC
NPC    = FCR1 + FCR2 + ...
ACC    = TPA/TPC
TPA    = PA1 + PA2 + ...
TPUC   = PUC1 + PUC2 + ...
FCEN   = 0.8

INV    = MIN (FA, FN) x FCE
FCE    = TABLE (FCET, ROIX, 0, 1.5, 0.3)
FCET   = 0/0.25/0.4/0.75/0.85/0.93
```

where:

NI = net income ($/year)

TR = tax rate (fraction)

ITC = investment tax credit (fraction)

REV = revenues ($/year)

P = price ($/Btu)

ACST = average cost ($/year)

CST<n> = cost of production option <n> ($/year)

TPR = total production (Btu/year)

GA = gross assets ($)

GAR = gross asset retirements ($/year)

ARF = asset retirement factor (fraction/year)
DEP = depreciation ($/year)
BLC = book life of capital (years)
VLI = value loss due to inflation ($/year)
INF = inflation rate (fraction/year)

NA = net assets ($)
ADF = accumulated depreciation factor (fraction)
EQ = equity ($)
DEBT = debt ($)
EF = equity fraction (fraction)
DF = debt fraction (fraction)
INT = interest ($/year)
IR = interest rate (fraction/year)
IRN = interest rate normal (fraction/year)
DRMT = debt repayment ($/year)
DL = debt life (years)

IF = internal funds ($/year)
DIV = dividends ($/year)
DPOT = dividend payout table (fraction/year)
ROI = return on investment (fraction/year)
ROIN = return on investment normal (fraction/year)
ROIR = real return on investment (fraction/year)
ROIX = return on investment index (dimensionless)
SMOOTH = DYNAMO exponential delay
EAT = economic averaging time (years)

INV = investment ($/year)
FCE = fraction to capital expenditures (fraction)
FCET = FCE table

FA = funds available ($/year)

MIN = DYNAMO minimum value function

MAX = DYNAMO maximum value function

EFA = external funds available ($/year)

GR = growth rate (fraction/year)

FN = funds needed ($/year)

TPUC = total plants under construction ($)

PUC n = plants under construction for production option <n> ($)

FPA = future physical assets ($)

NPA = normal physical assets ($)

SPA = smoothed physical assets ($)

ACC = average capital cost [$/(Btu/year)]

GD = gross demand (Btu/year)

AFTC = average facility construction time (years)

FTC n = facility construction time for production option <n> (years)

FCR n = facility construction rate for production option <n> ($/year)

NPC = new plants completed ($/year)

TPA = total physical assets ($)

The first set of equations above calculates net income generated through industry operations during the year by first calculating total revenue and total cost. Total cost is the sum of actually incurred industry costs. These costs include operating and maintenance (O&M) and fuel costs for each of the production processes, as well as depreciation expense and interest, which comprise the industry's capital charges.

The calculation of net income is an identity in the accounting sense except for tax determination. The tax rate used in each production sector is the effective tax rate observed in the industry's historical past, as opposed to the "raw" tax rate (commonly quoted at around 50 percent) determined by the industry's corporate tax bracket. In the oil industry, for example, the effective tax rate observed by the industry is actually 35 percent, the difference in rates attributable to the effects of accelerated depreciation methods and depletion allowances on taxable income. The use of the effective tax rate in the model adjusts the financial flows to incorporate these effects.

The calculation of net income in the generic structure also incorporates the effect of investment tax credits. Investment tax credits reduce income tax expenses as a percentage of the depreciable assets that an industry acquires in a specific year. The tax credit, therefore, increases net income as a percentage of the new assets which come on line. This addition in net income is accounted for directly in the structure.

The second of the above groups of equations defines gross assets and the financial variables that affect their growth and decline. The financial flows are correctly represented in FOSSIL2 by basing these flows on the assets' book value as is commonly done in industry financial analysis.

Gross assets grow each year by the amount of new capital investment and decline by the assets actually retired. Note that this financial retirement rate is essentially the same as the physical retirement rate used in the production sector. When an asset is physically retired in the field, its account must be "written off the books." However, the investment rate that increases the level of gross assets does not likewise increase the level of physical assets. Investments do not immediately become usable physical assets; they are recorded as physical assets only when new energy facilities have been constructed. A construction delay exists between the time the investment is made and the time the facility is completed, although no such delay exists when recording investments on the books as gross assets.

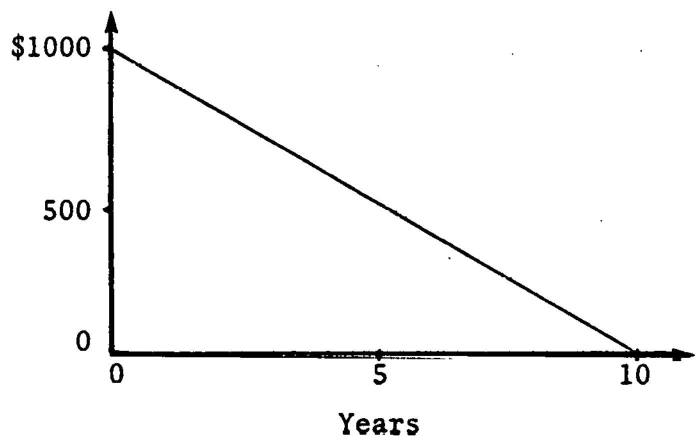
It also should be pointed out that depreciation expense, calculated in the model as the level of gross assets divided by the book life of capital, is not necessarily the same as the asset retirement rate. An example may serve to clarify the difference. If an asset with a service life of 10 years is purchased for $1000, $100 will be written off the books each year for 10 years as depreciation expense, assuming the straight-line method is used. Although this expense is correct to use in financial decision making, the asset produces output for the 10 years of its serviceable life in a physical sense. If the asset were an oil rig, for instance, it would be able to extract as much oil in its tenth year as in its first. It does not depreciate in a physical sense until it is retired in its tenth year, even though a portion of its value is written off each year in the financial books. Figure 9 depicts this distinction graphically. To account for this difference, gross and physical assets are retired at a much slower rate than they are depreciated in the model.

Examination of the equation for gross assets in the structure shows a financial variable other than retirements that can decrease the level of gross assets in a given year. The effects of inflation are captured in the model by reducing gross assets yearly by the inflation rate. The value loss due to inflation is calculated as the inflation rate times the level of gross assets. Adjusting the gross asset account is the major adjustment needed to capture the differing impacts of inflation on the various financial variables in the structure. The only other adjustments involve increases in the interest rate and expected rate of return to account for inflationary changes.

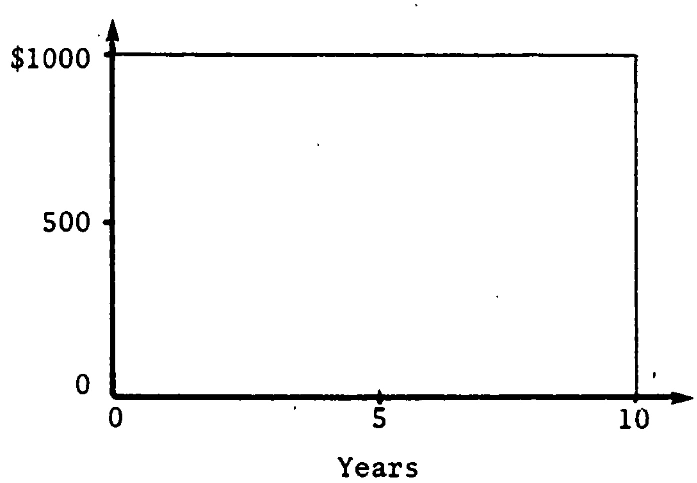
With this adjustment to gross assets, the constant dollar ROI is not understated when compared to the current dollar ROI commonly reported in financial statements. Computing an ROI with net income in constant dollars and gross assets reduced by the inflation rate is equivalent to performing the calculation with net income in current dollars and gross assets in current dollars unadjusted for inflation.

FIGURE 9

DEPRECIATION VS. RETIREMENTS



Net Value of the Asset on the Books
Depreciation Expense $100/yr



Physical Value of the Asset in the Field

Annual Retirements:
$0/yr Years 1-9
$1000/yr Year 10

The third group of equations defines the industry's net assets, equity, debt, and the interest and debt repayment payable by the industry in a given year. These variables can be calculated explicitly since the model tracks the industry's gross assets.

An industry's net assets, as reported on its balance sheet, are the differences between gross assets and accumulated depreciation. It is assumed, in the financing structure of the model, that the value of net assets can be calculated as a fraction of the level of gross assets. Although it is possible to create a new level in the structure representing accumulated depreciation (the inflow rate would be depreciation expense while the outflow would be asset retirement), such an increase in complexity does not seem warranted in view of the fact that this fraction is empirically observed to remain essentially constant in the energy industries.

The levels of long-term debt and equity in the model are formulated as a proportion of the net assets owned by the industry. The financial mix, or debt-equity fraction, is assumed to be constant for each industry and is derived from empirical data. The equations depicted above show an assumed 30/70 debt-equity fraction. The specific mix of financing may vary in the future from a constant fraction; the financing mix changes depending on a number of factors including long- and short-term interest rates, the liquidity of the industry's assets, the size of the industry, the strength of inflation, and the state of the external financing markets.

Including more causal structure to capture these changes in the financing mix only would mask structural clarity while adding detail unnecessary to FOSSIL2's stated purpose. The FOSSIL2 model is not intended to be an industry financial planning model - the financial sector is intended only to determine the amount of funds to be invested in capital equipment and to allocate these funds to the different methods of energy production.

Including a specific financial mix of debt and equity in the structure does allow the model to run under different financing assumptions. Behavioral tests show, however, that the long-term behavior of the United States energy system is relatively insensitive to realistic changes in each industry's financial mix. Therefore a more detailed structure to capture these changes is not used.

Once the debt fraction of the industry's total capital has been determined, calculating the interest cost and debt repayment paid out in any year is straightforward. Interest cost is equal to the annual interest rate times the level of debt; debt repayment is simply a fraction of the amount of outstanding debt, based on the average lifetime the debt is outstanding.

The fourth set of equations computes the internally-generated funds available for investment. Internal funds available are calculated as the sum of net income and noncash charges (e.g., depreciation) minus those funds needed for dividends and debt repayment. Dividends paid in a given year are calculated as a percentage of net income, the percentage varying with the industry's return on investment. The return on investment used in the calculation is the quotient of the sum of net income and interest payments and the sum of debt and equity.

The last three sections of equations define the total funds available to industry, the funds needed by industry, and the funds actually used or invested by industry. The investment in fixed assets is equal to the minimum of funds available and funds needed, as previously described. An industry can invest only as much money as it can raise (availability), but at the same time will invest only as much money as is warranted by the need for new facilities. This is accounted for in the investment equation. The investment equation also limits the amount of funds used in fixed asset investment, realizing the continual need for investment in working capital and the propensity for divestment in some energy industries (oil and gas, for example) based on their respective rates of return.

The funds available to industry are formulated as the sum of internally-generated funds and external funds available in the money markets (i.e., stock or bond issues). While no attempt is made to model the complex interactions of the money markets in FOSSIL2, the model does restrict the amount of external funds available based on the industry's size (gross assets) and earnings (ROI). Industries of larger size and earnings are able to attract more of the funds available in the external markets; they are perceived to be a better financial investment. As an industry's return on investment falls due to inadequate earnings, the external funds available dwindle and the industry is unable to grow at as fast a pace as another industry with higher earnings. The allowed growth rate is assumed to be a function of the industry's average return on investment.

The next ten equations in the source-of-funds relationships determine the amount of new investment needed by the industry to meet future demand. The funds needed are formulated by forecasting the amount of physical assets that must be on-line to meet future demand and comparing this forecasted value with the present value of physical assets, allowing for the depreciation of capital, the delay time inherent in facility construction, and the plants currently under construction. The process is detailed below.

First, the required physical assets necessary to meet future demand growth must be determined. The forecast period is set equal to the average facility construction time (AFCT) of the industry's various production processes, since funds invested in the present will not be realized as physically usable assets until AFCT time units have elapsed. The required value of physical assets needed to meet future demand is obtained by determining the growth trend in normal physical assets over the last AFCT years and extrapolating this trend AFCT time units into the future. Normal physical assets are simply the assets that the industry requires to meet demand at normal capacity utilization. Thus, the forecast of needed physical assets depends on changes in demand and/or capital cost. In the equations above, normal physical assets are equal to (demand/normal utilization) x average capital cost.

The past growth trend is determined using an exponential smoothing process. Once this extrapolation has been used to determine the required level of future assets, it is relatively simple to calculate the amount of funds needed for present investment. Funds needed are equal to the projected future assets less the sum of present physical assets and plants under construction, plus an allowance for asset retirements over the forecast period. It is important to consider the impact of past capital expenditures (i.e., plants under construction) because these expenditures will come on-line as physically usable assets during the forecast period.

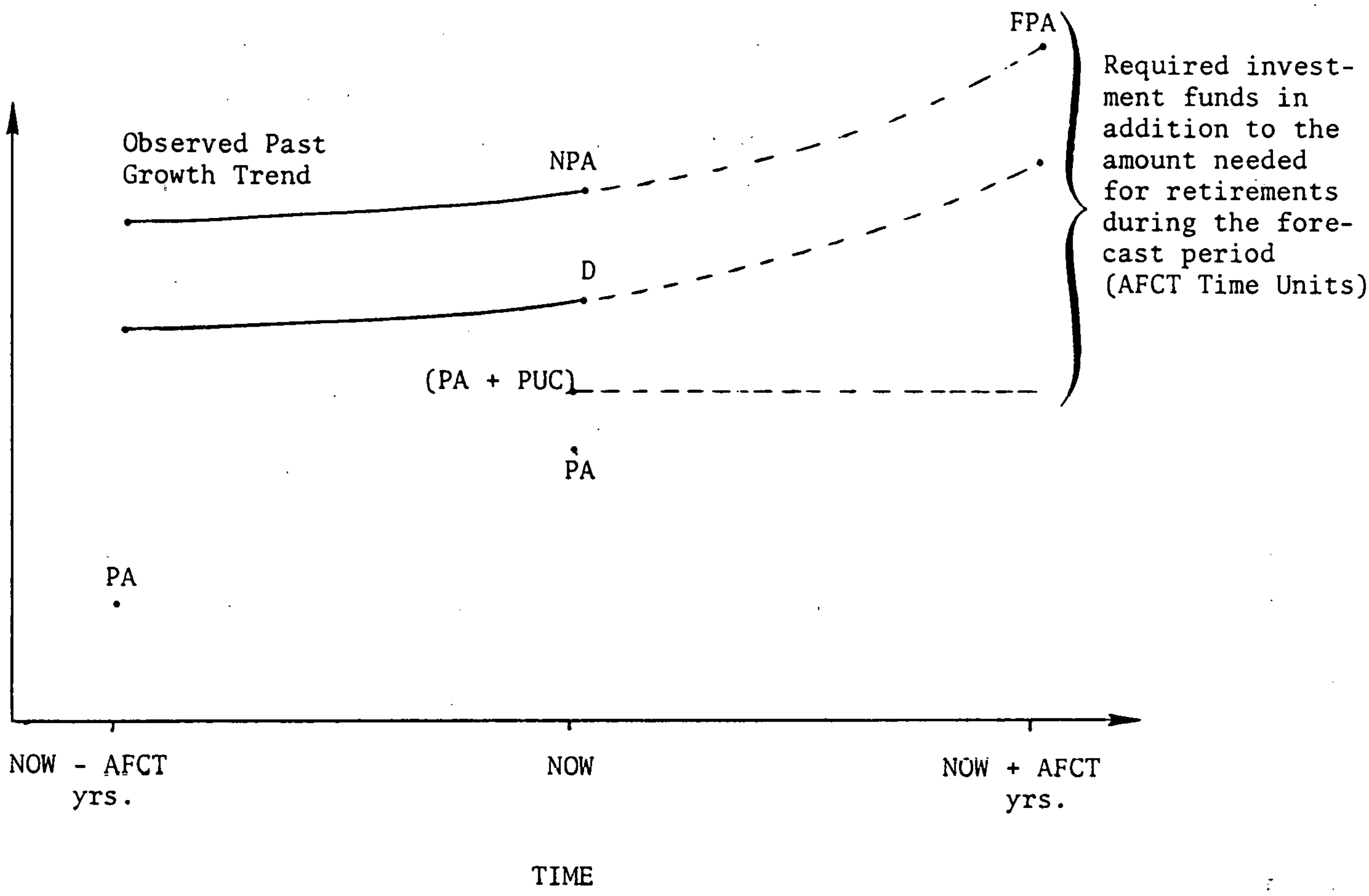
Though the process sounds somewhat complex, it is a rather straightforward method of determining the need for funds. Demand is simply extrapolated AFCT time units into the future, required future physical assets calculated, current physical assets and plants under construction determined, and funds needed set equal to an amount necessary to grow to the level of required future assets above the amount needed for asset retirement. Figure 10 is a simplified diagram of the process.

3.2.2 Use of Funds

The investment allocation structure calculates a marginal cost for each production process and allocates the most funds to those processes having the lowest marginal costs. The marginal cost is equal to a capital charge rate times capital cost, plus O&M costs and any associated feedstock costs or royalty payments. The capital charge rate is

FIGURE 10

DETERMINATION OF FUNDS NEEDED



Funds Needed = FPA - (PA + PUC) + RETIREMENTS (over AFCT years)

NPA	=	Normal Physical Assets	($)
FPA	=	Future Physical Assets	($)
PA	=	Physical Assets	($)
D	=	Demand	(Btu/year)
PUC	=	Plants Under Construction	($)
AFCT	=	Average Facility Construction Time	(years)

computed as a function of the depreciation, interest, and required rate of return on equity in the industry. This rate represents the annual equivalent cost of a unit of capital. The marginal cost is the minimum price needed to extract the next Btu of energy from the particular production process. It includes all relevant costs and a required rate of return.

One can understand the way in which the marginal cost is used to allocate funds by looking at the actual equations found in the use-of-funds section. The following is a typical set of equations for a two-choice allocation.

```
INV1  = TINV x AW1/TAW
INV2  = TINV x AW2/TAW
TAW   = AW1 + AW2
AW1   = MCST1↑WF
AW2   = MCST2↑WF
WF    = -10
MCST1 = (CCR1 x SCC1) + OMC1 + FCST1
MCST2 = (CCR2 x SCC2) + OMC2 + FCST2
CCR1  = 0.185
CCR2  = 0.243
SCC1  = (CC1/CUFN) x SCM1
SCC2  = (CC2/CUFN) x SCM2
SCM1  = TABLE (SCMT, GRI1, 0.06, 0.16, 0.02)
SCM2  = TABLE (SCMT, GRI2, 0.06, 0.16, 0.02)
GRI1  = (AGR1/Smooth(AGR1, EAT)-1)/EAT
AGR1  = MAX (PAMI, (PA1 + PUC1))
GRI2  = (AGR2/Smooth(AGR2, GAT)-1)/EAT
AGR2  = MAX (PAMI, (PA2 + PUC2))
PAMI  = 10E9
```

where:

INV<n> = investment allocated to one of the alternative production processes ($/year)

TINV = total investment funds ($/year)

TAW = total allocation weight (dimensionless)

AW<n> = allocation weight of one of the alternatives (dimensionless)

WF = weighting factor (dimensionless)

MCST<n>= marginal cost of one of the alternatives ($/Btu)

CCR<n> = capital charge rate of an alternative (fraction/year)

SCC<n> = specific capital cost of an alternative ($/(Btu/year))

CC<n> = capital cost of an alternative ($/(Btu/year))

CUFN = capacity utilization factor normal (fraction)

SCM<n> = secondary constraint multiplier (dimensionless)

SCMT = secondary constraint multiplier table

PA<n> = physical assets of an alternative ($)

PAMI = physical assets of a mature industry ($)

PUC<n> = plants under construction ($)

GRI<n> = growth rate for investment (fraction/year)

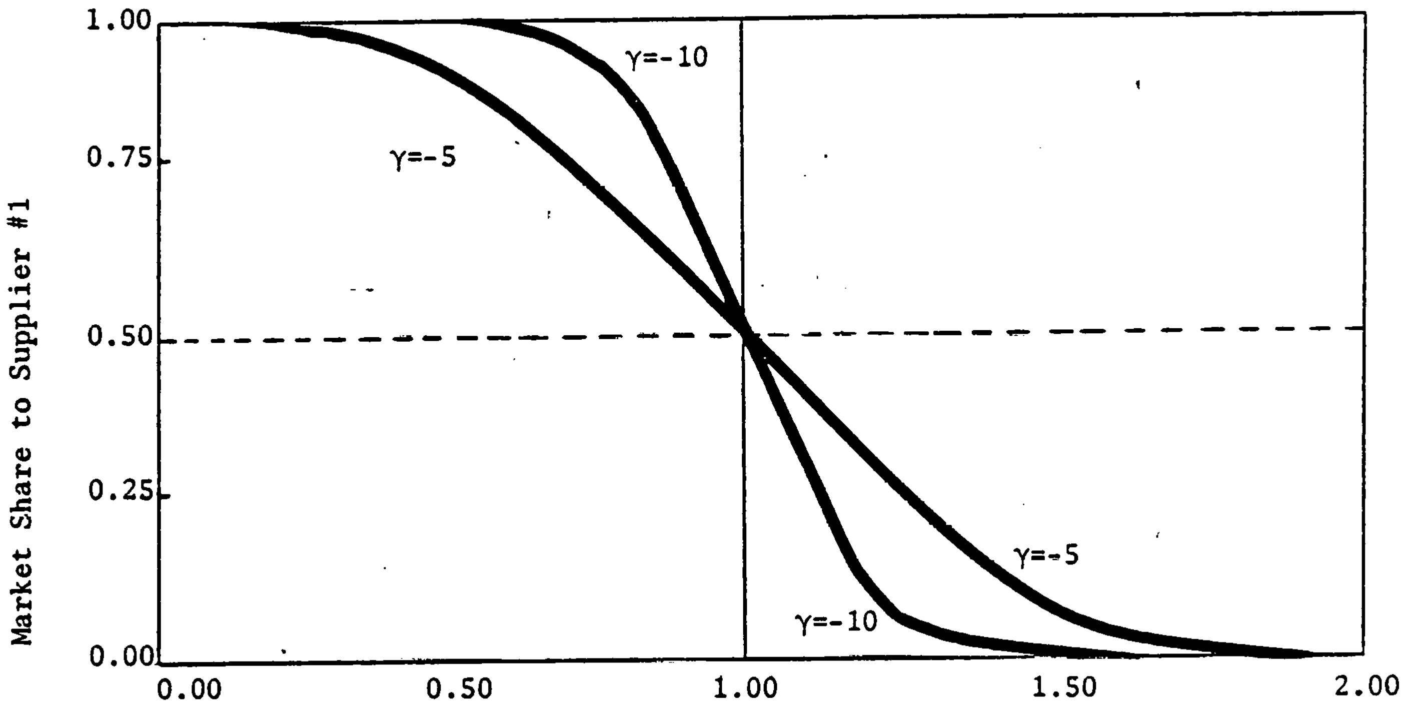
AGR<n> = assets for growth rate ($)

EAT = economic averaging time (years)

As seen in an examination of these equations, the marginal costs of the alternatives are used to establish allocation weights for each alternative. The allocation weights are computed by raising the marginal costs to the power of a negative weighting factor. This computation ensures that the alternatives with the lowest marginal costs will have the largest weights, thereby commanding most of the industry's funds. The particular mathematical form used here [$MCST1^a$ / ($MCST1^a$ + $MCST2^a$)] has been employed in models developed for use in demand forecasting, particularly the gravity model. This mathematical form generates a logit "S"-shaped distribution around alternatives, as displayed in Figure 11. This type of "S"-shaped curve is desirable for several reasons:

FIGURE 11

FINANCIAL INVESTMENT ALLOCATION



Cost Ratio $\frac{P_1}{P_2}$

$$\text{Market Share to Supplier \#1} = \frac{P_1^{\gamma}}{P_1^{\gamma} + P_2^{\gamma}} = \frac{1}{1 + \left(\frac{P_1}{P_2}\right)^{\gamma}}$$

- Economic priorities are never completely clear. This uncertainty creates a distribution effect around the "optimal" economic decision (the "S"-shape reflects the distribution).
- Sufficient risks are involved in each production process so that an industry is not willing to allocate all funds to one process unless the cost differences are extreme.
- At the aggregate national level of this model, distribution effects are prevalent. Although the average profitability of one product is greater than another, under some conditions or in some locations the profit situation is reversed.*

These notations are necessary for two reasons. First, the model calculates the marginal cost of each alternative process; it is important that the structure use marginal costs because they are widely quoted in discussions about alternative energy forms. Marginal costs are compared easily with the current product price to determine the economic feasibility of the various alternatives. Second, and more important, the use of the weighting system employed in this structure allows the investment allocation decision to be made in a simultaneous fashion.

Another important consideration in the use of funds structure is the use of a secondary industry constraint multiplier. This multiplier limits growth in production capacity when it reaches unrealistically high levels and controls unconstrained growth in capacity additions.

The multiplier works by raising the specific capital cost** in any production process growing at a rate that places unrealistically high

---

* The "S" table function as used here is closely related to the mathematically more formal Ojive functions used in demand forecasting and decision analysis. For a mathematical background, see Domencich and McFadden, Urban Travel Demand: A Behavioral Analysis (Amsterdam: North Holland, 1975) and McFadden, "Conditional Logit Analysis of Qualitative Choice Behavior" in Zarembka, Ed., Frontiers of Econometrics (New York: Academic Press, 1973).

** Specific capital cost is defined as capital cost divided by the normal capacity utilization factor.

demands on its secondary industries' production capacity (i.e., pressure vessels, machinery, engineering skills, etc.). The higher specific capital cost raises the marginal cost of that alternative, thereby shifting some of the funds to other production processes. When more realistic growth rates again are achieved, the secondary industry constraint multiplier is relaxed, and the lower marginal cost attracts more of the investment funds.

The value of the multiplier is calculated as a function of the individual production processes' growth rates, i.e., the newly completed facilities divided by the physical assets already in place.* If a production process is newly commercialized, the "growth" rate is computed as the newly completed facilities divided by the assets for a mature industry, thus allowing high growth rates during the initial startup phase.

Note that the risk associated with investment in unproven production processes is included in the use-of-funds relationships. A risk premium factor is included in the capital charge rate used in computing the marginal cost by requiring a higher minimum rate of return. This risk factor subsequently is valued at zero when the unproven industry grows to the size of a physically mature industry or when the unproven industry is given a loan guarantee (a policy that can be tested in FOSSIL2). This lowers the marginal cost and makes the production process more attractive to investors.

Finally, noneconomic considerations often are important to investment decisions. Laws (such as pollution standards) and physical constraints (such as the shortage of water for shale oil development) affect the allocation of investment. New technologies also are constrained initially

* If the secondary industries are shared by different technologies, then the secondary constraint is based on the combined growth of the technologies.

by their commercialization year: no investment can be made until the technology has been developed and made commercially available.

Environmental and physical constraints are modeled in FOSSIL2 by investment multipliers. These multipliers modify the economically determined allocation (economic considerations are assumed to be the first consideration) in a way that inhibits investment as constraints are approached. The multipliers are fractional quantities ranging in value from zero to one. The multiplier is unity and does not affect the economically-determined allocation as long as the constraint is not a limiting consideration but it does decrease below one as the limit is approached. A typical equation for an investment multiplier would be:

IM = TABLE (IMT, value reached/limit, 0, 1, 0.1)
IMM = 1/1/1/1/1/1/1/1/0.9/0.3/0

where:

IM = investment multiplier (fraction)
IMT = investment multiplier table.

In this example, once the process has developed to within 20 percent of its limit, the investment multiplier begins to reduce investment. If the limit is reached, the multiplier goes to zero, and no new investment can be made. Mathematically, the function form is similar to the basic investment allocation mentioned above. That is:*

IM = 1 - (value reached/limit)↑WF

In the case of commercialization, the investment multiplier is zero before the process is commercially available and unity thereafter.

* The logit function has the form (measure of merit) ↑WF, where "↑" denotes "raised to the power of."

This is done by a DYNAMO step function:

IM = STEP (1, commercialization year).

Figures 12 through 15 show the complete DYNAMO flow diagram of the generic finance structure.

3.3 PRODUCTION

The production structure of FOSSIL2 determines the production capacity and the unit production cost of each energy process in the model. The flow of investment funds to each technology is the principal input to the production structure. The new funds represent construction of new production facilities and determine the future production capacity of the industry. The production of energy, in turn, causes depletion of energy resources which drives up production costs and affects future demand and investment.

The production technologies of FOSSIL2 are essentially of two types --those which extract energy from a depletable resource base and those which convert the energy to other fuel forms. The generic production structures for the two process types are similar but exhibit several differences, which are discussed in this section.

Figure 16 shows the external information flows for both the extraction and conversion production structures. The two structures exchange identical information with the supply/demand balance and financing structures. Conversion processes differ only in that they must communicate with other sectors (industries) to obtain energy feedstocks. Coal liquids, for example, have no internal energy source and must purchase coal from the coal sector.

FIGURE 12

GENERIC FINANCING STRUCTURE

DYNAMO FLOW DIAGRAM

SOURCE OF FUNDS
(Determination of Gross Assets)

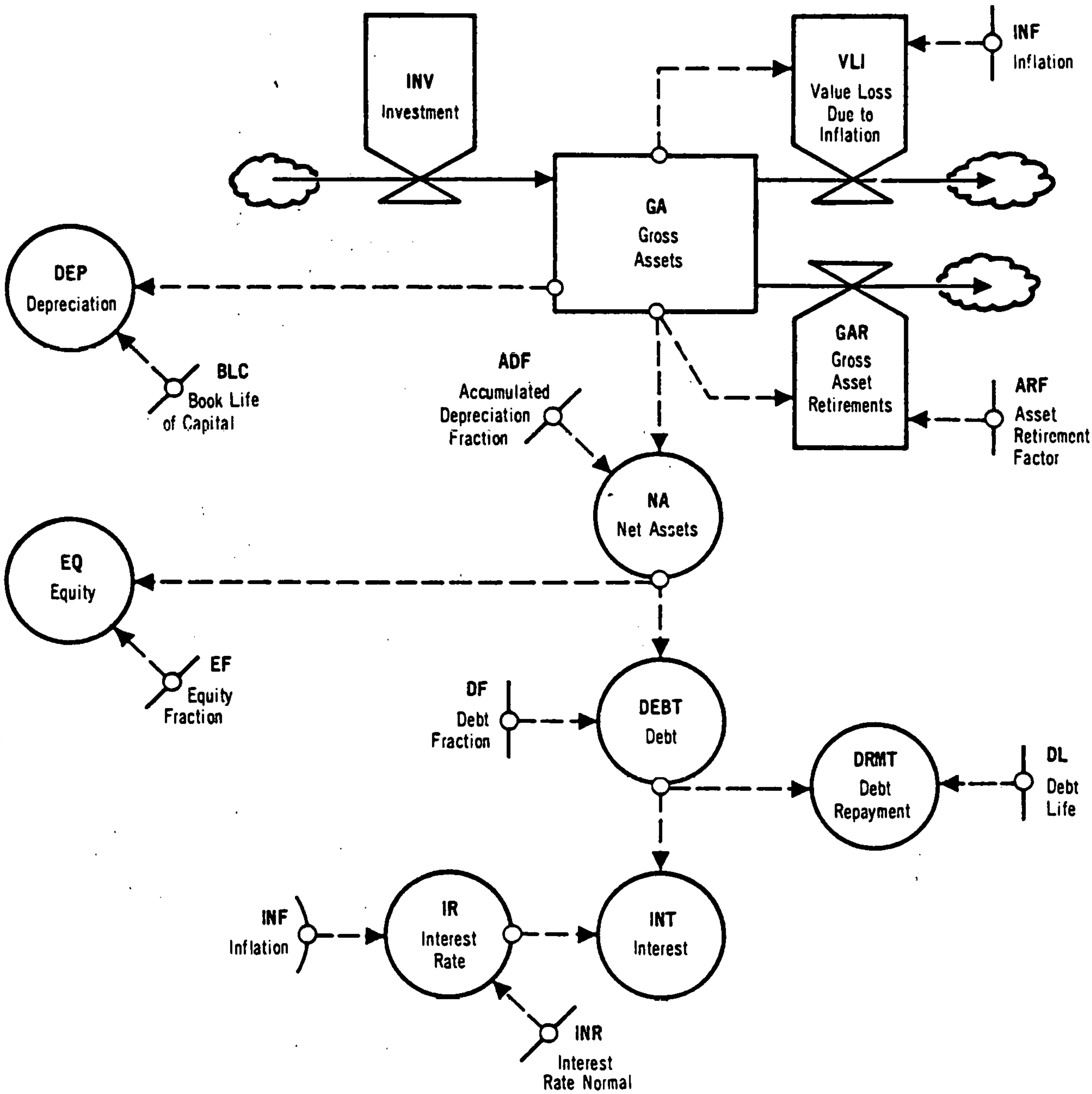


FIGURE 13

GENERIC FINANCING STRUCTURE

DYNAMO FLOW DIAGRAM

SOURCE OF FUNDS

(Determination of Investments for Industry with 2 Technologies)

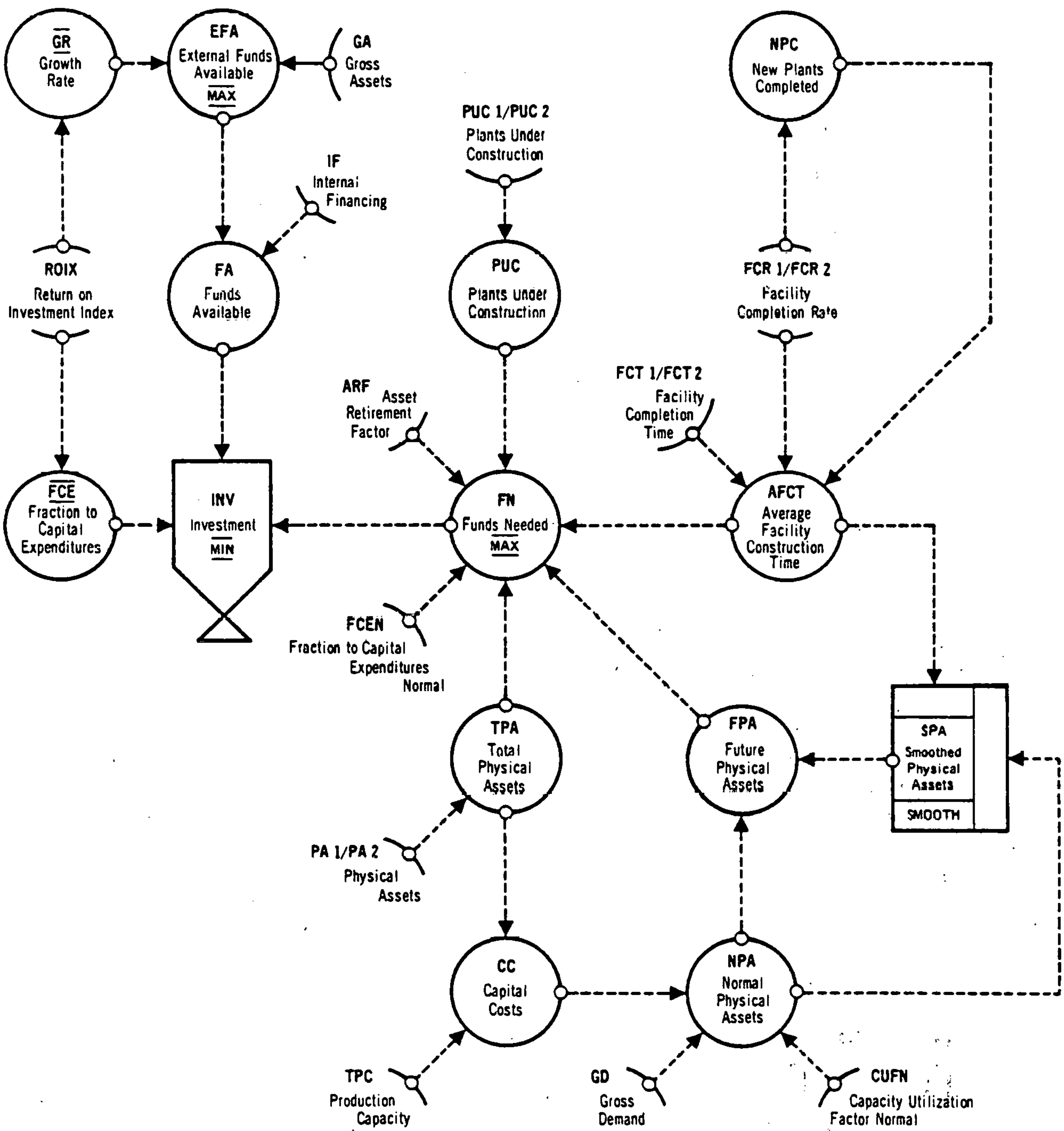


FIGURE 14

GENERIC FINANCING STRUCTURE

DYNAMO FLOW DIAGRAM

SOURCE OF FUNDS
(Determination of Internal Financing for Industry with 2 Technologies)

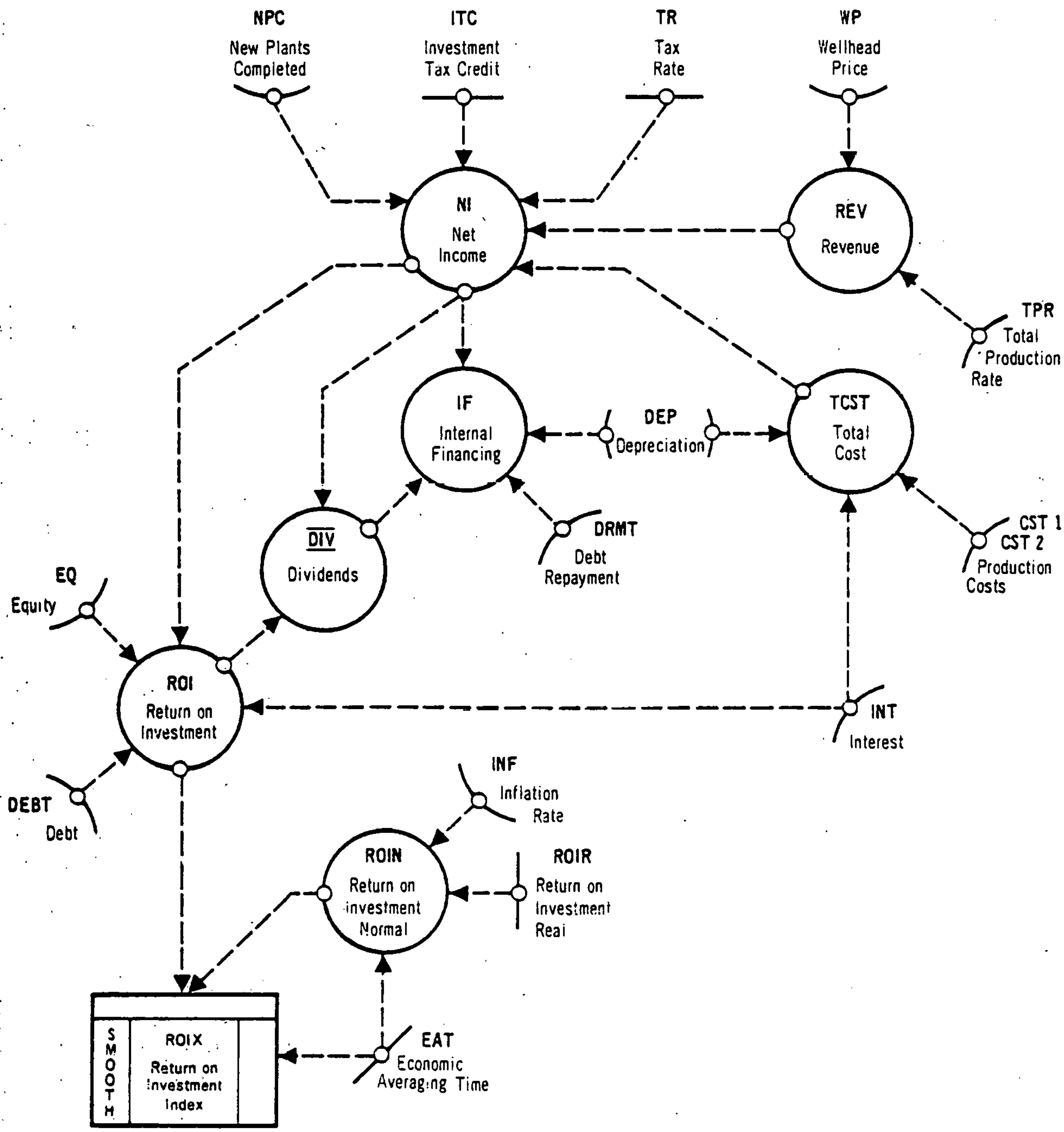


FIGURE 15

GENERIC FINANCING STRUCTURE

DYNAMO FLOW DIAGRAM

USE OF FUNDS
(Allocation Between Two Technologies)

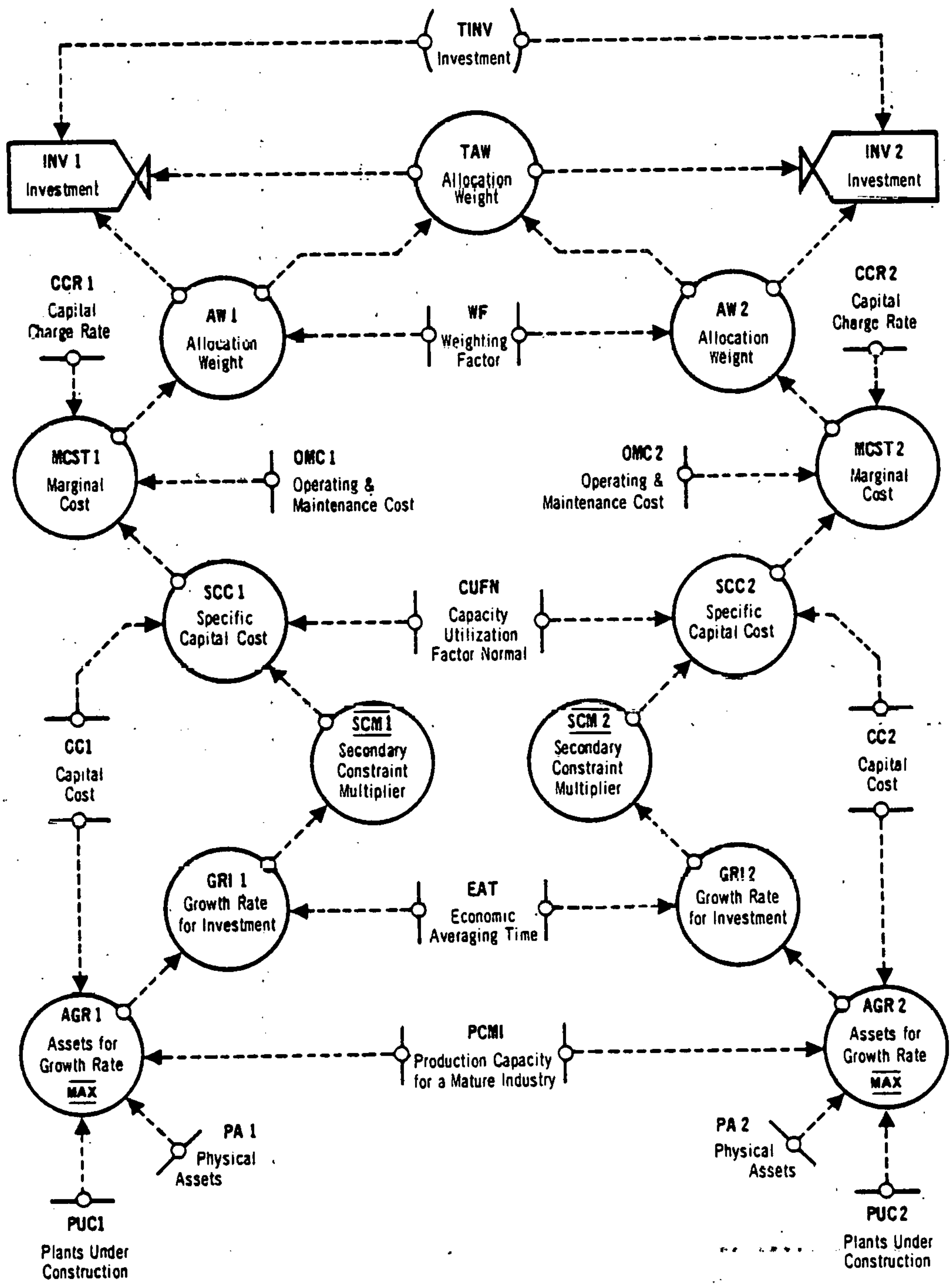
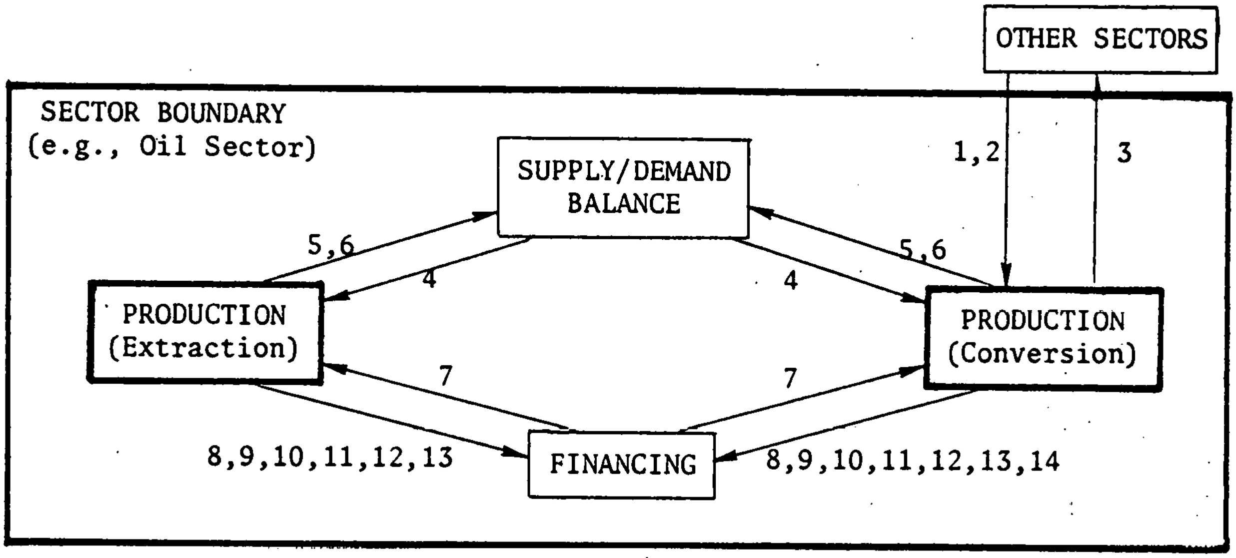


FIGURE 16

GENERIC PRODUCTION SUBSECTOR EXTERNAL INFORMATION FLOWS



	INPUT	OUTPUT
OTHER SECTORS	1. (Market) PRICE 2. AVAILABILITY	3. DEMAND (for feed-stocks
SUPPLY/DEMAND BALANCE	4. CAPACITY UTILIZATION FACTOR (for entire industry)	5. PRODUCTION RATES 6. PRODUCTION CAPACITIES
FINANCING	7. INVESTMENT FUNDS	8. PLANTS UNDER CONSTRUCTION 9. FACILITY COMPLETION RATES 10. PHYSICAL ASSETS 11. CAPITAL COSTS 12. OPERATING AND MAINTENANCE COSTS 13. PRODUCTION COSTS 14. FEEDSTOCK COSTS

3.3.1 Capital Stock Relationships

The generic production structure can be separated into two parts, the capital stock relationships and the production/depletion relationships. The growth of capital stock is modeled in an identical fashion for every process (whether conversion or extraction) in FOSSIL2. Funds invested annually in each process (as determined in the financing structure) result in the construction of new energy facilities (capital stock). A several-year (varying from three to 14 years, depending on the process) construction delay exists between the time the investment is initially made and the time a facility is completed.

A typical set of DYNAMO equations for the capital relationships follows:

PA.K = PA.J + (DT)(FCR-PAR)
PAR = ARF x PA
ARF = 0.045
FCR = DELAY3P (INV, FCT, PUC)
FCT = 7

where:

PA = physical assets ($)
PAR = physical asset retirement rate ($/year)
ARF = asset retirement factor (fraction/year)
FCR = facility completion rate ($/year)
INV = investment funds ($/year)
FCT = facility completion time (years)
PUC = plants under construction ($)

These assets increase in number as newly constructed facilities come on-line and decrease as assets retire. The retirement rate used in the generic structure is computed to account for the fact that the asset stock is in a state of growth. The asset retirement rate represents the actual wearing out of physical equipment; it should not be confused with the depreciation rate calculated in the financial structures.

Finally, note that the physical assets in the production structure are not affected by inflation. These assets represent equipment "out in the field" and, therefore, are unaffected by inflationary changes.

3.3.2 Production/Depletion Relationships

Different production/depletion relationships exist in FOSSIL2 for extraction and conversion processes. Figures 17 and 18 depict the internal information flows for an extraction and an conversion process, while Figures 19 and 20 exhibit the corresponding DYNAMO flow diagrams. As the most easily obtained resources are consumed, the more expensive, hard-to-obtain resources must be exploited. Capital productivity (a measure of the amount of energy that can be extracted per dollar of capital) consequently declines, increasing the unit cost of production and decreasing production capacity (assuming no change in the size of the capital stock). The capacity utilization factor from the supply/demand balance determines how much of the production capacity can be used to satisfy demand, that is, the production rate.

The production structure of each process sends information to both the financing and supply/demand structures within the sector. The production costs are transferred to the finance structure to determine the relative profitability of the process and its ability to attract new investment funds. The production cost and production capacity interact in the supply/demand sector to determine the price of the energy product.

Figure 21, which depicts the internal information flows of a reserves-resource extraction process, shows that the major addition in structure is a level of unproven reserves. This level of unproven reserves delays recording discoveries due to revisions and extensions. When a pool is first discovered, only a small fraction immediately becomes a proven reserve; the majority is developed over a longer time and becomes a proven reserve available for production only through the revision and extension process.

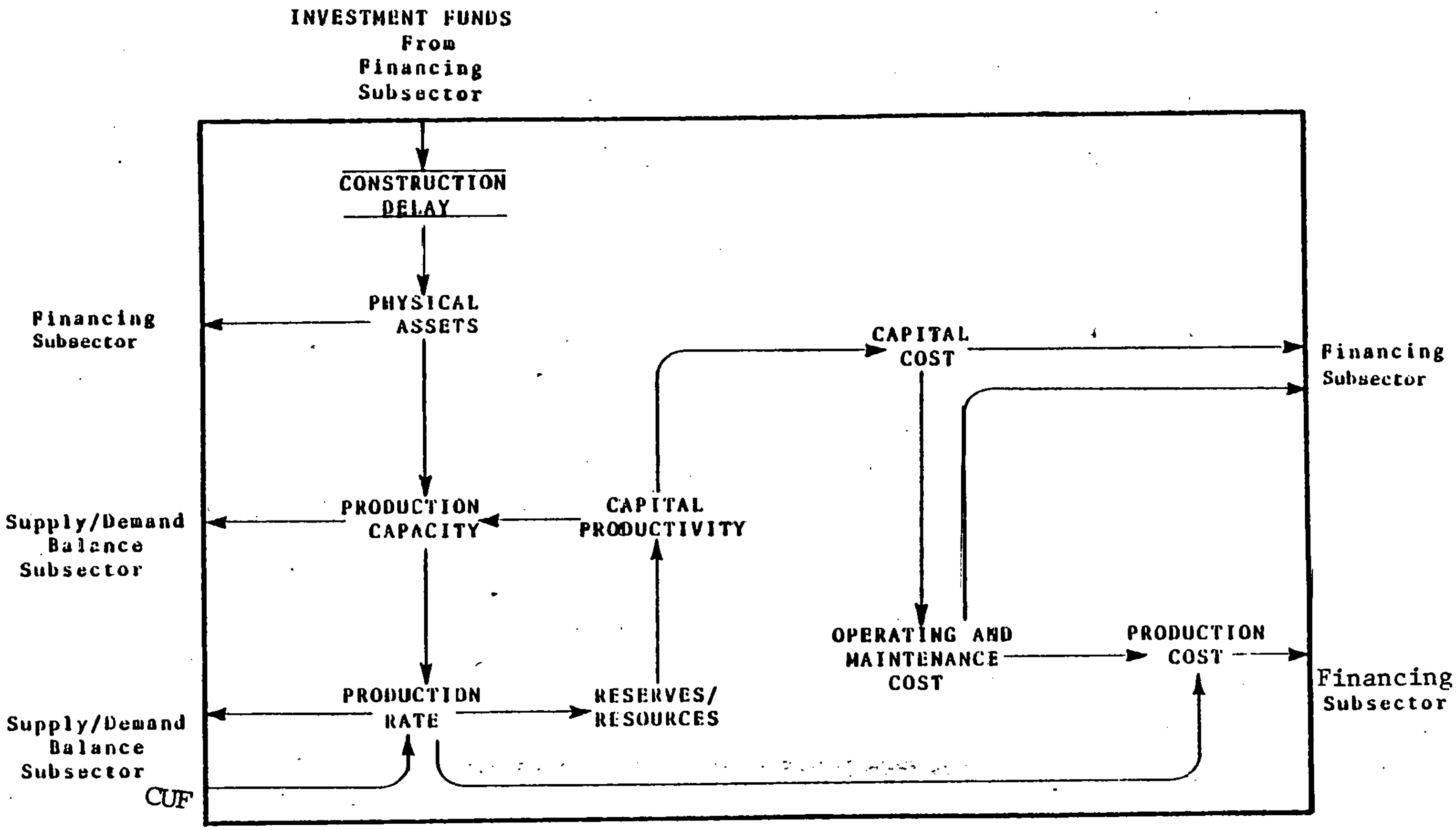


FIGURE 17

Generic Production Subsector Structure for an Extraction Process

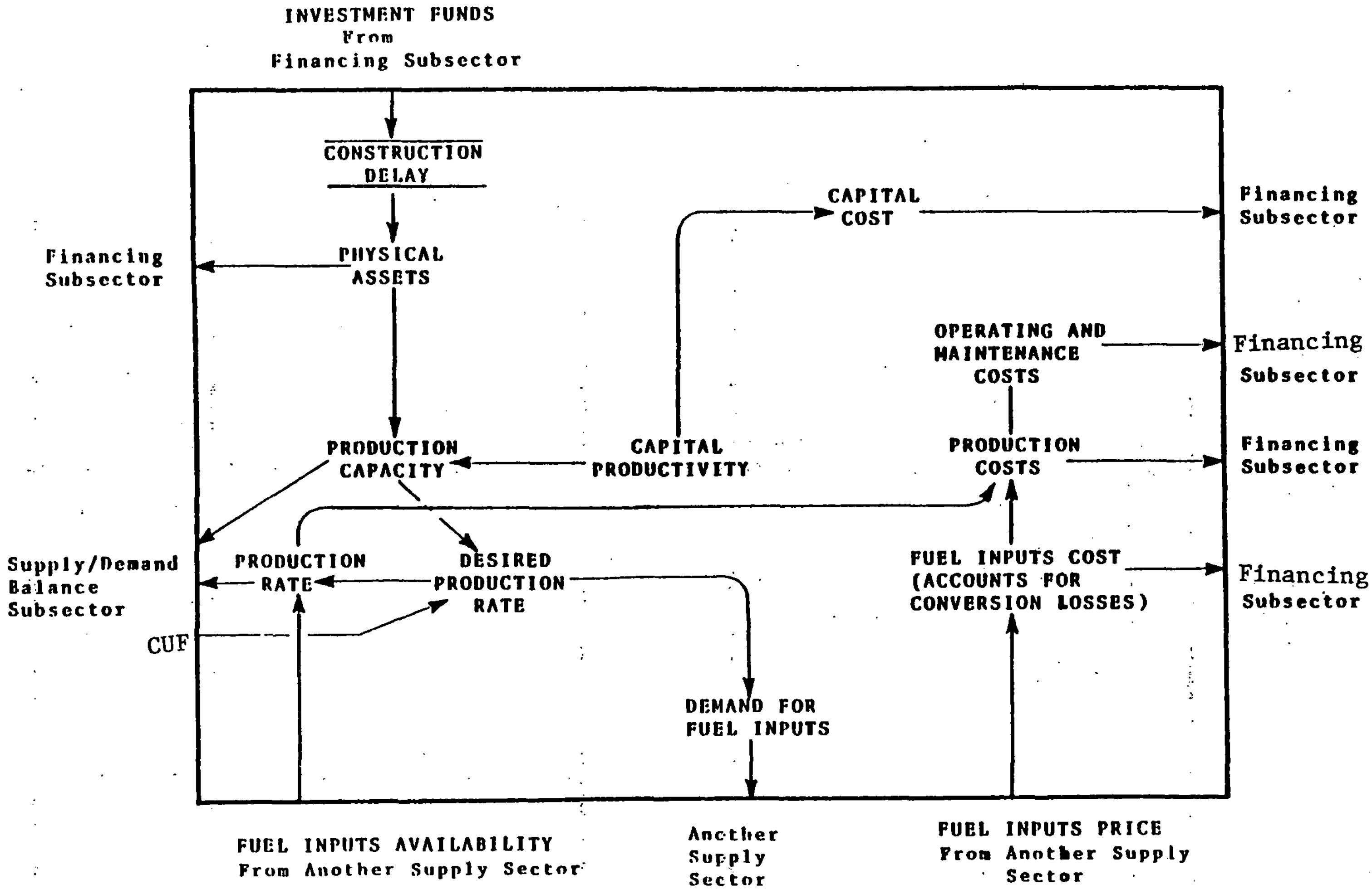


FIGURE 18

Generic Production Subsector Structure for a Conversion Process

FIGURE 19

GENERIC PRODUCTION STRUCTURE

DYNAMO FLOW DIAGRAM

EXTRACTION PROCESS

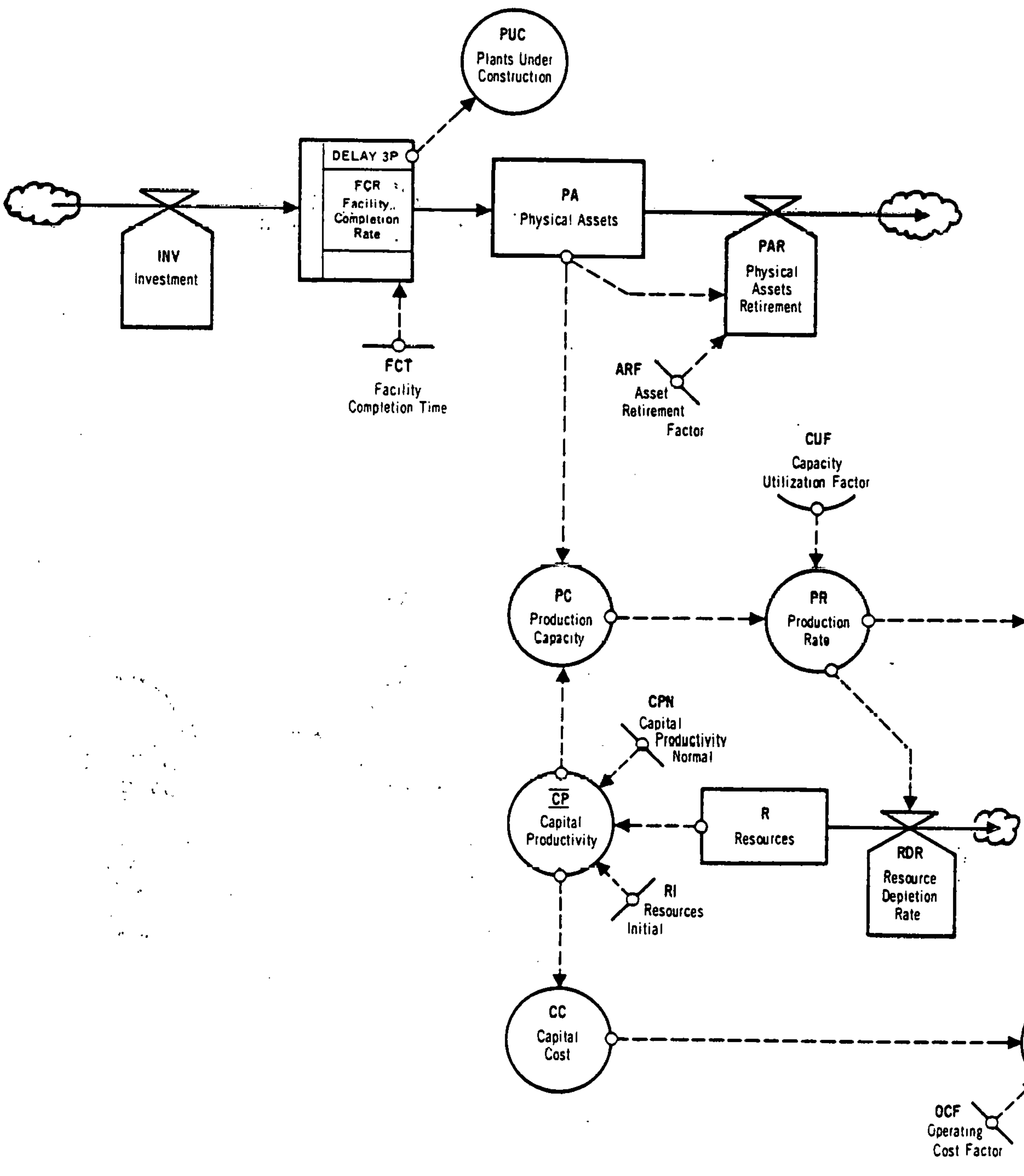
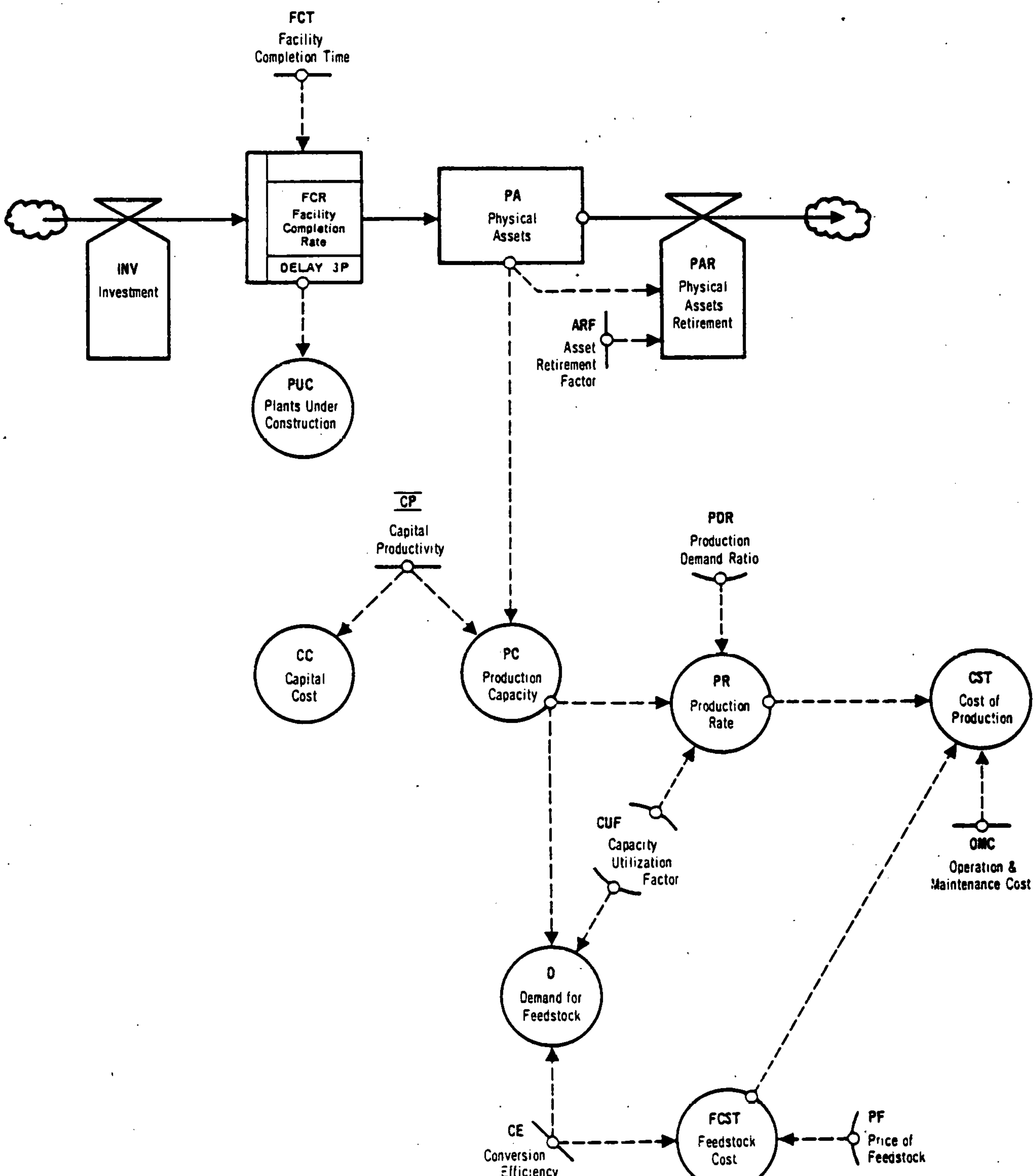


FIGURE 20

GENERIC PRODUCTION STRUCTURE

DYNAMO FLOW DIAGRAM

CONVERSION PROCESS



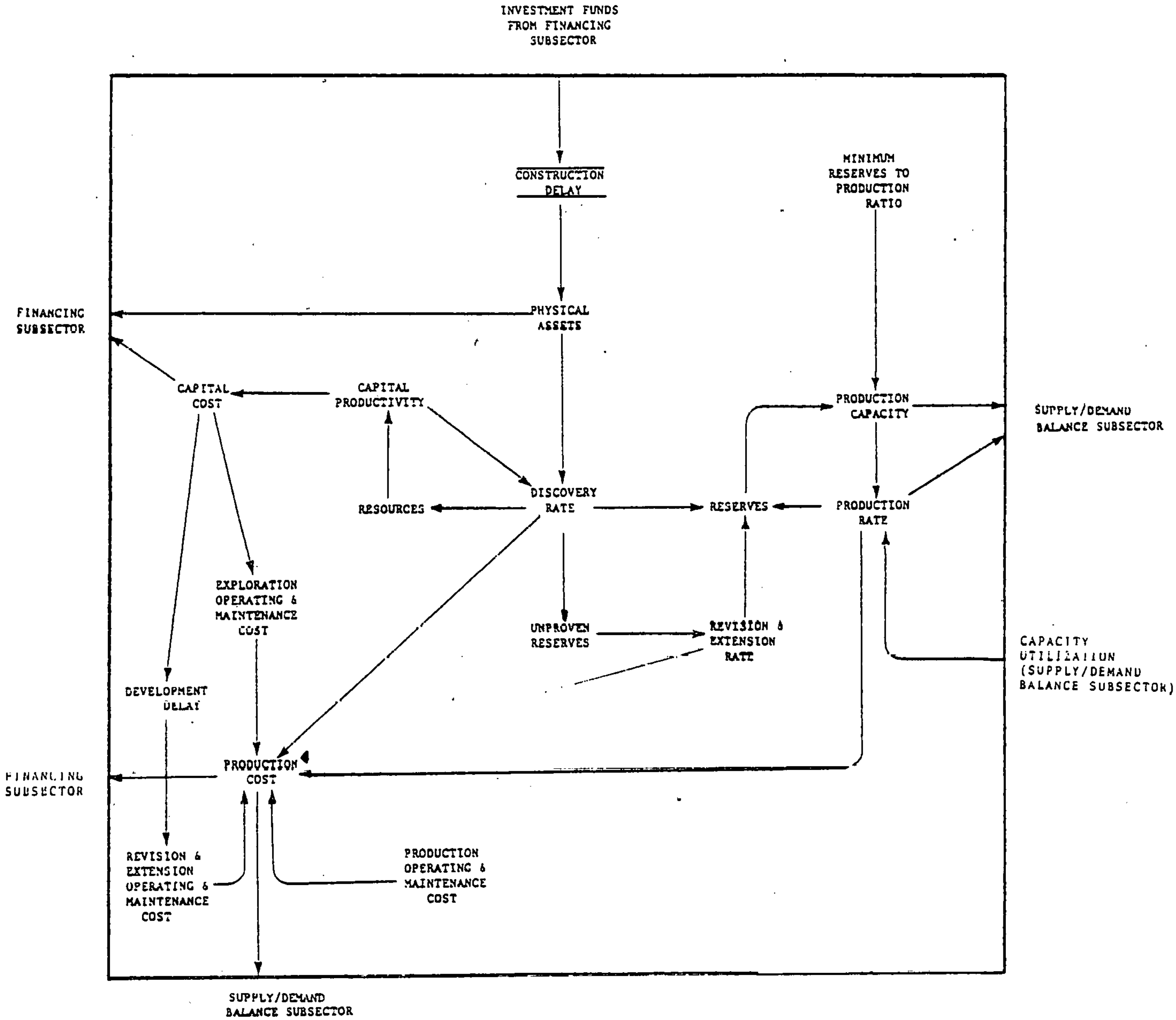


FIGURE 21

Generic Production Subsector Structure Case with Reserves and Resources

A better understanding of the workings of the reserve-resource extraction structure can be obtained by examining the equations that comprise the production/depletion relationships. A typical set of equations for these production relationships is listed below.

```
R.K    = R.J + (DT)(-RER)
RER    = PA x CP
DR     = RER/PDF
PDF    = 5.8
CP     = CPN x TABLE (DMT, R/RI, 0, 1, 0.1)
DMT    = 0/0.05/0.1/0.25/0.2/0.35/0.5/0.7/0.8/0.9/1
CPN    = 0.8E6
CC     = 1/CP
EOMC   = ECF x CC
ECF    = 0.15

URES.K = URES.J + (DT)(URA - RX)
RXF    = PDF - 1
URA    = (RER x RXF)/PDF
RX     = URES/RXD
RXD    = 13
ROMC   = RXCF x CC
RXCF   = 0.10

RES.K  = RES.J + (DT)(DR + RX - RDR)
RDR    = PR
PR     = PC x CUF
PC     = RES/MRPR
MRPR   = TABLE (RPRT, TIME.K, 1950, 2020, 10)
RPRT   = 11/10.6/7.5/6/6/6/6/6
POMC   = 0.05E-6
CST    = (DR x EOMC) + (RX x ROMC) + PR(POMC + RP)
RP     = RPF x MP
RPF    = 0.15
```

where:

R = resources (Btu)
RER = resource extraction rate (Btu/year)
DR = discovery rate (Btu/year)
PDF = potential discovery factor (dimensionless)
PA = physical assets ($)
CP = capital productivity ((Btu/yr)/$)
RI = resources initial (Btu)
DMT = depletion multiplier table
CPN = capital productivity normal ((Btu/yr)/$)
CC = capital cost ($/(Btu/yr))
ECF = exploration cost factor (fraction/year)
EOMC = exploration operating and maintenance cost ($/Btu)

URES = unproven reserves (Btu)
RXF = revision and extension factor (dimensionless)
RX = revisions and extensions (Btu/year)
RXD = revision and extension delay time (years)
URA = unproven reserve additions (Btu/year)
RDR = reserve depletion rate (Btu/year)
ROMC = revision and extension O&M cost ($/Btu)
RXCF = revision and extension cost factor (fraction/year)

RES = proven reserves (Btu)
PR = production rate (Btu/year)
PC = production capacity (Btu/year)
CUF = capacity utilization factor (dimensionless)
MRPR = minimum reserve production ratio (years)
RPRT = reserve production ratio table
POMC = production O&M cost ($/Btu)
CST = cost of production ($/year)
RP = royalty payment ($/Btu)

MP = market price ($/Btu)

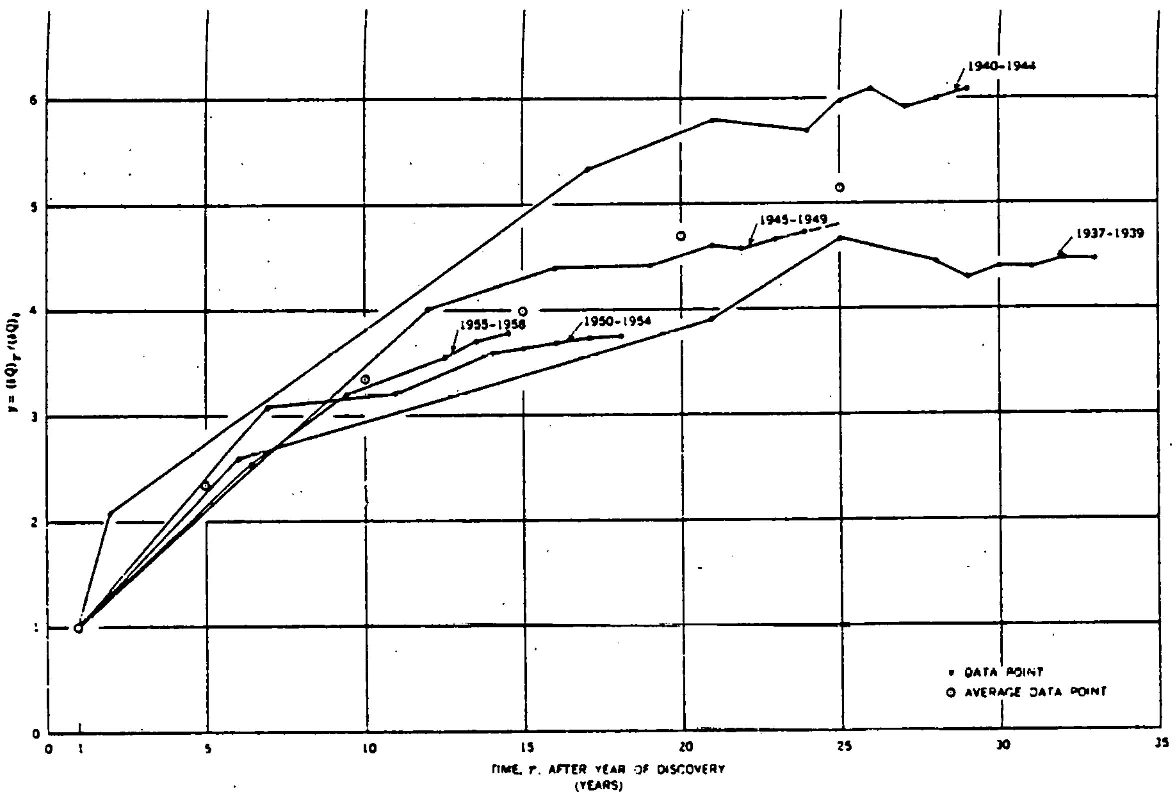
RPF = royalty payment factor (dimensionless)

The first set of equations defines those relationships that affect the recoverable resource base. The amount of resource removed in any year from the resource base depends on the physical assets available and their capital productivity. However, not all of the resource is immediately included in proven reserves as a new field discovery. When a new pool of resource is identified, only a small fraction immediately enters reserves as a new discovery; the rest remains identified as unproven reserves and must await further development of the pool before entering proven reserves as a revision or extension.

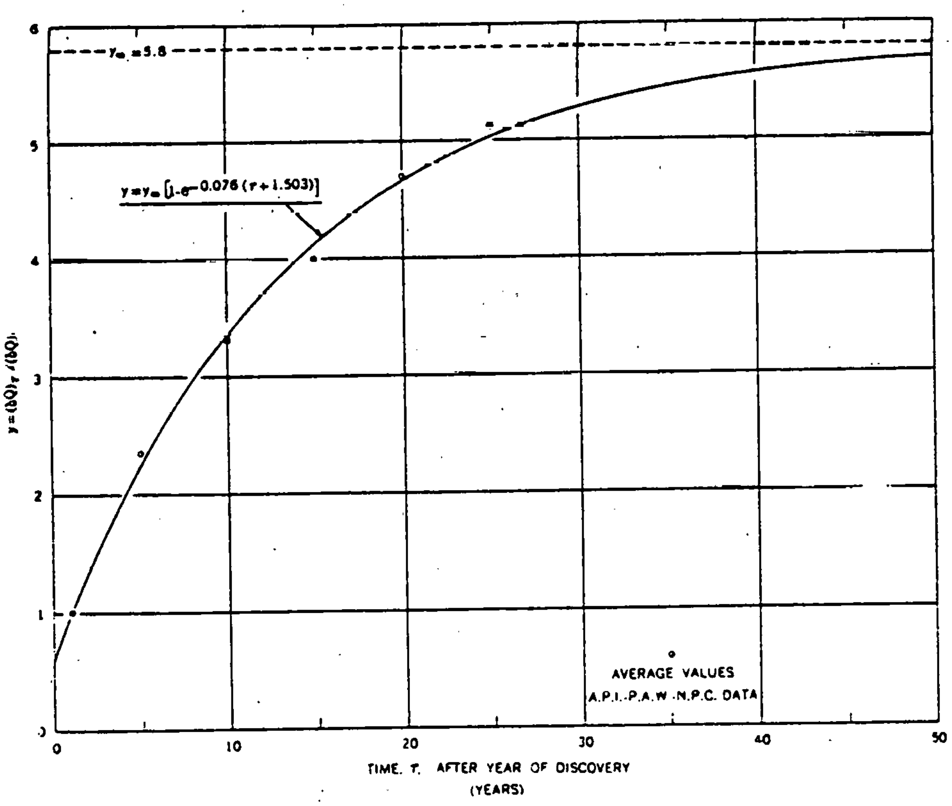
Much analytical and empirical investigation has been performed to determine the ratio of the ultimate amount of resource available in a given pool to the amount of new discoveries at the end of the first year, as a function of subsequent time. Figure 22 shows the results of such an investigation for the recovery of crude oil in the United States.* As can be seen from the figure, the ultimately recoverable United States crude oil from any one pool is approximately 5.8 times the amount of the initial discovery. In other words, only 17.2 percent (1/5.8) of the potential amount of oil to be discovered actually is reported as a new field discovery. The other 82.8 percent (4.8/5.8) eventually is reported as revisions and extensions to the old field. However, this amount does not become fully available for production (i.e., enter proven reserves) until many years after the initial discovery.

---

* M.K. Hubbert, U.S. Energy Resources: A Review as of 1972, U.S. Senate Committee on Interior and Insular Affairs, pursuant to S. Res. 45 -- A National Fuels and Policy Study, Serial No. 93-40 (92-75), U.S. Government Printing Office, Washington, D.C. (1974).



Growth of ratio of estimates of ultimately recoverable U.S. crude oil discovered in a given year to estimate of new discoveries at end of first year, as a function of subsequent time.



Graph and equation of average of the growth rates.

SOURCE:

M.K. Hubbert, U.S. Energy Resources: A Review as of 1972, U.S. Senate Committee on Interior and Insular Affairs, Serial No. 93-40 (92-75), (1974).

FIGURE 22

RATIO OF ULTIMATELY RECOVERABLE OIL RESOURCES TO VALUE OF THE INITIAL DISCOVERY

The structure accounts for revisions and extensions by placing the amount of resource eventually to be discovered by revisions and extensions (4.8 times the initial new field discovery in the case of oil) into a level of unproven reserves. (See the second group of equations above.) The actual development of the field then is represented in the model by a DYNAMO first-order delay. The response of such a delay to a step input of 5.8 with a delay time of 13 years closely resembles historical oil field development. The revisions and extensions in any year are calculated as the level of unproven reserves divided by the revision and extension delay time, shown to be 13 years for oil.

The third set of equations defines the level of proven reserves and, therefore, the available production capacity. Proven reserves increase in any year as the sum of new field discoveries and the revisions and extensions to old fields. The level of proven reserves decreases by the quantity produced. Production capacity is limited by the level of proven reserves; producers cannot, due to geological limitations, exploit more than 10-20 percent of existing reserves in a given year. If production were to rise above this geological limit, the ultimate amount of recoverable resource would decrease. Production capacity does not increase, therefore, until more reserves are made available through discovery and development. Discovery and development are limited by the level of physical assets, production is limited by the level of available proven reserves.

Note that the unit cost of production is computed explicitly in the generic structure. O&M costs are calculated as a fraction of capital costs. As the resource base is depleted and the capital costs of production rise, O&M costs necessarily rise with them. Wells must be drilled to greater depths, and the number of dry holes drilled increases, creating additional expenditures.

O&M costs are broken down by type: exploration, development (revisions and extensions), and production. This breakdown is important because revisions and extensions have different costs from those associated with discovery. In the case of new discoveries, little is known of the surrounding geology and the probability of success is small (under 20 percent). However, the dollar value of "hitting" a new field is high. On the other hand, the probability of success for developmental drilling is high (over 80 percent), but the additional value of oil found is smaller than for discovery. Thus, the expenses of discovery and development are different and must be calculated separately.

Actual production cost for the year is calculated simply as the sum of the products of the discovery rate and its O&M cost, the revisions rate and its O&M cost, and the production rate and its O&M cost. When the fixed capital charges subsequently are included in the finance sector, total industry cost is determined accurately. The selling price of the product can be determined by adding the profit margin to the total industry cost and dividing by the number of units sold (i.e., the production rate). Figure 23 shows the DYNAMO flow diagram for the reserve-resource extraction generic production structure.

Figure 20 shows the generic structure for a conversion process in FOSSIL2. The fundamental difference between an extraction and a conversion process is the location of the resource; with the conversion structure of Figure 20, the resource base is located in another energy sector and, consequently, the conversion process must demand energy as a feedstock from that outside sector. Electricity production technologies, for example, demand energy from all of the three remaining energy sectors -- oil, gas, and coal. The demand for a feedstock is determined as the following:

$$DF = PR/CE$$

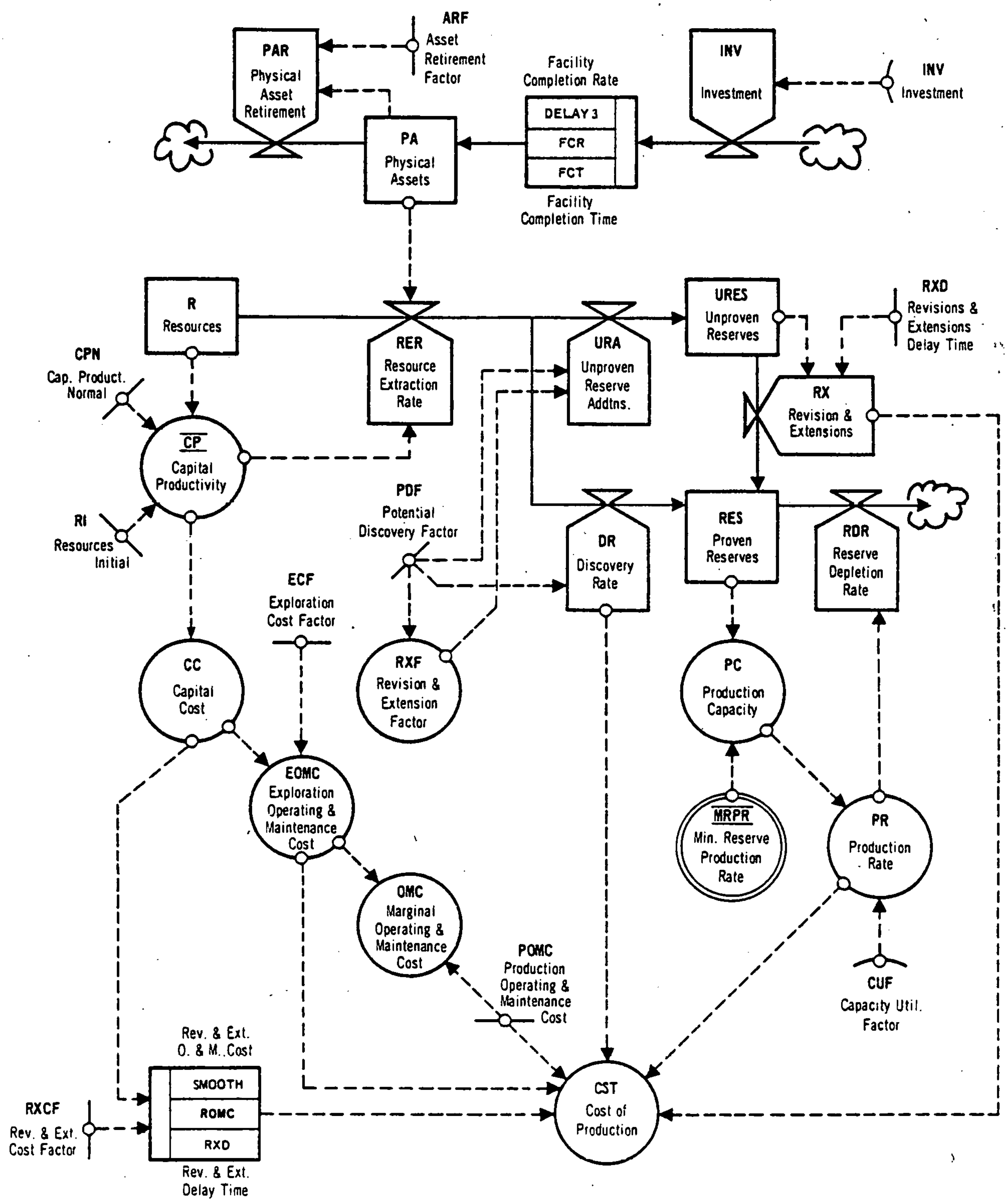
$$PR = PC \times CUF \times PDR$$

FIGURE 23

GENERIC PRODUCTION STRUCTURE

DYNAMO FLOW DIAGRAM

EXTRACTION PROCESS — RESERVES PLUS RESOURCES



where:

- PC = production capacity (Btu/year)
- DF = demand for feedstock (Btu/year)
- CE = conversion efficiency (fraction)
- PR = production rate (Btu/year)
- CUF = capacity utilization factor (fraction)

The capital productivity of a conversion process (unlike an extraction process) is exogenous to FOSSIL2 and is equivalent to the rated output of a conversion facility divided by the plant cost.

The unit (average) production cost of a conversion process is modeled as the sum of the unit O&M and feedstock costs. The O&M cost is specified exogenously. The feedstock cost is endogenous to FOSSIL2 and includes the cost of energy lost in the conversion process. Feedstock costs rise as the feedstock resource base is depleted.

☆U.S. GOVERNMENT PRINTING OFFICE: 1980-341-060/283

United States
Department of Energy
Washington, D.C. 20585

THIRD—CLASS MAIL
POSTAGE & FEES PAID
U.S. DEPT. OF ENERGY
PERMIT NO. G 20

THIRD CLASS MAIL

Official Business
Penalty for Private Use, $300