MARACO, INC.
33531 Marlinspike Dr., Monarch Beach, Ca. 92629-4426 Ph. (949) 388-6193 Fax (949) 489 1399

We are in 1982.

OPEC's OWEM: An integrated World Energy Planning System

E.L. Dougherty, J. Nugent, B. Zagalai U of Southern California & J. Johnston UCal-Irvine

Abstract

OWEM is a computerized world energy planning system resulting from four year's research work at USC. This paper:

1. presents the organization of the computer system and its data base,
2. reviews the major conceptual assumptions made in developing the system's computational algorithms and procedures,
3. outlines the flow of calculations between the system's segments during a run, and
4. discusses results from an example planning study.

Introduction

OWEM (OPEC World Energy Model) evolved from four year's (1978-1982) concentrated research and development work at the University of Southern California. Here we sketch OWEM's design and explain how the system works. We first briefly touch on design criteria and the conceptual design process. Then, we review OWEM's structure. The system has two dimensions:

1 geographic, and

2 activity considered, i.e., energy supplies, energy demands, economic activity and trade. For reasons given geographic subdivisions are not the same for all activities.

Next, we explain the overall computational process giving important aspects of the internal workings, data flows and procedures within each of OWEM's modular program elements. Here, we layout the inter-modular data flows. Finally, we present results from a set of example planning runs.

Goals & Objectives

Our goal was to create a system that generates reasonable projections of possible world energy futures. Specifically, the stated target was: given a future profile of OPEC oil price or production rate, develop plausible, realistic, projections of the following:

1. supply capacity and consumption rate of all major energy forms,
2. volumes of oil, gas and coal moving through international trade, and
3. impact of events in the energy sector on level of economic activity in producing and consuming countries.

The latter involves several factors that OWEM considers:

1. Increase in price of energy relative to other goods and commodities increases rate of inflation and reduces economic growth rate.
2. Both these changes act to reduce demand for energy.

3. A relative energy price increase results in significantly greater monetary flows from energy importers to the energy exporters. This wealth transfer increases non-energy trade flows in the opposite direction and expands investment in the economies of the energy importers.

SYSTEM DESIGN CRITERIA

Given the dynamic complexity of the world's energy recipe, OWEM must be adaptable. Achieving required flexibility dictated two characteristics:

1. Modularity of programmed structure, and
2. User-friendly interface. especially ease of data handling and entering control instructions.

Two other design criteria – model relevant effects and compute results in reasonable time – are standard.

OWEM projects dynamically through time a possible evolution of the world's energy system. The projection horizon is subdivided into one-year time periods (up to 30). Within each year, we assume that the world's energy demands are satisfied by selecting the minimum cost recipe from the then available feasible supply options, approximating the behavior of the world's energy purchasers. Because of time lags, actions in previous years determine the supply options available. Likewise, each year's investments in new energy supply capacity are based upon past, current and projected energy flows, costs, and profitability.

We do not assume there is sufficient insight among energy decision makers to warrant consideration of energy possibilities and needs during all planning years simultaneously. In this sense, our model philosophy differs from that of Dantzig(1), the IIASA team(2) or Rapaport(3). Our model is descriptive and attempts to project what well may be, whereas these (so-called optimizing) models are prescriptive and attempt to show what could be.

Structure of OWEM

Ordinarily, OWEM begins calculations in 1981 and ends them in 2005. Starting from the base year, 1975, calculated results for1976 -- 1980 are also available. These were (and still are occasionally) used to calibrate OWEM, but their primary purpose is to provide a readily available, consistent picture of recent history.

DEMAND REGIONS (ENDEM, GEM MODULES)

OWEM considers two separate models for each demand region, an energy demand model and a macroeconomic model of economic behavior. The demand regions considered are:

1. OECD - Three groups of countries are considered. These cover the geographic layout and correspond to a fairly uniform distribution of economic output and energy demand.
    1 NAMR - United States, Canada.
    2 WEUR – Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom.
    3 JANZ – Japan, Australia, New Zealand.
2. OPEC – Each country is modeled separately.
3. OWOCA (Other World Outside Communist Areas) - The remaining noncommunist countries are treated as a single demand region. This aggregation of many widely dispersed countries, which vary greatly in size, population, economic output and energy demand, results in a region comparable in energy demand and economic output to each OECD region. We believe the diversity of the aggregation's components has minor impact on computed results.

4. Communist Countries - are not modeled as demand regions; these areas are considered as net suppliers or importers of fuel.

SUPPLY REGIONS (ESAM MODULE)

OWEM considers four types of energy supply regions;

1. Oil and Gas
2. Coal
3. Uranium
4. Other

The geographic areas are not the same for these four types, nor are they the same as the demand regions. The areas were selected to balance detail on the energy supply side with the degree of disaggregation in the demand regions.

1. Oil and Gas Supply Regions – The 29 oil and gas supply regions represent all current or potentially significant oil and gas producers.

   1 27 endogenous regions

   - 13 OPEC Countries, Neutral Zone. OWEM considers exported OPEC oil as a uniform commodity feeding into a common world pool from which importers draw. Crude transportation costs are not considered. Price differentials are more closely related to supplier's marketing policies than to differentials in quality or transport cost. Thus, OWEM considers an average CIF OPEC oil price averaged over these differentials.
   - Canada, US Alaska, US Other, Mexico, Other Latin America, Norway, United Kingdom, Other North Sea, Other Europe
   - Australia (plus Japan and New Zealand), Other Asia, Other Africa, Other Middle East

   2 2 exogenous regions

   - USSR, China - Exports input versus time, no attempt being made to model reserves or capacities

2. Coal Supply Regions – Coal supply is divided into four exogenous and five exogenous regions. Together, these regions supply essentially all coal presently entering international trade, and no other major suppliers are on the horizon. OWEM models reserves, costs and capacities endogenous regions. Production rate of regions 5-6 are input vs time, as are net exports of coal from regions 7-9.

   1 4 endogenous regions

   1. North America
   2. Western Europe
   3. Australia
   4. South Africa

   2 5 exogenous regions

   5. South America
   6. Other Asia
   7. Poland
   8. USSR
   9. China

10. Uranium Supply Regions – Six uranium-producing areas, which collectively contain all currently known uranium reserves, are modeled endogenously.

    1 USA

    2 South Africa

    3 Australia

    4 Canada

    5 Niger

4. Unconventional Fuel Supply Regions - The following four sets of unconventional fuel supply regions are considered. Potential growth rate of each of these alternative fuels is modeled as a function of the amount by which the price of competitive fuels exceeds the alternative's fully amortized cost. Potential growth rate is moderated for logistical and policy considerations to obtain actual growth rate.

    1 Oil Shale

    - USA

    2 Tar Sands / Heavy Oil

    - Canada, Venezuela

    3 Coal Liquefaction

    - NAMR, WEUR, JANZ, South Africa

    4 Coal Gasification

    - NAMR

TRADE REGIONS (TRAM MODULE)

Inclusion of non-energy trade regions allows OWEM to consider the impact of non-energy trade upon economic behavior of the demand regions. With two exceptions, the geographic span of the trade regions and the demand regions is the same. OPEC countries are aggregated into a single trade region. Communist countries are modeled as a single trade region whose net flows of non-energy trade with all other regions are input exogenously vs time. Thus, six trade regions are considered:

1. NAMR
2. WEUR
3. JANZ
4. OWOCA
5. OPEC
6. Communist Countries

OTHER STRUCTURAL CONSIDERATIONS (INTEM MODULE)

OWEM considers exchange rates between currencies in the demand regions. In NAMR, WEUR and OWOCA the currency unit considered is (equivalent or pseudo) US dollars; in JANZ yen is the currency unit; and the local currency unit is used in each OPEC country. Provision to project relative changes in exchange rates vs time is included, but this feature has not proven satisfactory. Rather, exchange rates are input vs time. Historical values are used through 1980; exchange rates are held constant at the latter year's value thereafter.

Overall Computational Process

As shown in Figure 1, OWEM consists of eight modules, five computational and three interfaces with the user. The functions of the latter three are:

1. DATM (Data Module) - data input
2. SEGM (Scenario Generation Module) – input control instructions
3. REPM (Reporting Module) - print finished reports.

The data flow between OWEM's modules is shown in Figure 2. ESAM spans the world. Likewise, TRAM and INTEM reach across all geographic regions. ENDEM is divided into five segments, with the OPEC segment further subdivided into 13 pieces, one for each member. The regions in GEM are identical to those in ENDEM.

We explain two levels of computations

1. Each module's internal functions, and
2. How the modules interrelate, which is determined by information exchanged.

The remainder of this section discusses the second level, but to assist understanding here is a snapshot of each module's function:

1. ESAM (Energy Supply and Allocation Module)
    1. Keeps track of reserves, capacity and costs of energy supply alternatives,
    2. Derives the minimum cost way of supplying requested fuel demands given current producing, shipping and conversion capacities,
    3. Determines corresponding price of each fuel,
    4. Evolves expansion plans for energy supply alternatives.
2. ENDEM (Energy Demand Module)
    1. Projects energy demands taking into account price and income elasticities and historical lag in response to change in demand parameters
    2. Translates energy demands into demands for fuels.
3. GEM (General Economic Module)
    1. Projects level of economic activity and inflation in each demand region.
4. TRAM (Trade Module)
    1. Matches non-energy exports and imports and determines price of imports.
5. INTEM (Interperiod Module)
    1. Monitors currency exchange rates.

Figure 1 displays the information exchanged between the computational modules. The calculations that generate -- and are driven by -- these information flows fall into two categories; intraperiod and interperiod.

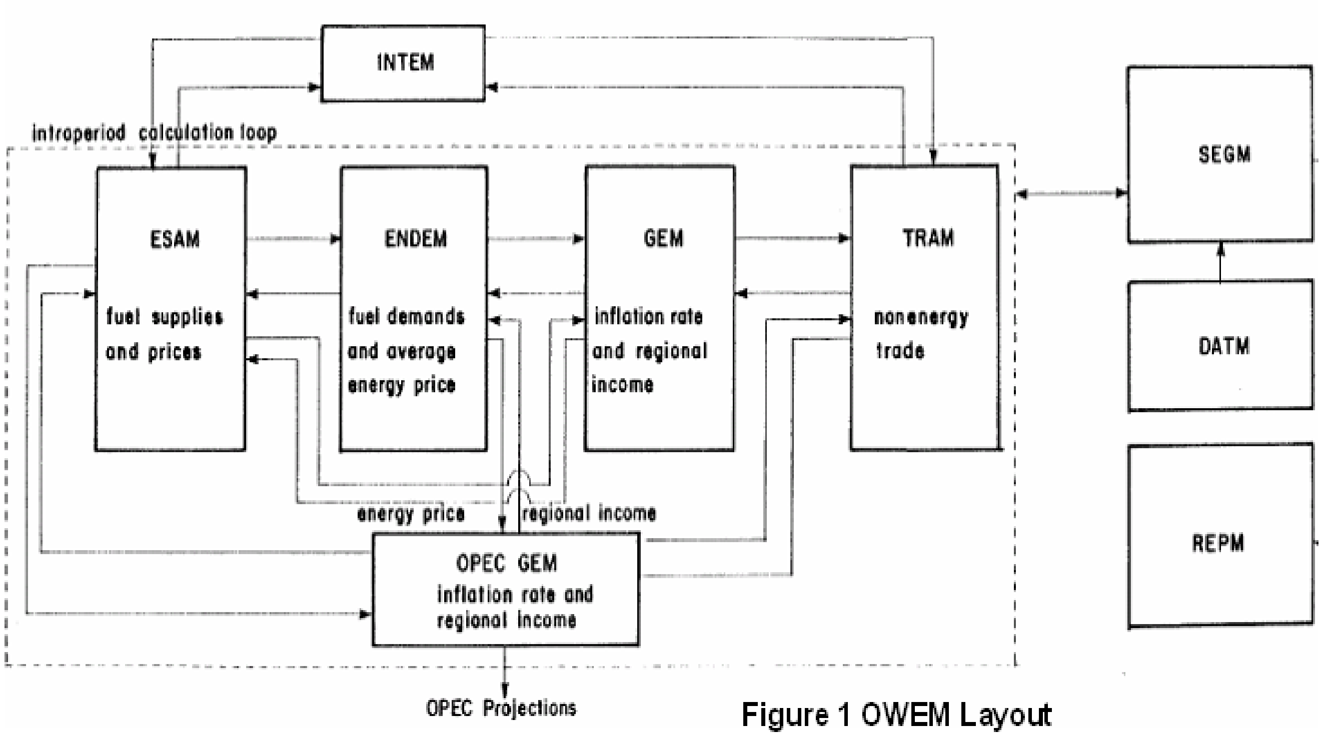

Figure 1 OWEM Layout

Intraperiod Calculations

These are iterative calculations made in each year of the planning horizon. As Figure 1 depicts, the intraperiod calculation loop encompasses ESAM, ENDEM, GEM and TRAM. The core of this determination is the barter between ENDEM and ESAM. ESAM receives fuel demands (derived by ENDEM using fuel prices quoted by ESAM on the previous iteration) and returns newly calculated fuel prices. ENDEM estimates new demands and calculates average energy prices, which are passed to GEM. GEM, in turn, calculates regional incomes (GDP) and price (inflation) levels; in making this calculation GEM passes demands for nonenergy imports and price of nonenergy exports to TRAM and receives in return nonenergy export demands and nonenergy import prices.

When the newly calculated regional incomes and prices are passed to ENDEM, they are used to reestimate fuel demands for passage to ESAM. When the change from one iteration to the next of every variable passed is less than a specified tolerance, the intraperiod iteration process is deemed to have converged on this time step. Usually 5-10 iterations are required for convergence..

Interperiod Calculations

Interperiod calculations occur once each time step after convergence of the intraperiod calculations. Reserves, capacities and costs are updated for changes taking place during the year just ending. Reserves are updated by subtracting that produced and adding that newly developed. Capacities are reduced by depreciation and increased by amount of new facilities becoming available in the following year. Investment and cost, and hence fuel prices, are adjusted for regional inflation and exchange rate changes. Financial balances are adjusted to account for net trade imbalances. After a single sweep through the interperiod calculations, if it has been so instructed, OWEM begins calculations for the following year.

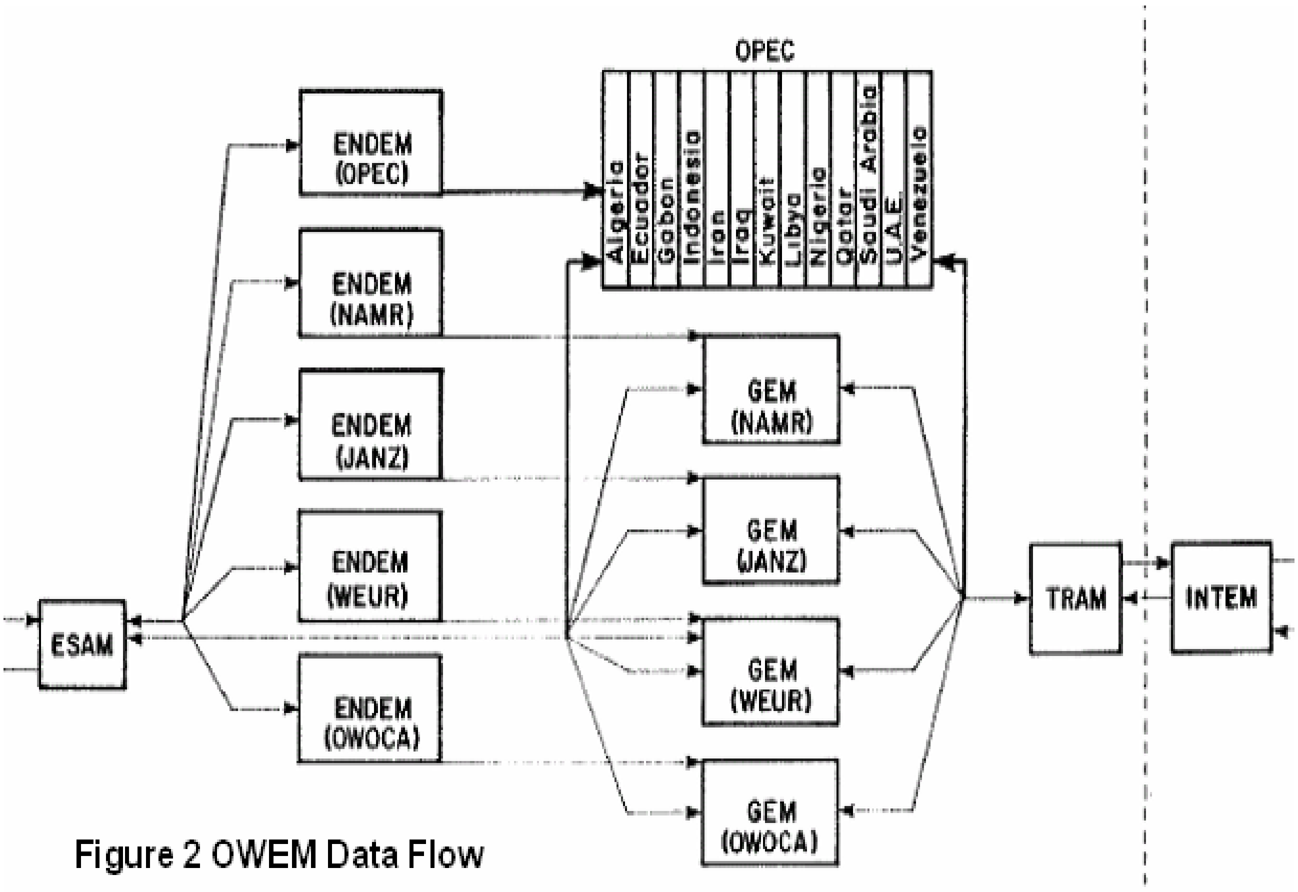

Figure 2 OWEM Data Flow

Prices, Costs, Inflation and Exchange Rates

In OWEM's calculations prices, costs and incomes are expressed in both real and nominal terms. 1975 is taken as base year for computing price indices and for measuring nominal monetary quantities such as regional income in real terms. Energy supply costs -- input in 1975 dollars – are converted to determine fuel prices in current dollars in ESAM. Using the current price index in the NAMR region, fuel prices, including the OPEC oil price, can be expressed in either real or current dollars.

To calculate energy demand in each region, ENDEM converts the US dollar prices for fuels to real local currency using the current exchange rate and the region's current price index. As a result, energy demands in each region are sensitive to relative differences in inflation rate. For example, if the inflation rate in NAMR is much higher than in JANZ whereas the exchange rate between the two currencies is unchanged, real fuel prices will tend to rise more rapidly in JANZ than in NAMR, with a corresponding reduction in the growth rate in energy demand. Frequently, such differentials in inflation rate tend to be offset by a counterbalancing movement in exchange rate; for example a decrease in the number of yen required to buy a US dollar would offset the increase in current dollar price of fuel.

In OWEM we attempted to model all these effects. Our experience with inflation rate projections has been moderately satisfactory, but this is not the case with exchange rates. As a result, we have opted in all runs to input exchange rates exogenously vs time.

Some Details Of The Modules

Here we sketch highlights of key calculations.

ENDEM (ENERGY DEMAND MODULE)

The basic equation used throughout ENDEM is the conventional demand equation:

$$\ln(Q_t) = (1-\lambda)*\left(A_o + \varepsilon_I \ln(I_t) + \varepsilon_p \ln(p_t)\right) + \lambda \ln(Q_{t-1}) \quad (1)$$

where

2 λ = lag parameter whose value is between zero and one. As a rule of thumb the number of years for full response is given by (1/(1- λ)). For λ = 0.90, ten years are required.

3 $έ_I$ = income elasticity -- percent change in demand after full response resulting from a one percent change in income.

4 $έ_p$ = price elasticity -- percent change in demand after full response resulting from a one percent change in price

These demand equations were fitted using consumption data from published sources, for OECD regions primarily from OECD headquarters. Price data, which are much harder to come by, were obtained from a variety of sources. Values of $έ_I$ & $έ_p$ were selected after an exhaustive survey of published results. Using these values, λ and A_o in Equation (1) were obtained via least squares.

A Fuel Share Equation – that approximates the competitive interaction between two fuels -- is obtained by taking the difference between Equation (1) written for, say, fuel A and fuel B. These two equation forms are used in OWEM's demand regions in different ways.

1 OPEC - Equation (1) is used with $έ_p$ = 0 to compute total energy demand for each country. All energy is assumed to be supplied by oil and gas, the shares of which are input exogenously vs time. Bunker fuel is an exogenous, time-dependent fraction of total energy.

2 OWOCA - Equation (1) is used to determine total energy demand. The parameters in the equation were obtained from a World Bank study of energy demand in a large group of developing countries. Exogenously derived shares of oil, gas and coal are input vs time. Bunker fuel demand is computed as a time dependent input percentage of total world energy consumption in the current year.

3 OECD – In each region ENDEM considers six energy demand sectors:

1. INDU: Industrial - Equation (1) plus three fuel share equations are used to determine the mix of oil, gas, coal and electricity.
2. HSCM: Household/Commercial - Equation (1) plus three fuel share equations are used to determine the mix of oil, gas, coal and electricity. An exogenously derived projection of solar energy consumed is subtracted from total sector demand before the fuel split is made.
3. TRNS: Transportation - Equation (1) is used directly to determine oil demand in TRNS.
4. ELEC: Electricity - Combined electricity demands from sectors 1 and 2 determine the total demand for electricity, which is assumed to be generated from a mix of oil, gas, coal and other sources. The exogenously derived other plus the endogenously computed nuclear is subtracted from total electricity demand to obtain fossil electricity. Two fuel share equations give the desired mix of fossil fuels. These shares are adjusted to resolve capacity infeasibilities or to reflect policy-specified shifts

5. PCHM: Petrochemicals – Demand -- assumed to be supplied entirely as oil -- is calculated as a time dependent input constant times current regional GDP
6. BNKR: Bunker Fuels - Demand for bunker fuel is obtained as a fraction of total energy demand in each region.

For coal and gas total demands are obtained by summing the demands in the INDU, HSCM and ELEC sectors, but for oil additional calculations are made. In the OECD regions, oil demand is broken down into demand for naphtha, middle distillates and residual fuel. For each of the six demand sectors the fraction of each of these fuel products is input vs time. Multiplying a fuel product's fraction times the oil demand in the corresponding sector and summing across all sectors gives demand for the fuel product; the three values thus obtained are passed to ESAM.

ESAM (ENERGY SUPPLY MODULE)

ESAM has three primary functions:

1. determine available energy supplies vs time, and
2. project prices of fuels vs time.
3. determine the fuel supply slate for all demand regions in each year.

To perform these functions ESAM considers the cost of converting an increasing proportion of ultimate recoverable resources (assumed known) into recoverable reserves and into available fuel supplies that can be delivered to satisfy end use energy demands. Development lead times are an important determinant of the time profile of fuel prices and availabilities, and are, therefore, duly considered by ESAM.

Figure 3 shows an overview of ESAM

1. ENDEM's demand regions are on the right. The Communist countries are included because at some point they may become net importers of some fuels; they also weakly affect the demand side through their non-energy trade interaction in TRAM.
2. The energy sources considered -- oil, gas, coal, nuclear fission, hydroelectricity, geothermal, and solar – are on the left.
3. A network flow model serves to integrate the energy supplies derived from these sources into a fuel supply slate in each year. The arrows shown in Figure 3 correspond approximately to the arcs in ESAM's network. Each network arc represents a significant processing or transportation link in the chain of activities required to convert some amount of an energy source into an onsite supply in a form desired by a consumer, e.g., a coal gasification arc connects a coal supply node to a node in the gas supply stream. The network also determines fuel prices and passes these to ENDEM. On each iteration of the intraperiod calculation loop, the network flow solution gives the minimum cost way of supplying ENDEM's current demands.
4. The minimum cost solution is shaped by the arc parameters, which are recomputed on each intraperiod iteration:
    - throughput capacity (quads/year) – an arc's flow limit,
    - unit cost (current dollars/quad) – an arc's throughput cost - the sum of fully amortized capital charge and operating cost, all expressed in current US dollars.
    - technology - (efficiency plus conversion taking place).
5. In passing to the next year, the interperiod calculations increase or decrease capacity and cost of each activity based upon a combine of endogenous estimates and exogenous inputs of resource availability, price & cost escalation, rate of technological growth or change.

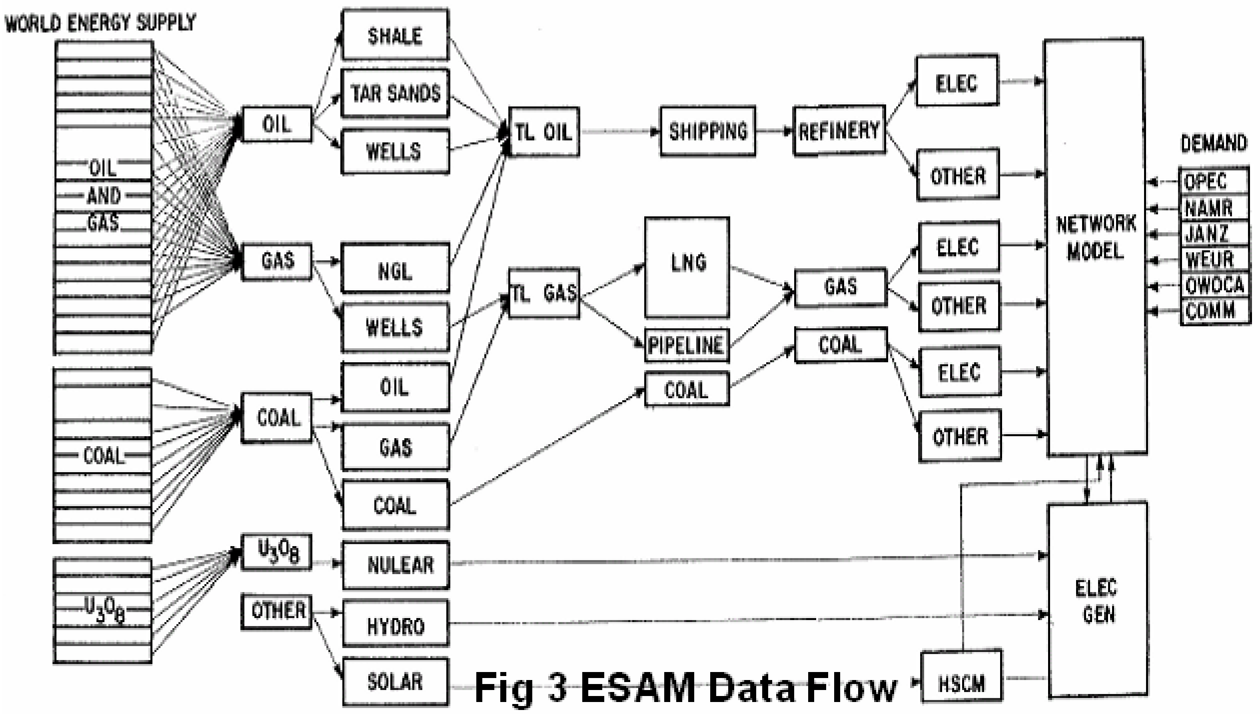

Fig 3 ESAM Data Flow

ESAM consists of seven submodels:

1. OilGas
2. Refinery
3. Coal
4. Electricity
5. Uranium
6. Unconventional Fuels
7. Capacity Expansion

Capacity Expansion Submodel

ESAM contains two groups of capital expansion procedures

1. CAPEXP submodel expansions or tailored expansions.
2. CAPEXP Submodel expansions are made for the following:
    1 Coal, Tar Sands/Heavy Oil/Oil Shale, Coal Gasification and Liquefaction, Fossil Fuel Generating Capacity, Nuclear Fission, LNG Export Facilities, NGL Type 2 Facilities.
3. For CAPEXP expansions desired capacity at each point in time is determined either from projected growth in demand for the facility's output or from an exogenous input table specifying total installed capacity versus time. In either case, this year's capacity increase is calculated. Then existing capacity is depreciated before the expansion coming on stream is added. The latter was calculated L years earlier, where L is the lead time specified for the facility in question.
4. The cost of a unit of output is calculated as the sum of the operating costs and the fully amortized capital cost, calculated for a specificied lifetime at a designated discount rate. This cost -- in current dollars of the decision year -- is inflated annually. The investment is spread uniformly over the lead-time and is also inflated to current dollars..

5. To determine size of expansion ESAM simulates the price/cost competition between fuels. CAP-EXP first projects the price of a unit of the facility's output in each year relative to the projected price for oil during the corresponding period. The price of oil is projected by rolling the oil price forward using the most recently calculated rate of escalation in real oil price. The price of the fuel in question is estiimated based on the hypothesis that the consumer price will move toward reestablishing the long term observed ratio relative to oil.
6. The long-term ratio of each fuel relative to oil is input to OWEM versus time, thus allowing ESAM to reflect changes in historical ratios arising from changes in consumer preference or producer marketing policies. A key example of such a change is LNG, whose price has moved from below parity to parity with oil in recent years.
7. Given the consumer price of the fuel, ESAM subtracts conversion and transportation costs to arrive at the producer's price. If this price is less than the computed unit cost, or if there is considerable excess capacity, the existing facility is depreciated. If the price is favorable, but there is too much excess capacity, existing capacity is maintained. With favorable price and growing tightness of capacity, an expansion is added, whose magnitude is a function of level of profitability and of recent growth rate of output, subject to specified upper and lower limits to keep the solution within reasonable bounds.
8. For nuclear electricity, the above procedure is modified slightly. The price against which the cost of nuclear electricity delivered to the consumer is compared is the average consumer price of electricity derived from fossil fuels.
9. Specially tailored capacity expansion procedures are used for:

   1 Oil, Gas and NGL Type 1 Capacity, Uranium, LNG Tanker and Import Facilities, Oil Refinery
10. ESAM does not model capacities of the other activities shown in Figure 3. Capacities of hydro-geothermal and solar energy and gas pipelines are obtained from input tables. ESAM does compute investment required for these facilities. Coal and oil transportation and distribution capacities are assumed available in whatever amount is called for and investments in these facilities are not explicitly considered by ESAM.

OilGas Submodel

The intraperiod calculations determine

11. production rates of each oil and gas producer,
12. how this output is distributed and
13. the (OPEC) world oil price.

Delivered prices of oil at demand points are determined by the network solution simultaneously with the world oil price. Delivered gas prices are determined from delivered oil prices using the Btu/price parity ratio specified in the input data.

The OPEC export price in each year is determined in one of two ways.

1. OPEC price is fixed exogenously. This price holds unless it is overridden because the sum of the minimum (or maximum) rate specified for each OPEC producer (an input fraction of capacity) yields a combined rate in excess of (or below) the market clearing rate, given the fixed price. In this case, the input price is overridden and allowed to fall (or rise) to the market-clearing price.
2. Total OPEC oil production rate is fixed exogenously. The market-clearing price is determined via ESAM's network solution. (The rate specified does not include the volume of natural gas liquids, which is determined by extraction capacity and gas production rate.) With this option no override of the maximum or minimum price is built into ESAM. In some runs in which total OPEC rate was specified to decline moderately while the internal OPEC oil demand, which ESAM is required to supply, increased at an unrealistic rate, the price of OPEC oil literally went "through the roof." In

these cases OWEM usually quit functioning when the price got completely out of hand, a perhaps not unrealistic simulation of what the real world behavior might be under the circumstances.

Reserves of oil and gas at the beginning of the year in each producing region establish the upper limit of oil and gas production rate. Reserves are a function of total footage drilled and cumulative production in each region.

1. For oil the upper limit is obtained by multiplying oil reserves times Q/R, production to reserves ratio. This parameter is input versus time for each region. The rate so calculated is a hard upper limit, whereas in real life producers vary their production policy in response to surges in demand if the price is attractive. Our experience with OWEM causes us to believe that a short run elasticity feature should be added to ESAM to model observed behavior more closely.
2. For gas the upper limit equals the sum of associated gas rate plus the specified upper limit on nonassociated gas rate. The former rate is obtained by multiplying actual oil production rate times GOR, gas/oil ratio, which is input versus time for each region. Nonassociated gas rate is obtained by multiplying gas reserves times the input value of production to reserves ratio for gas. As for oil, gas reserves are a function of total footage drilled and cumulative production. Associated and nonassociated gas are drawn from a common gas reserve base in each year.
3. Calculated oil and gas production limits may be overridden via exogenously input control limits. When these limits have been set in place in the network, the solution gives the flows through the chain of oil and gas facilities shown in Figure 3. Each producer's limit is increased by the projected volume of NGL liquids; this projection is based on the previous iteration's gas rate.
4. After the network solution the oil and gas flow rates and prices are plucked from the network. OPEC export rate is reduced by total exports of the fixed producers and the balance is allocated to the swing producers in proportion to net export capacity, i.e., capacity over and above internal requirements. The LNG production is allocated among LNG producers in proportion to export capacity.

Interperiod Calculations

1. These calculations update reserves and determine new capacities of NGL and LNG facilities. Since a one-year lead time is assumed for developing new oil and gas reserves, reserves are updated by adding new reserves discovered in the previous year to those existing at the beginning of the current year and subtracting production during the current year. At the same time, new reserves that will become available in the following year are added.
2. This addition is made using OilGas's drilling and discovery model. In this model footage drilled is raised (lowered) from last year's level according to profitability (unprofitability) of last year's drilling.
3. Profitability is determined as the ratio of the value of new oil and gas (including NGL) reserves net of all production costs to drilling costs. Profitability is thus approximately equal to net price times discovery rate (bbl/ft and MCF/ft).
4. Discovery rate is an exponentially declining function of cumulative discoveries. As cumulative discoveries approach ultimate discoverable reserves of oil and gas in a region, discovery rate and profitability plunge with corresponding rapid curtailment of drilling.
5. The drilling and discovery model was calibrated with data obtained by scouring all published sources and sifting through the range of published estimates to obtain a consensus of the consensuses. In OWEM's 27 endogenous producing regions, ultimate recoverable reserves of oil and gas add to about 1700 billion barrels and 1500 trillion cubic feet, respectively. Discovery rates were estimated by smoothing values calculated from recent reserve additions and footage drilled figures published by World Oil and the Oil and Gas Journal plus data for North America from the American Petroleum Institute and the Canadian Petroleum Association. Numerous simulations were made with the discovery model on a standalone basis to refine the parameter settings to yield results judged to be reasonable.
6. LNG facilities are expanded using a separate, small network flow model tying existing and potential LNG exporters to their existing and potential customers. This model considers full cost of sup-

plying LNG to each customer from each source including export liquefaction, LNG tankers and import regasification facilities. Because the model takes into account the cost competition between each potential supplier of each LNG demand, we believe the resulting allocation of new capacity is a reasonable approximation of what is likely to happen in the real world. The lead-time on all facilities in this expansion is assumed to be three years.

7. The expansion of NGL Type 1 facilities, which are meant to model flash separator operations with no intensive plant facilities, is handled without lead-time and in proportion to gas production rate. NGL Type 2 facilities, which are meant to model liquid recovery plants, are expanded based upon gas production rate and estimated profitability using the Capacity Expansion Submodel.

Refinery Submodel

The Refinery Submodel

1. translates ENDEM's demand for fuel products -- naphtha, middle distillates and residual fuel -- into demand for crude oil at the refinery gate,
2. generates wholesale fuel product prices given crude price at the refinery gate, refinery costs and efficiencies, and
3. estimates required refinery investment.
4. takes into account the effect of a changing product mix on relative amounts of distillation and cracking capacity and upon the associated processing cost. Additions to capacity of each type are added as required with no lead-time so that all of the investment shows up in the current year. The model is calibrated for crude of medium gravity (34 degrees API).

Coal Submodel

In the Coal Submodel

1. Flows from the three Communist regions are input versus time.
2. South America and Other Asia are treated similarly, except that the submodel keeps track of reserves and calculates required investment in coal capacity in each of these regions.
3. For North America, Western Europe, Australia and South Africa production, capacity, investment, reserves and supply cost are computed versus time. Total aggregate production rate in these four regions is determined by demands for coal, these arising from consumption in ENDEM's electrical, household/commercial and industrial sectors plus feed to coal gasification and liquefaction plants determined elsewhere in ESAM. Level of coal consumed in each of these end uses is strongly affected by the delivered price of the fuel form (coal, gas or oil) to the consumer. Hence, ESAM's projection of coal price has a significant impact on coal production and utilization.
4. ESAM’s method of determining coal price differs considerably from that for oil and gas. For coal we assume that economic rents will not arise, so that coal’s price will equal the fully amortized cost of delivering coal to each consumer, including any regional taxes or subsidies. The basis for this assumption is that excess reserves of undeveloped coal are available in the US, Australia and South Africa that will be brought into production in the event that the price of coal rises and presents potential investors with the opportunity to realize a premium rate of return. Accordingly, a careful analysis of coal production and transportation costs was made in order to determine delivered cost as accurately as possible. In this effort we were greatly assisted by the OECD publication "Steam Coal" and by data contained in the US Department of Energy's publication "The International Energy Evaluation System". In the Coal Submodel (full) costs of production are projected to increase gradually with cumulative production in each of the four endogenous coal supply regions. Ocean shipping costs are broken into three components, capital charge, operating costs excluding bunker fuel, and bunker fuel. The first two are increased in step with inflation while the latter is tied to OPEC oil price.

5. The allocation of total demand among suppliers is determined via ESAM's network flow model. Because cost of Western European coal frequently exceeds cost of imported coal, a lower bound was set on WEUR production rate to prevent this supply from being priced out of the market. Given this constraint the supplier's price in each region is obtained simultaneously with the supply allocation from the network solution.
6. In calculating capacity expansion, the amount of coal required to feed coal gasification and liquefaction plants (the growth of output of these being strongly influenced by profitability) is taken as fixed a demand whose magnitude is known over the lead time required to bring new coal capacity into production. A projection of the other coal demands at the end of the lead-time is made using ENDEM's demand equations. This projection may be moderated by input specification of a policy-mandated rate of shift of electrical generating capacity from oil and /or gas to coal.

Electricity Submodel

This submodel integrates

1. ESAM's network, which includes the requested amount of oil, gas and coal for electrical generation in the total amount of each fuel supplied, and
2. ENDEM, which determines the amount of electrical energy demanded by consumers.
3. The integration considers that electricity is generated from five energy sources -- oil, gas, coal, uranium and hydro/geothermal.
4. The submodel also considers "gas turbines" to be available as a high cost means of relieving electrical generating bottlenecks.
5. Capacity and cost of hydro/geothermal are input vs time; the other four fuels may be treated similarly, but in ESAM's usual operating mode these are determined endogenously.

<u>Intraperiod calculations</u>

1 On each iteration the Electricity Submodel calculates the weighted average wholesale price of electricity; ENDEM adds to this value retail margin and taxes and adjusts for electrical losses in the generation and distribution of electricity. The wholesale price is comprised of fuel and operating costs plus fully amortized capital charge.

2 For oil, gas and coal the fuel cost is the average cost of supply of each fuel to the demand region.

3 For nuclear fuel cost is obtained from the Uranium Submodel as discussed below.

4 If high cost "gas turbines" are used, this cost is also added into the weighted average electricity cost. Addition of this component usually raises price of electricity sufficiently to cause ENDEM to suppress demand enough to eliminate its use.

5 The Electriciy Submodel also converts generating plant input energy into output electrical energy using the heat rate for each type of generating capacity.

6 In addition to weighted average electricity price, ESAM passes fossil capacities. These are used to assure the fuel slate for generating electricity is feasible. In making these computations it is assumed that nuclear and hydro/geothermal generating capacity operate at a fixed percentage of capacity.

<u>Interperiod calculations</u>

1 Capacity is expanded using the Capacity Expansion submodel, as was discussed earlier.

2 In an expansion calculation profitability of fossil generating capacity is set equal to one, it being assumed that no economic rents (or debits) will accrue to a regulated industry.

3 For nuclear expansion the profitability is set equal to the ratio of average consumer price of electricity derived from fossil fuels to the consumer price of nuclear electricity. Thus, nuclear capacity

will be expanded endogenously only when its consumer price is less than the average price of fossil generated electricity.

Uranium Submodel

The Uranium Submodel

1. keeps track of consumption and reserves of uranium,
2. projects the cost of nuclear fuel used in nuclear power generation,
3. records levels of investment over time in required uranium mining and processing facilities,
4. does not consider breeder reactors nor fusion power.

The six uranium-producing regions considered by the submodel were listed earlier.

1 Yellow cake production from these regions feeds into a common world pool from which each year's total demands are drawn. The fraction supplied by each region is input versus time.

2 Cost of enriched uranium supplied to the Electricity Submodel is obtained by adding cost of mining and extracting U_30_8 to form yellow cake to cost of enriching uranium (conversion, enrichment, fabrication and carrying inventory).

3 Yellow cake cost increases with cumulative production in each region; a weighted average of these costs is used. Investment in refining uranium is at a level to meet current requirements and maintain a desired inventory level. This investment is split among the three OECD regions in proportion to the share of nuclear generating capacity in each.

Unconventional Fuels Submodel

This submodel

1 considers fossil fuels from five sources; coal liquefaction and gasification, shale oil, heavy oil and tar sands. Data were obtained from an extensive survey of recent publications covering present and possible future development of each source.

2 We tended to be very conservative in our expectations of near term growth because of a skepticism growing out of watching in years past actual commercial development fall far short of even the most pessimistic projections.

3 Key parameters affecting the rate of growth of these alternatives in OWEM are investment and operating cost estimates and allowed maximum growth rate. The latter parameter is included to simulate the fact that new technologies must pass through a considerable incubation period before commercialization at a rapid rate occurs.

4 Capacity expansion of these alternatives is computed in the Capacity Expansion Submodel. Hence, growth rate, being strongly influenced by projected profitability, is very sensitive to the specified or computed price of OPEC oil.

GEM (General Economic Module)

The fundamental purpose of each demand region's GEM is to model the interaction between energy price (actually energy price index, π_e), and the crucial macroeconomic variables real GDP, y, and the general price index, or GDP deflator, π.

1 Given y and π in a demand region plus a set of fuel prices, ENDEM makes conditional predictions of fuel demands.

2 These quantities are passed to ESAM, which responds with a new set of fuel prices -- which determine a new value of π_e in the region.

3 The new π_e effects both y and π in the region.

4 The loop is repeated with new demand predictions from ENDEM.

5 For the intraperiod iterations to progress quantitative estimates are required of the interconnection between π_e, y and π.

GEM - OECD Regions

Four principles guided construction of GEM for these regions.

1. A common type of model - Roughly the same set of structural equations was specified for each region, modified only by a priori knowledge of important regional differences or specific characteristics of a region's data set as revealed during the parameter estimation process.
2. Aggregate data rather than models - A regional model may be constructed
   - either by estimating models for the individual countries in a region and then aggregating the outputs of these models,
   - or by aggregating the data for the countries and fitting a single model to the composite. In order to reduce required work to a level compatible with available resources we adopted the latter approach.
   - As a first step, we found that the model fitted to US data gave nearly identical results to a model with the same structure fitted to the aggregate of US and Canadian data. Given that, economically speaking, Canada is only about ten percent of the size of the US, this result is not too surprising. However, the experience gives us greater confidence in use of the adopted approach in WEUR and JANZ.
   - In WEUR we elected to fit the model for aggregated data from the following six largest (in GDP) of the twenty OECD countries:
     - ✓ United Kingdom
     - ✓ France
     - ✓ Netherlands
     - ✓ West Germany
     - ✓ Italy
     - ✓ Spain
   - Together, these countries account for over 80 percent of the regional GDP. The performance of the model fitted to this aggregate turned out to be as good, if not better, than that of the NAMR model.
   - For the Pacific region (JANZ) unavailability of energy prices in Australia and New Zealand led us to construct a model for Japan, which accounts for over 80 percent of the regional GDP.
   - Thus, in OWEM's calculations the GDP computed for NAMR is used directly in ENDEM to compute energy demands, whereas for WEUR and JANZ the model's projection of GDP is multiplied by an amplifying factor to obtain the regional GOP. Historical data were scrutinized to derive a time trend for this factor. (With time the amplifying factor diminishes gradually in WEUR and increases gradually in JANZ.) A similar analysis of π values failed to reveal a trend, and indicated the model's projection to be a satisfactory estimate of π in each region.
3. Joint determination of prices and quantities - Models of inflation often focus on price and wage equations with real consumption, investment and income specified exogenously, and models of growth frequently concentrate on the real side of the economy and give inadequate treatment to monetary and nominal flows. For OWEM we believed it essential to have a balanced treatment with proper integration of the monetary and real sides.

4. Parsimonious specification - The target of development was to have as high a level of aggregation as possible, consistent with obtaining reasonably accurate results, in order to minimize GEM's size because:
    5. The larger the model, the more difficult is its use because of the inevitable need to "forecast" a larger number of exogenous variables over the projection period.
    6. Experience with a variety of models suggests that forecasts made with a smaller, more aggregative model tend to be at least as accurate as forecasts made with larger, disaggregated models.
    7. In a research effort it is much more sensible and efficient to start with fairly simple models whose properties can be analyzed and fully understood, and, if desired, to disaggregate in future research. A very large model built initially from scratch is almost certain to contain many specification errors that are difficult to resolve because the model's size makes its essential features hard to grasp.

Model Specification

We merely sketch here the high points of the specification, estimation and calibration of GEM. The underlying postulate is that there exists an (unknown) aggregate production function which gives real GDP as a function of real capital stock and (real) inputs of labor, raw materials and energy. Rather than try to estimate this function an alternative, less stringent approach was taken. Starting from the underlying postulate the two core equations of GEM were derived which indicate that:

1. Rate of change of real GDP, y, is related to rate of change of autonomous expenditures (current) and rate of change of price indices of energy, raw materials and labor.
2. Rate of change of GDP deflator is related to this same set of variables.
3. Other equations were added to the extent required to define the additional endogenous variables.
4. The final model contained 16 endogenous variables and, hence, a total of 16 equations.
5. The model also contained four variables determined elsewhere in OWEM
    6. (energy price index) (ENDEM),
    7. exports (current) and price index of nonenergy imports (TRAM),
    8. energy imports (current) (ESAM).
    9. In addition the model contains five variables exogenous to OWEM -- government expenditures (current), money supply, labor productivity, volume index of world trade in raw materials and economically active population.

Estimation of Equation Coefficients

1. Each of the 16 equations' coefficients were estimated independently using standard linear regression techniques. Various functional forms and lag structures were tried. In most instances an equation form involving a linear combination of first differences gave the best fit, based on standard statistical tests of significance.
2. No attempt was made to use more sophisticated simultaneous equation fitting procedures, since from the outset our plan was to simply treat the estimated values as the starting point from which to calibrate the full GEM model.

Model Calibration I

This calibration process, which was followed with all of OWEM's computational elements, involved two stages.

1. In the first stage, which we discuss in this section, the GEM model was tested on a standalone basis with values of the four OWEM-generated variables specified exogenously and input along with the five exogenous variables.
2. The second stage of the calibration process took place after GEM, and the other modules, had been integrated into OWEM. This phase of OWEM's development is discussed in the next section.
3. To conduct the standalone simulations required to calibrate OWEM's economic modules, a rather extensive and comprehensive Calibration Package of computer programs was written.
    1 The Calibration Package considers both the historical and projected period.
    2 Values of all variables, endogenous and exogenous, are input for the historical period along with values of the exogenous variables over the projection period.
    3 The Calibration Package picks up the required number of lagged values of the endogenous variables at the start of the historical period and carries the calculations forward from there using the input values of the exogenous variables and the calculated values of the endogenous variables during both the historical and the projection period.
    4 During the historical period the Package computes the percentage difference between the calculated and the input value of each endogenous variable and prints these error measures along with the calculated values versus time.
    5 During the projection period, of course, no error measure can be calculated so that only the calculated values of the endogenous variables are printed.
    6 The calibration process entails a careful scrutiny of the errors followed by suitable adjustment of the coefficients.
4. Once the error profile is acceptable, the projected values of the endogenous variables were carefully examined to make certain that the values were within reason and that the predicted trends made sense.
5. When the projection phase of standalone tests was judged complete, the economic model was ready for integration into OWEM.

GEM—OWOCA Region

The basic premises and specification of the OWOCA model differs considerably from the OECD models.

1. The OWOCA model was patterned after the regional models of developing countries constructed by UNCTAD for the LDC portion of Project Link. The model emphasizes the impact of economic events outside the region on internal economic behavior.
2. For example, the (explicit) production function includes three factors; capital, labor and imports of non-capital goods. Imports are limited by availability of funds within the region. Total available funds are given as the sum of exports, net factor income from abroad and foreign savings.
3. Likewise, the equation for inflation index, which evolved out of the calibration process, gives the rate of increase in the regional GDP multiplier as a linear combination of rate of increase of the price indices of energy and non-energy imports.
4. The version of the OWOCA model incorporated into OWEM contains 16 equations.

GEM-OPEC

A separate GEM model was developed for each of the 13 OPEC countries.

1. Each model considers an explicit production function with two sectors; energy and nonenergy.
2. Activity in the energy sector is entirely determined within ESAM, so that this sector is not only treated in detail, but its output is strongly influenced by goings on in the outside world.
3. The nonenergy production function, in a manner similar to the OWOCA model, contains nonenergy imports as one of the input factors.
4. For some of the countries net factor income from abroad is also a significant component of national income.
5. As for OWOCA the inflation equation relates inflation rate to prices of imports and energy.
6. Because of lack of data the models for United Arab Emirates and Qatar calculate inflation rate and GDP from input tables giving growth rate of these quantities vs time. For the other 11 countries, the model reflects a strong influence of outside events upon the country's economic development.
7. Each GEM-OPEC model was calibrated using the procedure explained for the OECD models.

TRAM (TRADE MODULE)

TRAM serves as an intermediary link between the regional GEM's.

Intraperiod Calculations

On an intraperiod iteration each economic model generates as part of its intermodular output

1 the price index of the region's exports, and the volume of non-energy imports during the year for which calculations are being performed.

2 Given these inputs, TRAM distributes each region's imports among the other demand regions.

3 Using the resulting distribution TRAM computes the price index of each region's imports as a weighted sum of the price indices of exports from the supplying regions. At the same time each region's exports are determined by totaling the imports assigned to it. TRAM then passes these derived quantities back to the demand regions.

4 The key element in TRAM's calculations is the trade-share matrix, which gives the fraction of each region's imports obtained from each supplying region. The base values of these shares are calculated from historical trade data.

Interperiod Calculations

In TRAM's interperiod calculations

1 the changes in the values in the trade-share matrix are computed using equations derived from statistical analysis of past trends. These equations project changes arising from price competition between potential exporting regions to moderate the historical time trend.

2 TRAM was calibrated using the Calibration Package described above. In many OWEM runs shares were input because of an unrealistic time trend.

INTEM (INTERPERIOD MODULE)

All of OWEM's interperiod operations are activated from INTEM

1 However, the only calculation that INTEM performs internally is to update the exchange rate of each economic region vis-a-vis the US dollar. As mentioned earlier, all exchange rates are specified exogenously vs time.

2 Even though the exchange rate from US to Canadian dollars is no longer unity, the exchange rate from the NAMR currency unit to US dollars is taken to be one everywhere in OWEM. Thus, each economic region's currency is measured relative to US dollars.

Systems Integration & Test

After the standalone calibration of each module was completed, OWEM's pieces were integrated and the second phase of calibration was carried out.

Model Calibration II

Calculations were made and results obtained with the full-scale OWEM.

1 During this phase of OWEM's calibration calculated fuel production and consumption rates and fuel prices were compared to historical values, and model adjustments were made to improve agreement. As stated earlier, 1975 was the start year of history.

2 During this phase projected values of key variables in 1981 - and beyond - were carefully scrutinized to assure that predicted trends were reasonable and that OWEM responded appropriately to changes in input.

3 Numerous changes to input data and to model relationships were made throughout OWEM to improve performance. Every segment of OWEM's computational modules received at least minor adjustment and refinement.

4 We do not elect to burden the reader with a long list of all the changes that were made. Be aware that a long time was required to complete this task; over a year of continued and intensive effort was spent

- o debugging the computer programs,
- o refining the computational procedures,
- o smoothing the user interface, and
- o "History matching" OWEM.

5 As a footnote, my estimate is that a half dozen others and I spent at least 50% extra time without extra compensation during this 2nd phase. However, when we installed OWEM in Vienna, OPEC's Director of Research - totally unversed in computer modeling - asserted that ***for the last year no significant work*** *had been performed on the project. He followed up his assertion by flying to the campus at USC demanding return of 7% of the funds OPEC provided. To this I objected strenuously, but when I went out of town for a day, USC officials cried uncle and kowtowed to his asinine demand!!!!!*

6 As is to be expected with an extremely complex modeling system rendered operational for the first time, we can see many ways in which OWEM can be improved. We anticipate that our creation will be extended and refined as it is used in the future.

Example Results

The result of our research effort has been to create an integrated, computerized world energy planning system, and the intent of this paper is to report this result. We are not in the business of generating and publishing possible energy futures. However, we could with

OWEM produce many energy futures in short order. The great advantage of a system such as OWEM is that it can

1. evaluate quantitatively assumptions about the world's energy system
2. test the significance of various possible outcomes, or
3. shed light on the long run implications of following certain energy policies.

Our academic experience tells us that to teach a theory, examples are required. Therefore, we present highlights of three planning runs made to test and validate OWEM's capabilities trusting that the reader will not construe the results to be anything other than examples. Runs 1FP and 2FR were made with all parameters set equal to the values that evolved from OWEM's calibration. In Run 3FP the only change in these parameters was to increase all price elasticities by 10 percent. In all three runs the exogenous fuel flows from the Communist countries were assumed as follows:

1. Oil imports to WEUR and JANZ drop to nearly zero in 1985 and to zero in 1990 and remain at that level through 2005.
2. Gas imports to WEUR rise from about two BCF/day now to eight BCF/day in 1990 and remain nearly constant through 2005.
3. Through 2005 coal imports increase only slightly from their present level.

In Run 1FP OPEC oil price was specified vs time, We call this a fixed price scenario. Nominal OPEC price was set equal to the historical value through 1981 and was increased by 15 percent per year from that point on. This high growth rate tested OWEM's operability on the upper fringes of possible price paths.

The economic growth and inflation rates projected for the OECD and OWOCA regions have a most considerable influence on OWEM's results. For Run 1FP the averages of these rates over the 30-year horizon are shown in Table I. For the OECD regions the average growth rates in GDP are reasonably consistent with those published recently by various energy/economic forecasting groups, but the growth rate for OWOCA is somewhat higher than the norm.

Table I – Approximate Average Growth Rates

1975 – 2005 - %/Year

	NAMR	WEUR	JANZ	OWOCA
	Real Fuel Prices			
Oil	**7.8**	**7.8**	**10.5**	**---**
Gas	**8.3**	**5.8**	**8.5**	**---**
Coal	**1.0**	**3.2**	**0**	**---**
Electricity	**1.5**	**0.9**	**2.9**	**---**
Ave. Energy	**5.0**	**4.2**	**5.8**	**7.2**
	Total Energy Consumption			
	0.8	**0.9**	**1.3**	**4.1**
	Real GDP			

	3.3	**2.5**	**3.7**	**6.5**
	Inflation Rate			
	8.1	**7.8**	**4.2**	**5.3**

Relative to current times an economic slowdown was predicted in NAMR, WEUR and OWOCA in 1981, which in NAMR and OWOCA was followed by rapid recovery in 1992. In WEUR full recovery did not occur until 1983 - 84. Growth in GDP in JANZ was largely unaffected during this period with the predicted value running close to average. (We now believe this result stems from a somewhat unrealistic parameter setting in the JANZ GEM'S GDP equation.) Above average inflation rates (by 2-4 percent) were projected through most of the 1980's. Below average inflation rates toward the end of the horizon brought the average down to the level shown.

The average growth rates of total energy consumption in the four non-OPEC regions, also shown in Table I, are considerably lower than the corresponding GDP growth rates. This result is, of course, not surprising, given the substantial real rate of increase in average energy price shown in Table I. Price elasticity acts to reduce the apparent income elasticity of total energy consumption in the OECD regions from the historical range of 0.9 - 1.1 to the range 0.25 - 0.4. Even with the higher rate of increase in energy price, the apparent income elasticity in OWOCA is 0.63 (4.1/6.5). Such a higher value for the developing economies may not be wholly realistic.

As Table I displays, the rate of increase in real energy price results from a combination of high rates of increase for oil and gas with low rates of increase in coal and electricity. As would be expected from these fuel-price increases, OWEM predicts a continuing shift from oil and gas to coal and electricity in the OECD regions throughout the horizon. Since the fuel shares in OWOCA are input exogenously, OWEM presently has no capability to make such a shift in this region.

With the average inflation rates shown in Table I, the real rate of increase in price of crude oil works out to a level considerably in excess of rates proposed by OPEC's Long Range Pricing Committee. The latter proposed rates in the range of 2-4 percent/year, considerably less than the 5-10 percent/year shown in Table I. Thus, Run 1FP represents an aggressive pricing strategy and should be regarded as only one observation on a spectrum of possibilities. During the early years, the strategy is not as aggressive as the averages indicate. Through most of the eighties inflation rates are two to three percentage points above the averages, so that during this period the strategy is only slightly above the upside of the Committee's proposed range.

The input production policies and the internally computed profile of reserves development in the oil supply regions has a significant impact on OWEM's results. In Run 1FP the reserves in all producing regions were maintained at a relatively constant level throughout the horizon. At beginning and end, total WOCA reserves are around 500 billion barrels. The cumulative percentage of the model's ultimate reserves developed by 2035 varied from 67 to 95 percent, with the WOCA average being equal to 80 percent. By way of comparison a total of 560 billion barrels of oil were produced during the horizon.

Inputs from unconventional sources were critical to the Run 1FP results. In 2005, about 10 percent of WOCA's useful energy supply was obtained from these sources. Coal liquids in OECD experience the greatest growth in volume, followed by heavy oil in Venezuela and shale oil and tar sands in NAMR. The growth rate projected for coal gasification in NAMR ends up far back in fourth place.

In Run 1FP the average growth rate of energy input to electricity worked out to 1.3 percent/year. This value is approximately 50 percent greater than the growth rate in total energy consumption in NAMR and WEUR, reflecting a gradual shift to more intensive use of electricity in these two regions.

OWEM projects a massive shift away from use of oil and gas to generate electricity. Between 1976 and 2005, the share of oil and gas drops from approximately 30 percent to less than 10 percent. The major replacement is nuclear followed closely by hydroelectric and other sources. A predicted gradual reduction in coal's input share is not considered to be of especially great significance. ESAM compares the cost of nuclear electricity to the weighted average cost of fossil electricity in deciding how much to expand nuclear generating capacity. Since coal is weighted down by its more expensive cousins, its competitive position is biased downward. The fact that coal's share is thus reduced in favor of nuclear is not worrisome. Various published energy studies have concluded that coal and nuclear are direct substitutes for fuel input to generate electricity. Were nuclear unable to grow as rapidly as projected, the deficit would be made up from coal leaving the share of oil and gas, the critical fuels, unchanged.

The lower three curves in Figure 4 give further insight into the low average growth rates in energy consumption in the OECD regions presented above in Table I. For Run 1FP almost all growth in energy consumption occurs before 1990, and at the end of the horizon, energy consumption is declining in all three regions. By contrast, in OWOCA energy consumption expands nearly uniformly throughout the horizon with only slight diminution toward the end. In striking contrast energy consumption in OPEC grew at an average rate of 8.4 percent/year between 1976 and 2005, and the rate was increasing significantly toward the end, a trend that seems highly implausible, suggesting adjustment is needed in the energy demand functions in OPEC.

Growth in oil consumption occurs entirely in OWOCA and OPEC. In the OECD share and volume of oil both decline gradually during the second half of the horizon, except in JANZ where the decline becomes precipitous near the end. The latter is believed to be a spurious result arising from the fact that the dollar inflation rate (NAMR) is twice that of the yen (JANZ). Since the exchange rate is constant, the dollar denominated OPEC crude price becomes increasingly onerous to the Japanese. It is apparent from an examination of Run lFP's results that assumed rapid turning of the screw on the oil market is made possible

1. by OPEC consuming a rapidly increasing volume internally, and
2. somehow financing growing sales to the developing countries.

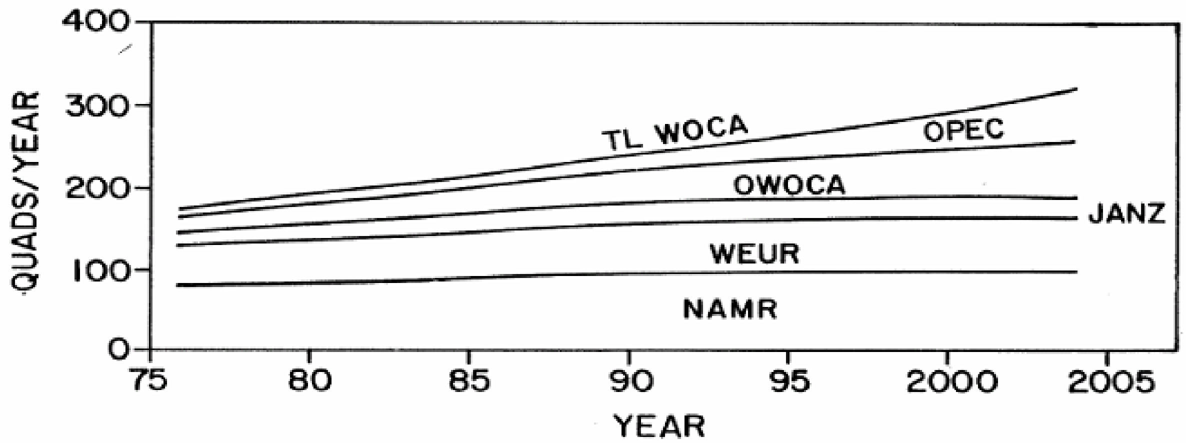

FIGURE 4 TOTAL WOCA ENERGY CONSUMPTION (INCLUDING BUNKER FUEL)

The sources for hydrocarbon liquids are shown in Figure 5.

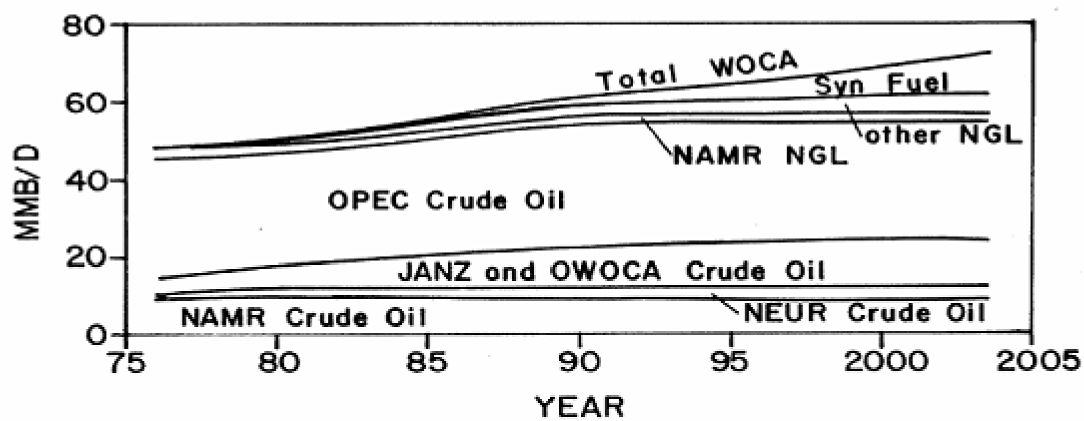

FIGURE 5 TOTAL WOCA OIL PRODUCTION

Production rate of crude oil in NAMR holds nearly steady and increases a small bit in WEUR. JANZ is combined with OWOCA since production rate in the former region is relatively small throughout. A large portion of the expansion in these two regions occurs in Mexico. As shown, OPEC crude oil production rate remains nearly constant. Production rate of NGL in NAMR decreases, but only gradually, with the passage of time, while NGL production rate in other regions, particularly OPEC, expands significantly. The critical role of liquids derived from unconventional sources after 1990 is readily apparent. In Run 1FP over 12 million barrels/day are obtained from these sources in 2005.

Increase in the rate of consumption of natural gas occurs almost entirely within OWOCA and OPEC. The increased supplies of Siberian gas in WEUR serve primarily to replace gas now coming from other sources.

Figure 6 displays the distribution of coal consumption.

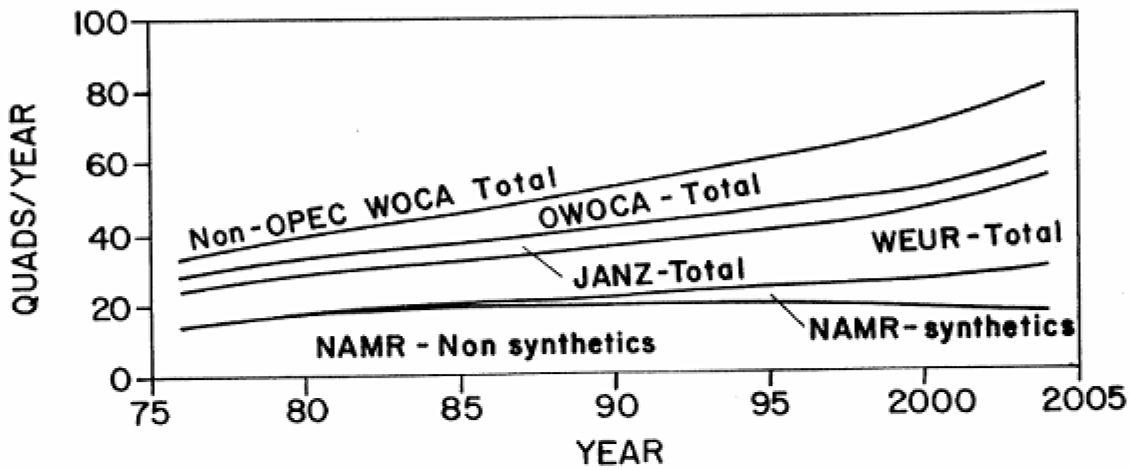

FIGURE 6 WOCA COAL CONSUMPTION

In NAMR volume of coal to conventional uses passes through a maximum and then declines. The downward trend near the end reflects the decreased volume of coal input to electricity generation. The bulge through the eighties is fattened by coal exports. Interestingly enough, for Run 1FP OWEM predicts that U.S. coal exports will cease by 1990, being replaced in the world market by coal from Australia and South Africa. This somewhat anomalous prediction is regarded with some skepticism, and, we believe, warrants careful scrutiny. Amount of coal used to manufacture synthetics in NAMR grows rapidly after 1990 and by 2005 almost equals that used conventionally. Annual consumption of coal in WEUR nearly triples during the horizon with most of the expansion coming from exports. Annual coal consumption in JANZ remains nearly constant, whereas that in OWOCA grows steadily throughout.

OPEC crude oil production rate for Run 1FP is shown in Figure 7. This rate, which is the market clearing value, accurately tracks the historical rate through 1979. However, in 1990 and 1981 OWEM overestimates OPEC rate, a point we will return to later. From 1982, onward OWEM predicts that OPEC crude oil production rate will be nearly constant at about 30 million barrels/day.

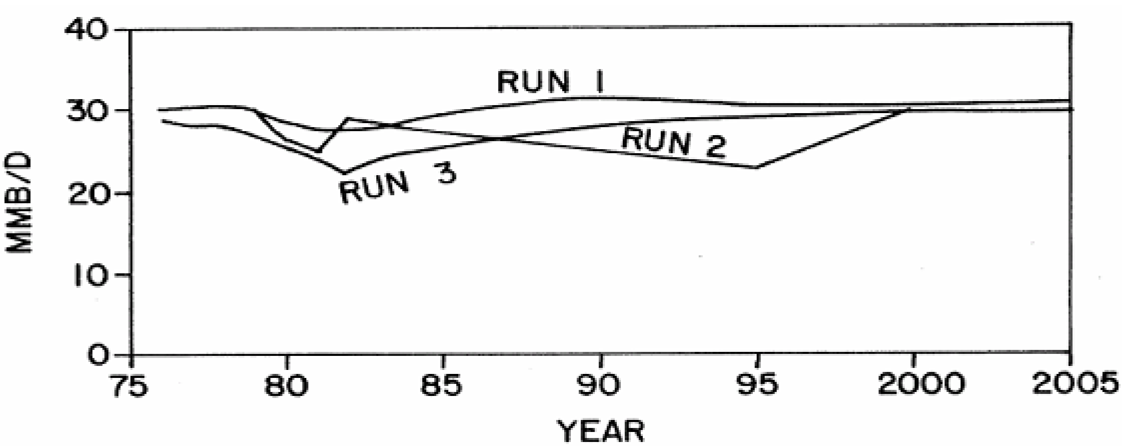

FIGURE 7 COMPARISON OF OPEC RATE

Figure 8 shows the level of OPEC exports for Run 1FP. Beyond 1990, exports fall steadily; reflecting the growing increase in domestic oil consumption in the OPEC countries. The corresponding OPEC oil price profile is shown in Figure 9. The rapid increase in real oil price, which underlies this nominal price curve, gives rise to fairly high growth rates in real GDP in most OPEC countries (from 5 to 12 percent/year). In the absence of price elasticity these high GDP growth rates give rise to high growth rates in energy consumption, thus accounting for the steady OPEC production rate in the face of rapidly declining exports. We believe this aspect of OWEM is unrealistic and needs further work. As might be expected from Figure 8, oil imports into NAMR and JANZ pass through a maximum in 1990, and imports into WEUR never again reach the 1975 level of 13,5 million barrels/day. OWOCA is a net importer toward the beginning and end of the horizon, but imports no oil during the middle years.

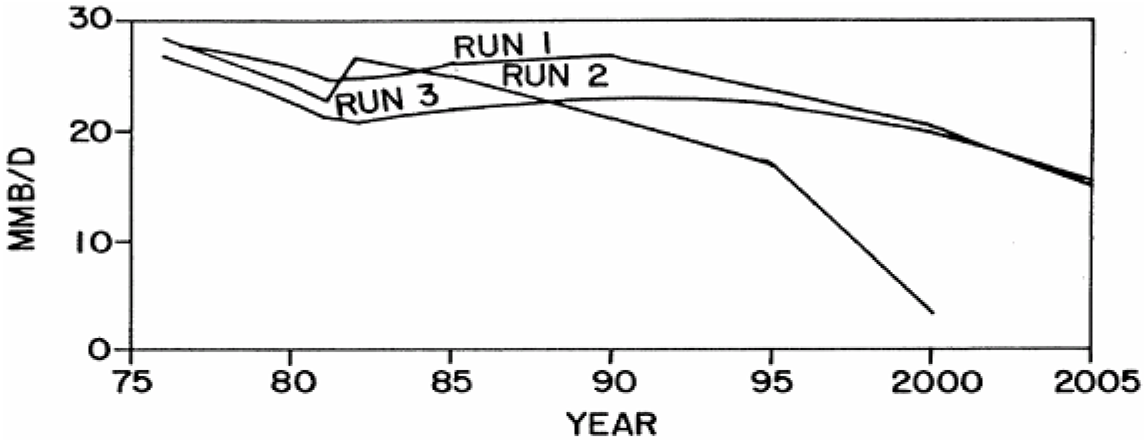

FIGURE 8 COMPARISON OF OPEC EXPORTS

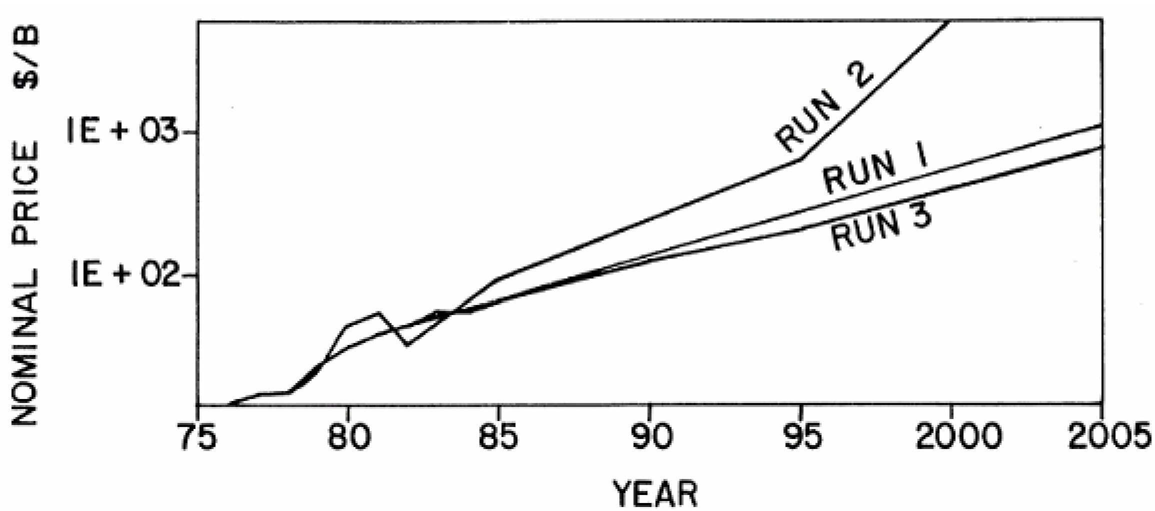

FIGURE 9 COMPARISON OF NOMINAL OPEC PRICE

Sensitivity Studies

Figures 7, 8 and 9 present an interesting comparison showing the sensitivity of OWEM's computed results to changes in a .basic assumption. Run 2FR is a fixed rate scenario; the specified rate tracks the historical values fairly closely through 1981, jumps back to about the 1979 level in 1982 and declines gradually thereafter. Run 3FP is identical to Run 1 (OPEC oil price specified vs time) except that all price elasticities were increased by 10 percent. Figure 9 shows, however, that from 1984 onward the OPEC price profile for Pun 3FP falls below that for Run 1FP. Such deviation occurs when input data values lead to a constraint that prevents the specified price profile from being realized. In this instance, the specified price suppresses demand such that the OPEC market-clearing rate is less than the allowed minimum OPEC rate, the latter being derived from the specified production policies. To resolve such an infeasibility price is allowed to fall until the minimum rate specified becomes equal to the market-clearing rate.

Let us compare Runs 1FP and 2FR. Through 1979, the (specified) production rate was the same. Hence, the small differences in computed results before 1990 for these two runs result from numerical divergences between a fixed rate and a fixed price scenario. In 1980

1. In Run 2FR, fixing OPEC production rate at 26.6 million barrels/day, the apparent historical value for that year, gave a price of $45.27/barrel.
2. In Run 1FP (with OPEC price set at $31.90/barrel) OWEM's computed rate was 23.7 million barrels/day.
3. Consideration of these numbers suggests that the price elasticities used in OWEM (at least for oil) are too small.

Similar comparison in 1981 and 1982 leads to the same conclusion. In Run 2FR

1. Dropping OPEC rate in 1991 to 25 million barrels/day resulted in a price of $54.70/barrel, whereas in actuality a price of only about $37/barrel was sufficient to cause such a reduction in rate.
2. Raising the rate in 1982 to 29.1 million barrels/day resulted in an equilibrium price of $33.30/barrel, a year to year price drop of nearly 40 percent.
3. OWEM's responses in Run 2FR as compared to Run 1FP are in the right direction, but the price/volume response is too large, indicating price elasticity is too low.

As Figure 7 shows

1. In Run 2FR after 1982 specified OPEC rate held steady at about 30 million barrels/day.
2. As was anticipated, nominal OPEC price increased at a much higher rate in Run 2FR than Run 1FP, as Figure 9 shows.
3. Scrutiny of Figure 8 reveals that in both Run 1FP and Run 3FP OPEC export rate decreased to about 15 million barrels by 2005. This is because the higher OPEC price yields a steady increase in OPEC's GDP and a more rapid increase in internal demand.
4. This effect snowballs into an avalanche in Run 2FR after 1995. As a result of the soaring price OPEC export volume plunges. In 2001 the now roaring avalanche sweeps across the terrain; OWEM quietly turns out the lights in North America, Europe and Japan; and darkness settles over the land.

Let us now consider Run 3FP, which is a direct test of the price elasticity hypothesis; all price elasticities were increased by 10 percent and the price profile was specified to follow that of Run 1FP. Figure 9 shows

1. Through 1983 the realized price profiles were identical.
2. Figures 7 and 8 show that during these early years OPEC production and export rates responded as expected -- with the specified price increases, the drop in rate in Run 3FP is higher than Run 1FP.

3 It appears that if OWEM were recalibrated with higher elasticities -- to remove the shift in 1976 (from Run 1FP to Run 3FP) -- that Run 3FP would yield a much better approximation of historical behavior than Run 1FP.

4 Given the fairly accurate projection of the trend in OPEC export volume shown in Figure 8, it is perhaps worthy of noting that OWEM projects OPEC export volume will fall by another 500,000 barrels/day in 1982.

Summary

Our purpose has been to describe the anatomy and give some insight into the behavioral characteristics of our OPEC World Energy Modeling System. OWEM treats the workings of the world's energy system in considerable depth, but is able quickly to integrate a broad set of assumptions and data into a cohesive picture of probable or possible behavior well into the future. Properly used, this capability can serve as a useful planning and learning tool.

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Dr E. L. Dougherty
Pres, Maraco, Inc.