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ENERGY RESERVES

RAYMOND G. TESSMER, JR., STEVEN C. CARHART, AND WILLIAM MARCUSE

March 1977

Prepared for the
OFFICE OF CONSERVATION PLANNING AND POLICY
UNITED STATES DEPARTMENT OF ENERGY
by the
ECONOMIC ANALYSIS DIVISION
NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS

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ABSTRACT

There is an increasing concern about scarcity of the world's remaining natural energy resources and, in particular, the future supply of oil and natural gas. This paper summarizes recent estimates of energy reserves and economic supply models for exhaustible resources.

The basic economic theory of resource exhaustion is reviewed, and recent estimates of both discovered and undiscovered energy resources are presented and compared. Domestic and world-wide reserve estimates are presented for crude oil and natural gas liquids, natural gas, coal, and uranium. Economic models projecting supply of these energy forms, given reserve estimates and other pertinent information, are discussed. Finally, a set of recent models which project world oil prices are summarized and their published results compared. The impact of energy conservation efforts on energy supply is also briefly discussed.

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I. INTRODUCTION

Production of domestic natural gas reached a peak of 22.5 trillion cubic feet in 1971, and had declined to about 20.1 trillion cubic feet in 1975. Production of domestic crude oil peaked in 1970 at 3.52 billion barrels, and it had declined to approximately 3.05 billion barrels by 1975. Because of dwindling reserves and more costly exploration and extraction, there is little chance for oil and gas production to resume their 3% and 5 1/2% respective annual growth rates of the 1960's, even with successful development of North Slope and off-shore Atlantic resources.

Concern over our scarce resources and their escalating costs has raised the question: Just how much oil and gas is still in the ground-both domestically and world-wide? Equally important is the question as to what the future price path of oil and gas will be. As fuel prices continue to rise, shale oil and synthetic fuels from coal become more attractive. Competition from these fuels will at some point in time act as a brake on the prices of conventional gaseous and liquid fuels as will the availability of other backstop energy supply technologies - those with high capital costs, but an unlimited resource base.* Future price trajec-

*The concept of a backstop technology was introduced by W. Nordhaus in Reference 34.

tories for gaseous, liquid, solid, and electric energy forms are important from the standpoint of energy conservation because they will be a major determinant of modifications and additions to energy using capital stock.

Section II presents the theory of exhaustible resources and its implications for future energy supply. In Section III we look at alternative definitions of energy reserves and summarize various U.S. resource estimates that have been made by others. In addition to estimates for oil and natural gas, estimates for coal and uranium are presented because of their impact on the future price of electricity and synthetic fuels. Reserve estimates help determine when domestic oil and gas resource exhaustion might become a problem. Important world energy parameters are presented in Section IV, including production levels, proved reserves, and ultimate resources for oil, gas, coal and uranium. Section V summarizes the methodologies which utilize reserve data to project future supply (price and quantity) of various fuel forms and which can be used to examine the sensitivity of these results to uncertain parameters, given the theoretical framework presented in Section II. The effect of resource exhaustion on patterns of extraction and production of fuel is discussed. Cost estimates and possible introduction dates for shale oil, synthetics based upon coal, and other backstop technologies are introduced. Finally, Section VI summarizes a large set of models developed subsequent to the 1973 oil embargo which are based on the theory of resource exhaustion discussed in Section II. These models project future world oil prices under a range of alternative behavioral patterns and economic conditions. At present, a distillation of their output with the user's favorite set of input parameters is probably the best estimate one can make of the price path of world oil for the next quarter century.

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II. The Theory of Resource Exhaustion

A. Theory

The theoretical foundation for projecting price paths of exhaustible resources was published by Harold Hotelling in April 1931.[18] This classic article sets forth a fundamental principle of resource economics that has been rediscovered or confirmed by all subsequent investigations: that the marginal profit (or value) of a resource in the ground increases exponentially over time at a rate equal to the rate of interest. In his Presidential Address to the American Economic Association, Robert Solow presented an excellent review of the literature of the economics of resource extraction, including Hotelling's principle.[38] Solow said,

> "A resource deposit draws its market value, ultimately, from the prospect of extraction and sale. In the meanwhile, its owner, like the owner of every capital asset, is asking: What have you done for me lately? The only way that a resource deposit in the ground and left in the ground can produce a current return for its owner is by appreciating in value. Asset markets can be in equilibrium only when all assets in a given risk class earn the same rate of return as the interest rate for that risk class. Since resource deposits have the peculiar property that they yield no dividend so long as they stay in the ground, in equilibrium the value of a resource deposit must be growing at a rate equal to the rate of interest. Since the value of a deposit is also the present value of future sales from it, after deduction of

extraction costs, resource owners must expect the net price of the ore to be increasing exponentially at a rate equal to the rate of interest.

If the mining industry is competitive, net price stands for market price minus marginal extraction cost for a ton of ore. If the industry operates under constant costs, that is just market price net of unit extraction costs, or the profit margin. If the industry is more or less monopolistic, as is frequently the case in extractive industry, it is the marginal profit--marginal revenue less marginal cost--that has to be growing, and expected to grow proportionally like the rate of interest..."

"...According to the fundamental principle [that marginal profit rises at the rate of interest], if we observe the market for an exhaustible resource near equilibrium, we should see the net price-or marginal profit-rising exponentially. That is not quite the same thing as seeing the market price to users of the resource rising exponentially. The price to consumers is the net price plus extraction costs, or the obvious analogy for monopoly. The market price can fall or stay constant while the net price is rising if extraction costs are falling through time, and if the net price or scarcity rent is not too large a proportion of the market price. That is presumably what has been happening in the market for most exhaustible resources in the past. (It is odd that there are not some econometric studies designed to find out just this. Maybe econometricians don't follow the iliction returns.) Eventually, as the extraction cost falls and the net price rises, the scarcity rent must come to dominate the movement of market price, so the market price will eventually rise, although that may take a very long time to happen. Whatever the pattern, the market price and the rate of extraction are connected by the demand curve for the resource. So, ultimately, when the market price rises, the current rate of production must fall along the demand

> curve. Sooner or later, the market price will get high enough to choke off the demand entirely. At that moment production falls to zero. If flows and stocks have been beautifully coordinated through the operations of future markets or a planning board, the last ton produced will also be the last ton in the ground. The resource will be exhausted at the instant that it has priced itself out of the market. The Age of Oil or Zinc or Whatever It Is will have come to an end. (There is a limiting ca e, of course, in which demand goes asymptotically to zero as the price rises to infinity, and the resource is exhausted only asymptotically. But it is neither believable nor important.)"

The above description applies to a competitive market. Solow goes on to point out that under oligopolistic or monopolistic market conditions the same principle applies except that the rate of exhaustion is decreased. (Monopolists and conservationists have something in common.) He further discusses the effects of substitution and backstop technologies (complete substitution above a given price) and problems that can arise in the short run based on the lags in creation of the means of producing or using the substitute or the backstop. Finally he discusses the "proper" discount rate and recognizes that the use of the private sector market rate will lead to a faster rate of extraction than the assumed lower social rate of discount.

There are major limitations to this theory of exhaustible resources, however. The main restrictive assumptions are perfect knowledge and certainty about the future, and a known, finite stock of the resource.

The major tenant of the theory - that the value of a resource deposit in the gound must be growing at a rate equal to the discount rate - can be called into question if one recognizes that there is considerable risk and uncertainty in the discovery and exploitation of additional stocks. Although the theory of resource extraction is not particularly useful in modelling future price paths, it does shed light on the determinants of resource extraction in the real world.

B. Implications

Based on this framework, with reasonable assumptions concerning reserves, technology, cartel behavior and costs, it should be possible to develop likely world price trajectories for oil. Long run supply price possibilities are shown in Figure II.1 where the price ultimately rises to the price of a substitute technology P_B at time t_n when resources recoverable at that price are exhausted.

Developing a good estimate of this trajectory depends upon a reliable estimate of the substitute price P_B and the time of resource exhaustion t_B. The parameter t_b depends upon estimates of production over time and the quantity of ultimate recoverable resource

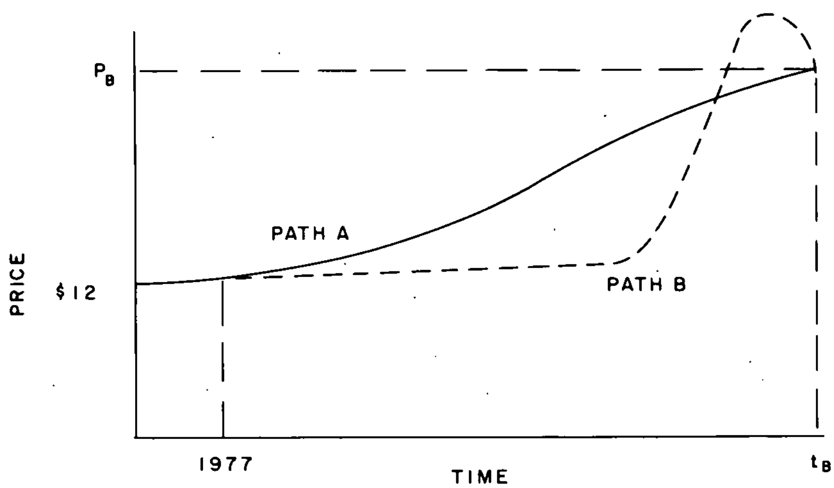

Figure II.1. Oil price trajectories.

at price P_B. Any programs which produce better information on these two parameters serve to make the projection of price paths more accurate.

It is important to note that political decisions may serve to limit access to available resources, thus bringing t_B closer. This could occur if countries with large reserves and low ability to absorb oil revenues at home - Saudi Arabia being the prime example - choose not to produce their maximum potential. This possibility has been discussed at various times by Saudi spokesmen. Even if calculations demonstrate that a greater present value could be achieved through oil production accompanied by investments abroad, the Saudi's may feel that such investments could be expropriated (just as they expropriated oil company properties) and prefer to keep their oil in the ground for safety.

In terms of changing energy utilization technologies, the critical parameter is the rate and period over which transition is made to P_B. If this change is rapid (1-3 years) compared to the time it takes to reoptimize consumption patterns (decades), severe economic disruption could result. Thus, it is very important that every effort be made to make the transition smoothly (path A) rather than succumb to policies postponing even gradual price increases which would lead ultimately to shortages, rapid price increase, and a transition more like path B.

The domestic natural gas situation is an example which might be characterized by price path B, with rapid changes and economic dislocations. If controls are maintained too long, a likely result might be a temporary (several years) period of higher than equilibrium prices resulting from the lag in bringing additional natural gas or substitute technologies on line. Insofar as some technology alternatives are precluded for environmental or safety reasons, the problem may be accentuated.

Thus, a key need for conservation planning and the implementation of new energy utilization technologies is the clarification of the key parameters t_B and P_B, followed by the development of plans to make this transition - including transition to fuels other than oil - as smooth as possible.

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III. ESTIMATES OF U.S. ENERGY RESERVES

A. Discovered Reserves

1. Oil and Gas. The traditional measure of discovered, recoverable oil and gas energy reserves has been the concept of *proved reserves*, which are

> those resources estimated to be recoverable from proved reservoirs or deposits under the economic and operating conditions existing at the time of the estimate.

The key points in this definition are the inclusion of only those discovered resources which are recoverable, and the assumption of current extraction technology and economic conditions. The data are particularly useful if one is interested in short term levels of, and geographical shifts in, production. It should be emphasized that this concept provides no basis for estimating the total amount that is in the ground. It should be noted that this definition implies that increased fuel prices or improved (lower cost) extraction technology will increase the quantity of proved reserves already discovered.

Estimates of proved oil and gas reserves are made annually by industrial trade groups. Canadian and United States data are presented in a joint publication of the American Gas Association (AGA), American Petroleum Institute (API), and Canadian Petroleum Association (CPA).* Precise definitions of reserves are listed

*See Reference 1, pp. 14-15, 102-104.

as well as historical data on production and reserves by state. A second definition of crude oil reserves is also utilized in this volume, *indicated additional reserves* which are

> those additional recoveries in known reservoirs (in excess of the proved reserves) which engineering knowledge and judgement indicate will be economically available by application of improved recovery techniques such as fluid injection (secondary recovery techniques).

Again, this concept provides no basis for estimating the total amount of crude oil that can be produced in future years. Note that the definition of *indicated additional reserves* does not include additional oil production from discovered sources based upon higher oil prices. Historical U.S. estimates for oil and gas proved reserves are presented in Table III.1.

The relationship between proved reserves and annual production* has been fairly stable over the last two decades. For crude oil the ratio of reserves (barrels) to production (barrels per year) has been within the range of 9.3 to 12.8 years. In 1975 it was 11.3 years of supply. For natural gas the ratio was in the low 20's in the latter 1950's, declining steadily thereafter to an 11.6 years' supply in 1975. To increase this ratio will require increased direction of investment funds to exploration by the natural gas industry.

*1975 production was 2.886 x 10^9 bbl. crude oil, 0.701 x 10^9 bbl. NGL, and 19.719 x 10^{12} ft^3 natural gas.

Table III.1

Proved U.S. Reserves of Oil and Gas (1945-75)

Date of Estimation (Dec. 31)	Crude Oil, 10^9 bbl	Natural Gas Liquids, 10^9 bbl	Natural Gas 10^{12} ft^3 Total	Natural Gas 10^{12} ft^3 Interstate**
1975	32.68*	6.27	228.2	106.8
1974	34.25	6.35	237.1	120.5
1973	35.30	6.45	250.0	134.3
1972	36.34	6.79	266.1	146.9
1971	38.06	7.30	278.8	161.3
1970	39.00	7.70	290.7	173.6
1969	29.63	8.14	275.1	187.6
1968	30.71	8.60	287.3	195.0
1967	31.38	8.61	292.9	198.1
1966	31.45	8.33	289.3	195.1
1965	31.35	8.02	286.5	192.1
1964	30.99	7.75	281.3	189.2
1963	30.97	7.67	276.2	188.5
1962	31.39	7.31	272.3	
1961	31.76	7.05	266.3	
1960	31.61	6.82	262.3	
1955	30.01	5.44	222.5	
1950	25.27	4.27	184.6	
1945	19.94		147.0	

*Indicated additional crude oil reserves as of 12-31-75 were 5.02 x 10^9 bbl.

**As of June 30.

Sources: "Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada and United States Productive Capacity," AGA, API, and CPA; Tables I, III, XIII-1; May 1976.

"The Gas Supplies of Interstate Natural Gas Pipeline Companies - 1975," Federal Power Commission, Table 2; January 1977.

One additional definition of reserves of natural gas is of importance. This is *dedicated reserves*.

> The volume of remaining recoverable, salable gas reserves committed to, controlled by, or possessed by the pipeline company.

These are reserves dedicated to interstate sales and under regulation of the Federal Power Commission. Estimates are presented in EPC Annual Reports,[2] and these figures are listed in the interstate natural gas column of Table III.1. The reserve/production ratio for interstate gas has declined from 20.2 years in 1963 to 9.3 years in 1974.

Actual reserves (known only to the producers) may differ from reserve quantities reported by the same producers to the trade associations due to institutional and market factors.

2. <u>Coal</u>. Estimates of U.S. coal reserves are prepared by the U.S. Geological Survey with the most recent data contained in "Coal Resources of the United States, January 1, 1974."[43] Emphasis is placed on estimating the amount of coal in the ground and not, as with oil and gas, only that portion which is recoverable. A number of definitions are used to describe remaining coal reserves.* The most important one with

*See Reference 43, pp. 105-106.

regard to discovered reserves is *remaining identified resources,*

> those resources estimated to remain in the ground based on assured coal-bed correlations, specific observations, and reasonable geologic projection.

Detailed resource estimates are compiled by state, type of coal, heating value, method of mining, and overburden. Summary information as of January 1, 1974 is presented in Table III.2.

The Department of the Interior generally assumes that 50% of this coal would be recoverable if mined; so these estimates should be halved to provide comparability with the reserve estimates presented for oil and gas. The portion of total coal resources that can be extracted economically and legally as of January 1, 1974, is estimated at 4.9×10^{18} BTU. This implies that only about 20% of current resources are recoverable at present prices and with existing technology. With 1973 production at 15×10^{15} BTU, the reserve/production ratio for coal in 1973 was approximately 327 years.*

3. Uranium. The U.S. Energy Research and Development Administration annually compiles the most complete data on U.S. uranium reserves.[45] A comprehensive national uranium resource evaluation has also been initiated by ERDA, and the most current estimates of uranium reserves are presented in their preliminary report of June 1976.[46]

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*See Reference 43, pp. 105-106

Table III.2

Remaining Identified Coal Resources, 1-1-74
(10^9 short tons)

Bituminous		747.4
Subbituminous		485.8
Lignite		478.1
Anthracite/ Semianthracite		19.7
	TOTAL	1730.9

Source: U.S. Geological Survey, Coal Resources of the United States, January 1, 1974.

Because discovered ore exists in various grades of varying thickness at differing depths, reserve estimates are further categorized in terms of their "forward" cost of production. Forward costs are defined as those operational and capital costs not yet incurred in ore production at the time an estimate is made. They do not include profit or costs already incurred.* Estimates of recoverable reserves in known deposits are listed in Table III.3. Reserve/production ratios for 1975 are also presented.

B. Undiscovered Resources

To estimate the total amount of undiscovered energy resources that might be economically recoverable is not an easy task. Discovery and extraction will be dependent upon finding rates, future prices, technological change, governmental policies, and other factors. A variety of estimates have been made for oil, gas, coal and uranium.

It is useful at this point to introduce the resource classification scheme developed by the U.S. Department of the Interior.** In it they ascribe two

*The Uranium Resource Group of the Committee on Nuclear and Alternative Energy Systems estimates the proper ratio between minimum selling price and forward cost at 1.5 to 2.0.

**This scheme has gone through a process of evolution in recent years. Early forms are presented in Reference 42, pp. 11-12, and Reference 43, pp. 3, 105-106. The one documented here is described in Reference 44, pp. 8-9.

Table III.3

Uranium Ore Reserves, 1-1-76
(thousand tons U_3O_8)

Maximum Forward Cost, 1975 $	Total Reserves	Reserve/Production Ratio, years
$10/lb	270	22
$15/lb	430	35
$30/lb	640	52

Source: U.S. Energy Research and Development Administration, National Uranium Resource Evaluation, Preliminary Report GJO-111 (76), June 1976.

primary dimensions to their resource estimates; (1) the certainty with which deposits are known to exist; and (2) their degree of economic recoverability. Estimates can be classified, at least hypothetically, within the box diagram framework of Figure III.1.

Economic resources are

> those, both identified and undiscovered, which are estimated to be economically recoverable.

Subeconomic resources are

> identified and undiscovered resources that are not presently recoverable because of technological and economic factors, but which may be recoverable in the future.

In the case of gas and oil, *measured reserves* are equivalent to the industry's *proved reserves*. For oil, *indicated reserves* are equivalent to the industry's *indicated additional reserves*. Both categories gain increments from the subeconomic demonstrated resources if resource prices rise.

1. Oil. Many estimates have been made of how much recoverable oil is still in the ground. These are characterized by widely varying estimates of different investigators. Moreover, the periodic estimates of the U.S. Geological Survey have dramatically decreased with each succeeding estimate in the 1970's. However, succeeding USGS estimates represent an increasing degree of sophistication in technique and data sources.

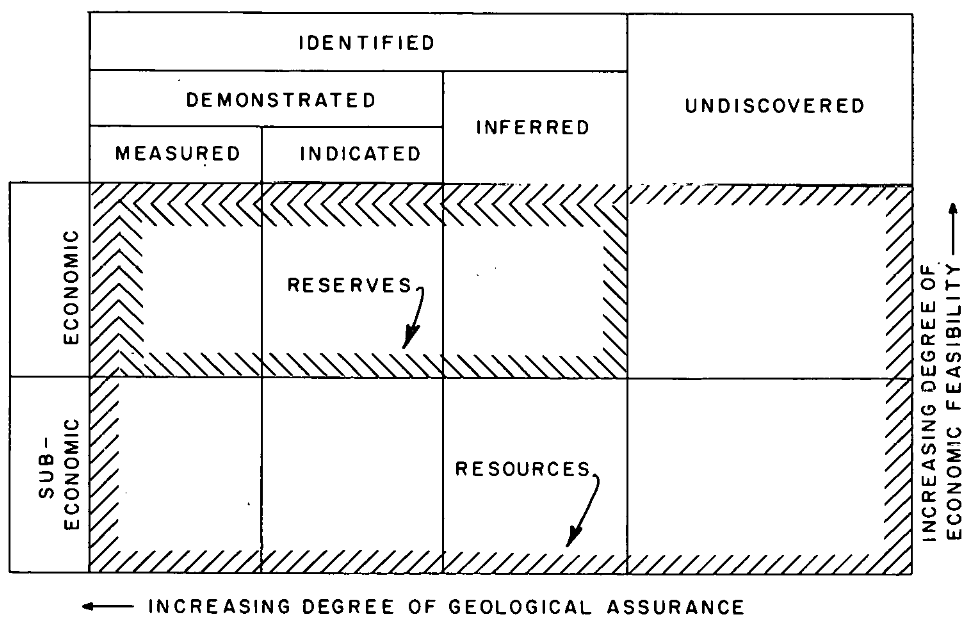


Figure III.1. Classification of mineral and fuel resources.

Estimates that have been made in the last two decades fall into three basic categories:*

1. Performance or behavioristic methods extrapolate data drawn from historical experience-discovery rates, cumultive production or productive capacity curves, and then fit past data to mathematical functions called logistic or growth curves which are projected into the future. Such techniques are not valid in frontier basins where little history exists or areas that are not a geological and economic replica of the historical model. They are most applicable to the later stages of exploration in a mature area. Examples of these models are: M.K. Hubbert's growth curve projections;[19,21] C.L. Moore's rate of discovery curves;[32] and C.R. Pelto's rate of discovery curves.[36]

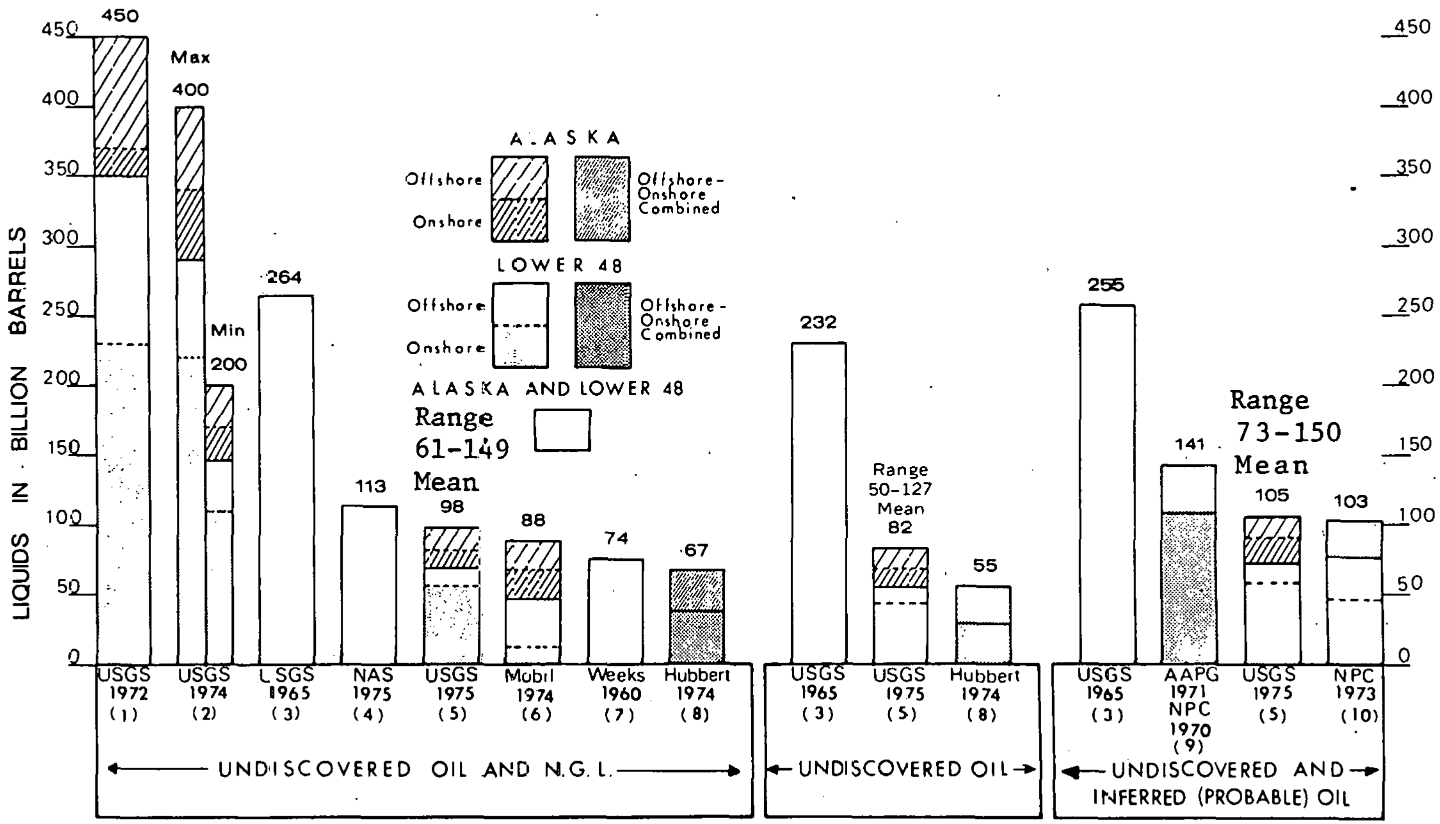
2. Volumetric yield methods have been applied in a number of ways. They range from worldwide average yields per cubic mile of sedimentary rock or per square mile of surface area applied uniformly over a sedimentary rock area to sophisticated analyses which compare geologically analagous basins. Examples of these methods are Weeks,[48] Zapp,[49] and Hendricks.[17]

3. Finally, combined methods have been employed which draw upon geological and statistical models. Large amounts of data are required as well as complicated mathematical and computer methods. This is the approach taken for the most recent Geological Survey estimates.[44]

Figure III.2 compares estimates of recoverable oil resources in the United States.** All of the estimates include at least the Continental Shelves to 200 meters water depth, and qualifications are noted

*Taken from Reference 44,p. 18.

**From Reference 44, pp. 24, 45-46.



(1) Theobald and others, U.S. Geol. Survey Circ 650, 1972. Includes water depth to 2,500 m (8,200 ft).
(2) U.S. Geol. Survey News Release, March 26, 1974. Includes water depth to 200 m (660 ft).
(3) Hendricks, U.S. Geol. Survey Circ. 522, 1965. Adjusted through 1974. Includes water depth to 200 m (660 ft).
(4) Nat'l. Academy of Sciences, "Mineral Resources and the Environment," 1975. (See National Research Council). Water depth not indicated.
(5) U.S. Geol. Survey "Mean", Oil and Gas Branch Resource Appraisal Group, 1975. Includes water depth to 200 m (660 ft).
(6) Mobil Oil Corp., Expected Value: Science, 12 July 1974. (See Gillette). Includes water depth to 1,830 m (6,000 ft).
(7) Weeks, L.G., Geotimes, July-Aug., 1960. Adjusted through 1974. Water depth not indicated.
(8) Hubbert, Senate Committee Report, 1974. Includes water depth to 200 m (660 ft).
(9) Am. Assoc. Petroleum Geologists Mem. 15, 1971. Also National Petroleum Council, "Future petroleum provinces of the United States," 1970. Some areas are excluded from this estimate. Includes water depth to 2,500 m (8,200 ft).
(10) National Petroleum Council, "U.S. Energy outlook -- oil and gas availability," 1973. Includes water depth to 2,500 m (8,200 ft).

Figure III.2. U.S. undiscovered recoverable resources of liquid hydrocarbons onshore and offshore.

in the footnotes. The discussion which follows concentrates on the overall range of the estimates. Detailed descriptions and comparisons of the estimation techniques can be found inthe references cited.

U.S.G.S. estimates have become increasingly pessimistic in the 1970's. Their 1975 high estimate (5% probability that at least this amount will be found) and low estimate (95% probability that at least this amount will be found) bracket those of other investigators. As shown by Table III.4 their estimates for recoverable (identified plus undiscovered) crude oil and NGL represent a resource/production ratio of 34 to 58 years at 1974 production levels. Their estimates for subeconomic crude oil recovery represent a further extension of resources of 44 to 66 years. The total potential resource/production ratio for liquid hydrocarbons thus ranges from 78 to 124 years, as of the end of 1974. It is important to note that the "recoverable" estimates may be conservative in that they reflect prices and costs which existed prior to 1974 and no resources at water depths greater than 200 meters. On the other hand, the subeconomic estimate may be overly optimistic in that subeconomic recovery is assumed to ultimately reach 60% of the oil-in-place, a large increase above the current national average of approximately 32%. Figure III.3 shows the 1975 USGS estimates in terms

U.S. RESOURCES OF CRUDE OIL AND
NATURAL GAS LIQUIDS, 1-1-75

(10^9 bbl.)

	IDENTIFIED			UNDISCOVERED
	DEMONSTRATED		INFERRED	
	MEASURED	INDICATED		
ECONOMIC	40.6*	4.6	23.1	61–149
SUB ECONOMIC	120 – 140			44–111

* INCLUDES PROVED RESERVES OF 6.35 x 10^9 bbl. NGL

Figure III.3. U.S. resources of crude oil and natural gas liquids, 1-1-75. (10^9 bbl.)

of their resource classification system.

2. Natural Gas. Figure III.4 shows comparative estimates of recoverable gas resources in the United States.* The lowest estimate is that of the USGS (1975), with a 95% probability that at least that amount will be found. The USGS high estimate is below that of the American Association of Petroleum Geologists (1971), the National Petroleum Council (1973), and the Potential Gas Committee (1973). Estimates of USGS are discussed below, those being the most recent and embodying the most comprehensive methodology.

At the 1974 production level, the USGS estimates for recoverable (identified plus undiscovered) natural gas represent a resource/production ratio of 36 to 51 years, as shown in Table III.4. Figures for sub-economic recovery provide a further extension of 6 to 9 years. The total potential resource/production ratio for natural gas thus ranges from 42 to 60 years, as of the end of 1974.

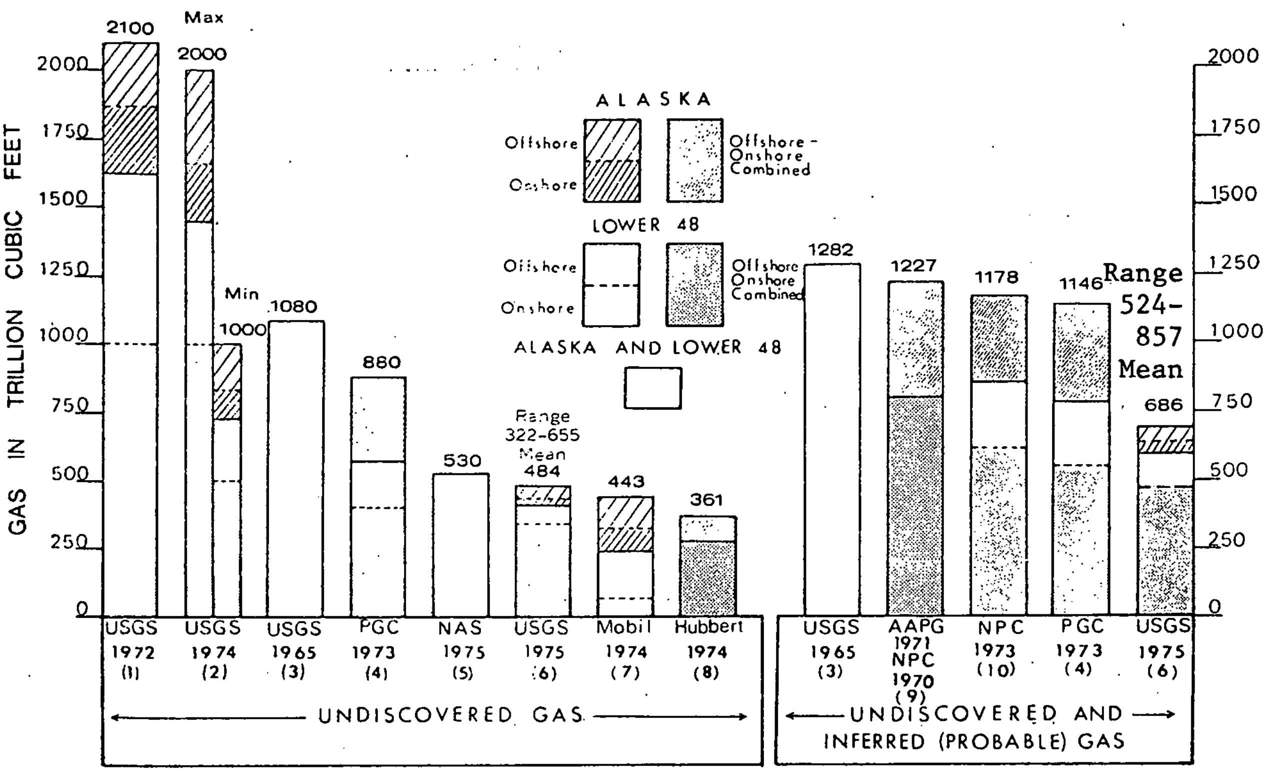
As with liquid hydrocarbons, the "recoverable" estimates may be conservative in that they reflect prices and costs which existed prior to 1974 and no resources at water depths over 200 meters. Subeconomic resource estimates for natural gas assume that recovery can be increased from the present average of 80% of

*From Reference 44, p. 47.

Table III.4

Years to Oil and Gas Exhaustion
at 1974 Levels of Production

	Oil & NGL	Gas
Economic		
Proved (Measured)	11	11
Indicated	1	10
Inferred	6	
Undiscovered	16-40	15-30
Subtotal	34-58	36-51
Subeconomic		
Identified	32-37	4-5
Undiscovered	12-29	2-4
Subtotal	44-66	6-9
TOTAL	78-124 years	42-60 years



(1) Theobald and others, U.S. Geol. Survey Circ. 650, 1972. Includes water depth to 2,500 m (8,200 ft).
(2) U.S. Geol. Survey News Release, March 26, 1974. Includes water depth to 200 m (660 ft).
(3) Hendricks, U.S. Geol. Survey Circ. 522, 1965. Adjusted through 1974. Includes water depth to 200 m (660 ft).
(4) Potential Gas Committee, "Potential supply of natural gas in the United States," 1973. Includes water depth to 460 m (1,500 ft).
(5) Nat'l. Academy of Sciences, "Mineral Resources and the Environment," 1975. (See National Research Council). Water depth not indicated.
(6) U.S. Geol. Survey "Mean", Oil and Gas Branch Resource Appraisal Group, 1975. Includes water depth to 200 m (660 ft).
(7) Mobil Oil Corp., Expected Value: Science, 12 July 1974. (See Gillette). Includes water depth to 1,830 m (6,000 ft).
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(10) National Petroleum Council, "U.S. energy outlook -- oil and gas availability," 1973. Includes water depth to 2,500 m (8,200 ft).

Figure III.4. U.S. undiscovered recoverable resources of natural gas onshore and offshore.

the gas-in-place to 90%, and this may be overly optimistic. In any case, estimates of recoverable gas at pre-1974 prices and technology give 1974 resource/production ratios that are comparable to those for liquid hydrocarbons. Figure III.5 shows the 1975 USGS estimates in terms of their resource classification system.

3. Coal. Estimates of undiscovered coal resources are shown in Table III.5.[43] These, again, represent estimates of remaining coal in seams of at least certain minimum thicknesses depending upon the type of coal. Not all of this coal can be recovered. When mining takes place, some coal is left in pillars, between augur holes, in reservations for oil and gas wells and under populated areas, interstate highways, etc. Historically, recovery has been estimated to average 50%, although it may be as great as 90% in some strip mines. In any case, it is apparent that the amount of undiscovered coal is probably as great as our known resource base, and there is no possibility of exhausting that base within the next century.

4. Uranium. Estimates of total remaining uranium resources* are listed in Table III.6. Potential resources, those that are incompletely defined or undiscovered, are further broken down into probable, possible

*From Reference 46, p. 5.

<table>
<tr><td rowspan="3"></td><td colspan="3">IDENTIFIED</td><td rowspan="3">UNDISCOVERED</td></tr>
<tr><td colspan="2">DEMONSTRATED</td><td rowspan="2">INFERRED</td></tr>
<tr><td>MEASURED</td><td>INDICATED</td></tr>
<tr><td>ECO-NOMIC</td><td>237.1</td><td>201.6</td><td></td><td>322-655</td></tr>
<tr><td>SUB ECO-NOMIC</td><td colspan="3">90-115</td><td>40-82</td></tr>
</table>

Figure III.5. U.S. resources of natural gas, 1-1-75.
(10^{12} ft^3)

Table III.5

Remaining Identified and
Undiscovered Coal Resources, 1/1/74

(10^9 short tons)

Remaining Identified Resources	1731
Hypothetical Resources	1850
Additional Resources in Deeper Basins	388
Total	3969

Table III.6

United States Uranium Resources, 1-1-76

(tons U_3O_8)

$/lb. U_3O_8 Cutoff Cost	Defined	Incompletely Defined or Undiscovered Potential Resources		
	Reserves	Probable	Possible	Speculative
$10	270,000	440,000	420,000	145,000
$15	430,000	655,000	675,000	290,000
$30	640,000	1,060,000	1,270,000	590,000
By product*	140,000			
Total:	780,000	1,060,000	1,270,000	590,000

*Estimated by-product of phosphate and copper production, 1976-2000.

and speculative categories.* If all of the potential resources plus by-product production estimated in this table were added to the current reserve base, the resource/production ratio would increase from 52 to 290 years, at the 1975 level of production. This can be misleading, given the projected growth of nuclear electric capacity, but it is probably safe to assume that U.S. uranium resources will last longer than oil and gas, although not as long as our coal resources.

*An earlier estimate of remaining uranium resources up to a cutoff cost of $100/lb. is presented by the Electric Power Research Institute in Reference 9.

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IV. ESTIMATES OF WORLD ENERGY RESERVES

A. Oil

Estimates of proved reserves are a useful point of departure for an examination of the world oil supply situation. As defined in Section III of this paper, proved reserves represent resources estimated to be recoverable from known reservoirs under technical and economic conditions prevailing at the time of the estimates. Estimates of proved reserves for major world geographical regions are summarized in Table IV.1.*

The outstanding feature of the table is the dominance of the Middle East as the respository of most of the world's oil-55.5% of proved reserves. The next most important major area is the U.S.S.R. at 12.1%. The U.S. has 5.6% of the total.

The quantity of reserves does not necessarily correspond to production. Due to the large undeveloped reserves in the Middle East, the output of that region represented only 35.9% of the world's oil *production* in

*Data on world-wide reserves and production of oil and gas are presented annually in the International Petroleum Encylopedia, Reference 24. For current, monthly production figures one can consult trade journals and a biweekly publication of the U.S. Central Intelligence Agency entitled "International Oil Developments, Statistical Summary," Reference 40. Other useful references are the "Directory of International Energy Statistics," Reference 3, and "World Energy Supplies 1950-1974," Reference 50.

Table IV.1

World "Published Proved" Oil Reserves
at End 1975

	Billion Tonnes	Share of Total	Billion Barrels
U.S.A.	5.1	5.6%	38.9
Canada	1.1	1.2%	8.2
Total North America	6.2	6.8%	47.1
Latin America	5.0	5.5%	35.4
Total Western Hemisphere	11.2	12.3%	82.5
Western Europe	3.4	3.8%	25.6
Middle East	50.1	55.5%	368.3
Africa	8.7	9.6%	65.1
U.S.S.R.	11.0	12.1%	80.4
Eastern Europe	0.4	0.5%	3.0
China	2.7	3.0%	20.0
Other Eastern Hemisphere	2.9	3.2%	21.2
Total Eastern Hemisphere	79.2	87.7%	583.6
World	90.4	100.0%	666.1
World (Excl. U.S.S.R. E. Europe & China)	76.3	84.4%	562.7

Notes

1. Proved reserves are generally taken to be the volume of oil remaining in the ground which geological and engineering information indicate with reasonable certainty to be recoverable in the future from known reservoirs under existing economic and operating conditions. Probable and possible reserves are not included.
2. The recovery factor, i.e. the relationship between proved reserves and total oil in place, varies according to local conditions and can vary in time with economic and technological changes.
3. For the U.S.A. and Canada the data include oil which it is estimated can be recovered from proved natural gas reserves.
4. The data exclude the oil content of shales and tar sands.

Source: BP Statistical Review of the World Oil Industry, 1975.

1975. The leading Middle East countries were Saudi Arabia at 12.7% and Iran with 9.9%. The two other largest producing areas were the U.S.S.R. with 17.9%, and the U.S. at 17.4%. Additional production details are presented in Table IV.2.

The high production and low reserves of the U.S.A. reflect its position as a relatively mature-perhaps even declining-oil producing area which has been in production for a long time. The Middle East, on the other hand, has yet to reach its peak production. This is probably also true of the U.S.S.R. and other oil producing regions, but in most of these areas the data on oil reserves are less reliable than for the U.S. and the Middle East.

How adequate will these reserves be for future demand? World oil consumption grew at 5.9% per year between 1965 and 1975. At this rate, half of the world's remaining proved reserves would be consumed by 1987 (assuming there were no political constraints on the availability of these resources).

Of course, no one expects that there will be no further additions to world oil reserves. Additional oil is being found in places such as the North American Arctic, the North Sea, and Mexico. The real question is-how much oil might ultimately be discovered?

Many geologists have made estimates of the world's ultimate recoverable resources of oil. A chronological

Table IV.2

World Oil Production 1975 and 1974

Country Area	Thousand Barrels Daily 1975	1974
U.S.A. --Crude Oil	8,360	8,795
--Natural Gas Liquids	1,635	1,685
Total	9,995	10,480
Canada	1,735	2,000
Total North America	11,730	12,480
Latin America		
Argentina	390	415
Brazil	170	175
Colombia	160	170
Ecuador	160	175
Mexico	795	640
Trinidad	205	180
Venezuela	2,410	3,065
Other Latin America	150	165
Total Latin America	4,440	4,985
Total Western Hemisphere	16,170	17,465
Western Europe		
Austria	40	45
France	20	20
Italy	20	20
Norway	190	35
Turkey	60	65
United Kingdom	25	‡
West Germany	115	120
Yugoslavia	80	70
Other Western Europe	70	70
Total Western Europe	620	445

Table IV.2 (Con't)

Country Area	Thousand Barrels Daily 1975	1974
Middle East		
Abu Dhabi	1,400	1,410
Dubai	255	240
Iran	5,395	6,065
Iraq	2,230	1,975
Kuwait	1,840	2,275
Neutral Zone	500	540
Oman	340	290
Qatar	435	520
Saudi Arabia	6,970	8,350
Sharjah	40	30
Other Middle East	235	190
Total Middle East	19,640	21,885
Africa		
Algeria	965	1,040
Egypt	270	230
Gabon	200	200
Libya	1,490	1,525
Nigeria	1,785	2,260
Other North Africa	100	85
Other West Africa	200	225
Total Africa	5,010	5,565
South Asia	190	180
South East Asia		
Brunei	190	200
Indonesia	1,315	1,395
Other South East Asia	90	80
Total South East Asia	1,595	1,675
Japan	10	15
Australasia	415	385
U.S.S.R.	9,740	9,075
Eastern Europe	400	395
China	1,305	1,085
Total Eastern Hemisphere	38,925	40,705
World	55,095	58,170
World (excl. U.S.S.R., E. Europe & China)	43,650	47,615

Note-Egypt (UAR) includes onshore Gulf of Suez and Sinai production.

‡=Less than 5 thousand barrels daily.

Source: BP Statistical Review of the World Oil Industry, 1975.

summary of these estimates appears in Table IV.3.* From this table we can see a convergence of recent estimates in the area of 2000 billion barrels. There is a substantial range on either side of this estimate, but this seems like a useful median estimate.

Production of world oil through 1975 was 341 billion barrels. If we assume 2000 billion barrels as the ultimate recoverable resource base, this leaves 1659 billion barrels to be produced. If we assume the continuation of 5.9% growth in oil consumption, half of ultimate resources would be consumed by 1996. At present levels of consumption half of the estimated remaining resources would be consumed by the year 2016.

Obviously this analysis is greatly oversimplified, but it serves to indicate the timescales and magnitudes associated with the world oil supply problem. Further analysis is needed to examine the effects of the following factors:

a) Ultimate recoverable reserves may be either higher or lower than the figure used here for illustrative purposes.

*The U.S. Geological Survey has estimated oil and gas world resources, Reference 41, on an order of magnitude basis, but they do not present a quantitative estimate for the world as a whole. Estimates for all potential energy sources (including conventional fuels plus thorium, oil shale, tar sands, hydraulic and other renewable resources) are gathered and presented every six years by the World Energy Conference Survey of Energy Resources. Reference 47 is their latest publication.

Table IV.3

Recent Estimates of World Ultimate Resources of Crude Oil from Conventional Sources

		10^9 BBL
1967	Ryman (ESSO)	2090
1968	Shell	1800
1968	Weeks	2200
1969	Hubbert	1350-2100
1970	Moody (Mobil)	1800
1971	Warman (BP)	1200-2000
1971	Weeks	2290
1975	Geiger and Moody	2000

Source: Geiger and Moody "Petroleum Resources: How Much Oil Where?" Technology Review, March/April, 1975.

b) Many oil producing countries which are unable to use all of the revenues from oil production may limit output, thus making these growth rates impossible even if the resource base is available to support it.

c) Price increases may greatly slow the rate of consumption growth, thus leading to a leveling of oil consumption followed by a gradual decline, rather than a sharper peak and decline.

d) Even if the ultimate resource base is there, it may not be discovered fast enough to support the rates of production implied by high growth rates, given the fact that minimum reserve/production ratios must be maintained. This consideration is bolstered by the fact that the preponderance of existing reserves are the result of very few discoveries. With no areas in sight that have the potential of the large Middle East fields, future reserve additions may have to come from many small discoveries. Consequently, even if the resources are there it may take more time to find the same volume of reserves than it has in the past.

e) Other fuels may become more attractive for a substantial set of end uses. Although this is unlikely in isolation, the possibility increases when combined with oil and gas price increases and indications that supply may be interruptible as in 1973.

Some of these considerations have been examined in detail in the recent report of the Workshop on Alternative Energy Strategies.[51] The Workshop found that the process by which ultimate resources are added to actual reserves is difficult to predict with confidence and may serve to limit oil production and consumption before the half-life of the total resource base is approached.

Historical experience shows that the greatest contribution to total reserves have come from a very small number of oil fields. Most of the thousands of fields which have been developed-while making useful contributions-have been insignificant compared to the key giant fields. This is illustrated in Table IV.4.

The implication of this finding is that continued growth in oil consumption will require continued major discoveries if the ultimate resources are to be made usable. With current world consumption at the 20 billion barrel/year mark this requires discovery of two ten billion barrel fields *per year* or the equivalent in smaller ones if we are to stay even. In the last ten years, the only fields of this size or larger which have been discovered have been on the Alaskan North Slope, in the North Sea, and in Mexico. Most of the additions to reserves in the last forty-five years have in fact come in fields which were already discovered in the Middle East. This is shown in Figure IV.1 which backdates additions to reserves to the year in which the relevant field was discovered. Additional discussion of the process of adding to reserves and accounting for them may be found in reference 51.

For purposes of analysis, WAES adopted estimates of 10 billion and 20 billion barrels per year of additions to gross reserves, the former regarded as

Table IV.4

Approximate Size of World Oil Fields

	Number of fields discovered	Estimated % of WOCA reserves
A. All fields	30,000	100
B. Fields greater than 0.5 billion bbl. recoverable reserves	240	73
C. Fields greater than 10.0 billion bbl. recoverable reserves	15	34
D. 4 largest fields: Ghawar (Saudi Arabia); Greater Burgan (Kuwait); Bolivar Coastal (Venezuela); Safaniya-Khafji (Saudi Arabia/Neutral Zone)	4	21

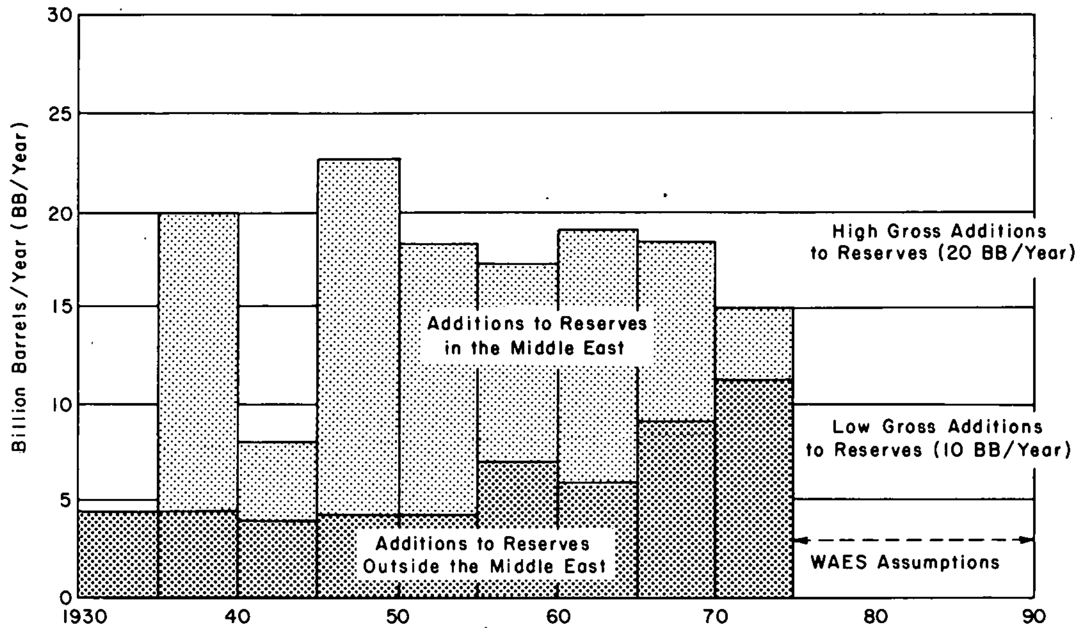

Figure IV.1. Oil discovery rate in WOCA from 1930 (five-year average obtained by backdating discoveries to year of field discovery). Source: EXXON Press Briefing, World Energy Outlook, December 7, 1975.

pessimistic and the latter as optimistic. These include additions to reserves in existing fields made possible by enhanced recovery techniques. It is significant that these additions to reserves figures probably will not be bolstered by continuing additions in the Middle East.

Another key limitation on turning resources into reserves and production is the possible imposition by Arabia Peninsula nations (Saudi Arabia, Kuwait, Qatar, and the United Arab Emirates) of production levels. This might arise because these countries cannot use increased revenues internally for development and would prefer holding oil in the ground to foreign investments; or it may arise in order to obtain political concessions. Three possible levels of Arabian Peninisula limits were considered: 13 mbd (current level); 20 mbd; and 25 mbd.

When these production potentials are combined with various demand projections (incorporating price and policy induced conservation and fuel switching effects) the supply/demand balances for oil in WOCA (world outside communist areas) emerge as shown in Figures IV.2 and IV.3.

The top line for each production curve reflects the potential production limited only by the level of additions to reserves. The lower levels reflect

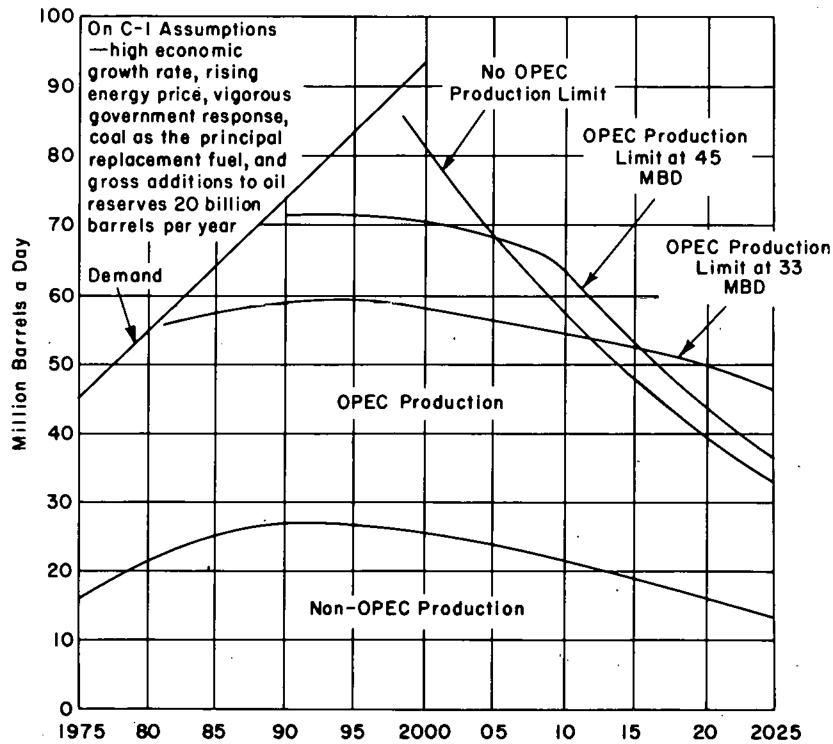

Figure IV.2. WOCA oil production for C-1.

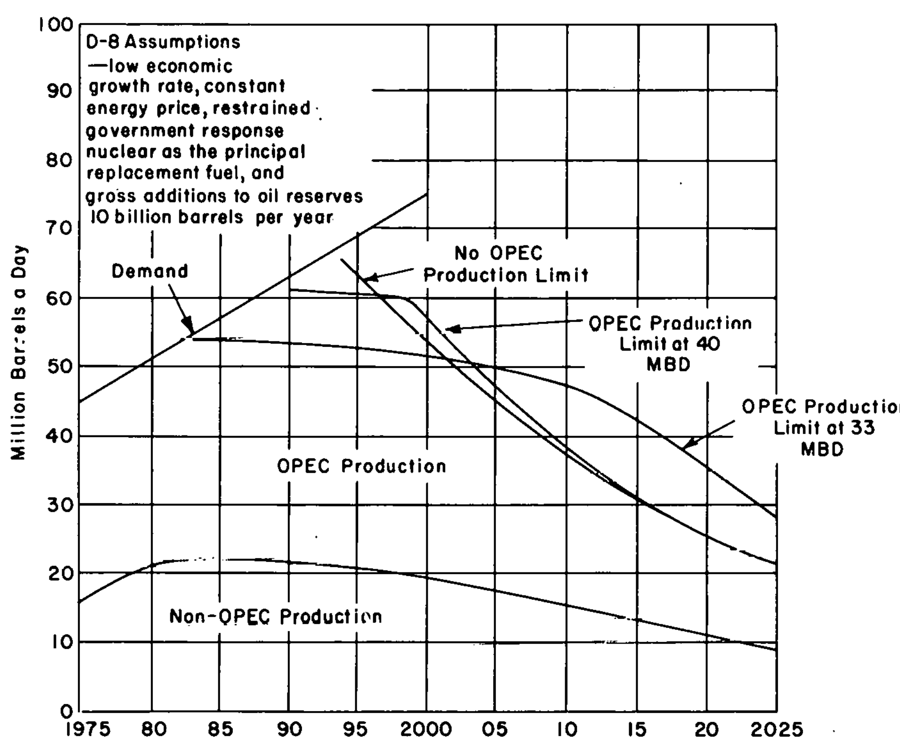

Figure IV.3. WOCA oil production for D-8.

successively lower levels of political limitations by Arabian Peninsula producers. Where demand diverges from production, the WAES case assumptions are not longer internally consistent. In real world terms, the implications of this divergence would be lower economic growth, higher oil prices, fuel switching, or some combination of these.

These projections have implications similar to those of the recently released CIA report on world oil.[52] This report places greater emphasis on the prospective emergence of the Soviet Union and China as oil importers, thus adding to imbalances on the world oil market. This report is also less optimistic than WAES concerning the potential for conservation. The character of these two views of the future of the world oil market can be seen in Table IV.5.

B. Gas

As with oil, estimates of proved reserves are a useful point of departure for analysis of the world gas situation. The analysis continues by comparing demand growth with ultimate recoverable resources.

Current remaining proved natural gas reserves are shown in Table IV.6.

In the 1965-1975 period, natural gas consumption in the world rose at an average rate of 5.5 per cent per year. At this rate of growth half of the presently

Table IV.5

1985 Oil Balance
For Non-Communist World

	MB/D CIA	WAES-C	WAES-D
WOCA Oil Demand	68.3-72.6	63	58
Non-OPEC WOCA Oil Supply	23.9-26.9	24	22
Comecon and China Net Supply	-3.5 - -4.5	0	0
Required OPEC Output	46.7-51.2	39	36
OPEC Outside Arabian Peninsula	21.0-22.4	20	20
Arabian Peninsula	25.7-28.8	13/20/25	13/20/25
Arabian Peninsula Outside Saudi Arabia	6.0-6.5	5	5
Saudi Arabian Production	19.7-22.3	14	11

Note: Numbers may not add due to rounding.

Table IV.6

Proved World Natural Gas Reserves

(10^{12} cf)

Africa	209.7
Western Hemisphere	367.8
Europe except U.S.S.R.	169.8
Middle East	595.8
U.S.S.R., Other Asia and Oceania	935.1
WORLD TOTAL	2278.2

Source: Institute of Gas Technology
<u>A Survey of U.S. and Total World Production, Proved Reserves, and Remaining Recoverable Resources of Fossil Fuels and Uranium, 1977</u>

known proved reserves would be consumed by 1992.

There is a good deal of variance in the ultimate recoverable resource figures for natural gas. One median figure is 10200 tcf, of which 850 have been produced. At the 5.5% growth rate, this means that half of the ultimate resource will be consumed by the year 2011. On the other hand, at the 1975 level of consumption half of the estimated remaining resources would be consumed by the year 2030.

The distribution of these remaining gas reserves is shown in Table IV.7. As is shown in the table, Middle East gas reserves, while substantial, are not as dominant in a world perspective as Middle East oil reserves. In fact, it seems that the U.S.S.R. and China will be substantial sources of additional gas-perhaps for export-in the years to come.

Clearly the problem with natural gas on a world scale is not the resource base in the same sense as for oil. Resources are more than adequate for anticipated demand. However, the resource is not located where it is needed - in Western Europe, the United States, and Japan. Furthermore, the necessary transportation and handling equipment - principally LNG tankers, liquefaction and gasification, and long distance pipelines - are very expensive and require long lead times for construction. Consumer resistance

Table IV.7

Estimated Remaining Recoverable
Natural Gas, Midrange

(10^{12} cf)

North and Central America	1927
South America	850
Europe except U.S.S.R.	492
Africa	999
Middle East	1744
U.S.S.R. and other Asia	2840
Oceania	500
TOTAL	9352

Source: Institute of Gas Technology
A Survey of U.S. and Total World Production, Proved Reserves, and Remaining Recoverable Resources of Fossil Fuels and Uranium, 1977.

to high LNG prices and social objections to LNG tanker docking and gas handling facilities are likely to be limiting factors on gas consumption long before resource availability is.

C. Coal

Current production of coal in the world is highly concentrated in a few areas. These include the U.S., the U.S.S.R., China, and a few key countries in Europe (especially Poland, West Germany, and Britain). Production is summarized in Table IV.8, and figures are in line with reserve and resource estimates shown in Table IV.9.

Based on the average heat content of 22.6 x 10^6 J/kg reported by the World Energy Conference, estimated proved reserves are the equivalent of 2200 billion barrels of oil. Assuming 50% recovery, the total resource base indicated for estimated coal resources is equivalent to 20,000 billion barrels-about ten times the estimated resource base of oil. Thus, coal availability is not likely to be affected by resource limitations for the forseeable future.

D. Uranium Resources

Uranium resources are very unevenly distributed around the world. Most of the world's known supply is concentrated in just four countries - the U.S., Canada,

Table IV.8
World Coal Production, All Ranks
(Kilotonne)

Nation or Area *Pays ou Region*	Anthracite *Anthracite*	Bituminous *Bitumineux*	Brown Coal and Lignite *Houille brune et Lignite*	Peat** *Tourbe*	Total *Total*	Percent of World Production *% de la production mondiale*
USSR	79,000	404,000	154,000	57,000	694,000	22.7
United States	8,830	495,300	5,800		509,930	16.7
China, P.R. of	20,000	390,000*	U		410,000	13.5
Canada		14,600	3,000		17,600	0.6
Europe						
Western	27,800	132,300	111,100	320	271,520	8.9
Southern	3,140	8,650	46,270		58,260	1.9
Northern	3,760	143,550	90	5,020	152,420	5.0
Eastern	200	187,700	447,730	50	635,680	20.6
Total	34,900	472,200	605,190	5,390	1,117,680	36.4
India		69,120	3,700		72,820	2.4
Australia		48,920	23,390		72,310	2.4
South Africa	1,680	56,840			58,520	1.9
Japan	1,040	32,940	130		34,110	1.1
North Korea	21,800	6,170*	U		27,970	0.9
South Korea	12,400				12,400	0.4
Turkey		4,180	5,820		10,000	0.3
Rest of Asia	3,000	8,150*	450		11,600	0.3
Rest of Oceania		1,920	160		2,080	0.1
Rest of Africa	430	4,970			5,400	0.2
Latin America	7	10,970			10,980	0.1
Total	183,090	2,020,280	801,640	62,390	3,067,400	100.0

*Include some lignite for P. R. of China, P. R. of Korea, Mongolia and Pakistan.
**Includes peat used for fuel only.

Source: World Energy Conference,
<u>Survey of Energy Resources</u>, 1974

Table IV.9
World Coal Reserves, All Ranks
(Megatonnes)

Country or Continent *Pays ou continent*	Reserves *Réserves* Recoverable *récupérables*	Reserves *Réserves* Total *totales*	Total Resources *Ressources totales*
USSR	136,600	273,200	5,713,600
China, P.R. of	80,000	300,000	1,000,000
Rest of Asia	17,549	40,479	108,053
United States	181,781	363,562	2,924,503
Canada	5,537	9,034	108,777
Latin America	2,803	9,201	32,928
Europe	126,775	319,807	607,521
Africa	15,628	30,291	58,844
Oceania	24,518	74,699	199,654
World Total	591,191	1,402,274	10,753,880

Source: World Energy Conference,
<u>Survey of Energy Resources,</u> 1974

Australia, and South Africa. This is dramatically shown by the figures in Table IV.10. Little is known about uranium supplies in the communist areas and prospecting has been geographically limited. For comparison, current production in the world excluding Communist countries is 21,000 tonnes (1972).

Although possible future growth rates of nuclear power are highly speculative, at an arbitary 10% per year growth, half of the reasonably assured free world resources would be consumed by 1984. Half of the total uranium resources would be used by 1996. This is probably an unduly pessimistic assessment. First, uranium exploration has been limited because of depressed uranium prices until very recently. Second, the use of Uranium in large quantities is of recent origin; hence the historical effort directed to finding it has not been of the same magnitude as effort directed to finding fossil fuels. Third, breeder reactors would stretch out these resources by more than three orders of magnitude.

Table IV.10

World Uranium Resources

Nation *Pays*	Reasonably Assured Resources up to $26/KgU (tonnes) *Ressources raisonnablement assurées jusqu'à $ 26 kg U (tonnes)*	Total Uranium Resources (tonnes) *Ressources totales en uranium (tonnes)*
United States	329 267	2 041 156
Canada	185 799	716 984
Sweden	–	308 381
South Africa	202 000	298 004
Australia	120 949	160 049
France	34 850	85 000
Niger	40 000	80 800
India	–	61 862
Colombia	–	51 000
Argentina	12 665	38 590
Gabon	20 400	30 240
Rest of Europe	21 834	73 863
Rest of World	16 710	78 023
Total	984 474	4 023 948

Source: World Energy Conference, Survey of Energy Resources, 1974

V. ENERGY SUPPLY AND PRICE PROJECTIONS

A. Projection Based on ERDA Forecast and U.S. Resource Estimates

A key question in regard to domestic energy supply is, When will the U.S. run out of its oil and gas? The answer depends, of course, upon future demand as well as upon the quantity of known and undiscovered hydrocarbons that can be economically supplied. Given a future path of demand over time, one can make rough calculations by using published estimates of remaining resources.

To illustrate this approach we will assume the base case (F-2) forecast levels of domestic oil and gas production in an internal ERDA planning document,[53] and we will ask whether or not there are sufficient resources to satisfy this projection. Table V.I shows annual and cumulative production estimates for oil and gas through the year 2000. For crude oil and natural gas liquids, cumulative production from 1975 through 2000 plus proved reserves equal to a twelve year reserve/production ratio in 2000 would equal about 162 billion barrels. This is within the USGS 1975 estimate of from 129 to 217 billion barrels recoverable at pre-embargo economic conditions. Based upon these estimates it is probable that domestic resource scarcity will add on economic rent to rising costs of production and declining U.S. oil pro-

Table V.1

Historical and Projected U.S. Production of Oil and Gas

	Crude Oil & NGL, 10^9 bbl		Natural Gas, 10^{12} ft^3	
	annual production	cumulative production	annual production	cumulative production
1975	3.59	3.59	19.7	19.7
1976	3.50*	7.09	19.3*	39.0
1977	3.52*	10.61	18.9*	57.9
1985	5.25**	46.6	22.3**	224.5
1990	4.86**	71.6	20.2**	329.7
2000	3.93**	115	17.6**	517

*Based on Independent Petroleum Association of America estimates.[23]

**ERDA-APAE internal planning estimate, from Reference 53.

duction by the year 2000. For natural gas, cumulative production plus proved reserves equal to a fifteen year reserve/production ratio in 2000 would equal about 781 trillion cubic feet. This is also within the USGS 1975 estimate of from 761 to 1093 trillion cubic feet recoverable at pre-embargo economic conditions. Again, it is probable that ultimate resource scarcity will generate an economic rent to be added to rising costs and thus impact upon production and prices by the year 2000, although under the F-2 demand assumptions and supply production estimates scarcity rents would be smaller on natural gas than on crude oil.

In view of the USGS estimates for subeconomic oil and gas resources, it is very probable that the major factor determining production in the year 2000 would be the market price of oil and gas which will presumably be that of substitute energy forms. In short, the U.S. will not run out of oil and gas, but the cost of domestic oil and gas may be very high. This conclusion is strongly backed up by Harry W. Richardson: "the real problem is one of rising costs of energy rather than of physical exhaustion of supplies,"[37] and by William Nordhaus: "The clear evidence is that the future will not be limited by sheer availability of important materials; rather, any drag on economic growth will arise from increase in costs."[35]

B. Projections from Economic Investments Models

The question of what determines the rate of resource extraction has also been analyzed by economic investment models of producer behavior. The model of Cox and Wright is a particularly useful one because it incorporates parameters that are directly related to current federal and state policies and legislation.[7] It assumes that crude petroleum producers maximize the present value of after-tax cash flow, subject to the constraints of a constant elasticity of substitution (CES) production function and an accounting identity. By explicitly modelling investment for acquisition of proved reserves the authors are able to statistically test the significance of special federal tax provisions for this industry, state market-demand prorationing, and the federal oil import quota. It is not particularly useful for simulation of future production levels, however.

The National Petroleum Council has employed economic investment models to simulate future oil and natural gas supplies.[33] Their 1973 study begins with historically based investment and operating cost functions. Factors considered include the cost of adding secondary and tertiary recovery, drilling costs, future well depths, cost escalation exclusive of inflation, and depletion of proved reserves. It is a short term supply model - up to fifteen years. Pre-embargo applications indicated large supply responses to price increases. The conclusion that can be reached from their analysis is that market prices for oil and gas will have a large impact on domestic production in the short term (ten to fifteen years).

The FEA's Project Independence projections were made in 1974.[10,12] The methodology used by both the oil and gas task forces is a modification of that used by NPC. Essentially, assumptions were made on leasing policies and schedules, drilling rates, finding rates, and percentage of gas produced from new reserves. This was done for each NPC region separately. These projections were modified in FEA's "1976 National Energy Outlook" to reflect lower FEA and USGS resource estimates, an advanced Federal leasing schedule, and other factors.[13] Price elasticities of supply from this study are shown in Table V.2. They are somewhat below the NPC estimates and range between 0.4 and 0.8.

Figures V.1 and V.2 present a variety of domestic oil and gas supply estimates. As can be seen, the future of national supply is not at all certain. Recent estimates have tended to be lower. For example, the Ford estimates are based on the then current USGS resource estimates that have since been revised sharply downward.

Table V.2

FEA Supply Elasticities for U.S. Oil and Gas*

Petroleum Liquids (business-as-usual)	1985 Production, 10^6 bpd	1985 Imported Oil Price, 1975$/bbl	% Change in Quantity	% Change in Price
	10.1	$8		
			46%	63%
	14.7	$13		
			10%	23%
	16.1	$16		

Natural Gas (reference scenario)	1985 Production, Tcf	1985 Ave. City Gate Price, 1975$/Mcf	% Change in Quantity	% Change in Price
	20.4	$1.79		
			10%	16%
	22.5	$2.07		

*Source: FEA, 1976 National Energy Outlook.

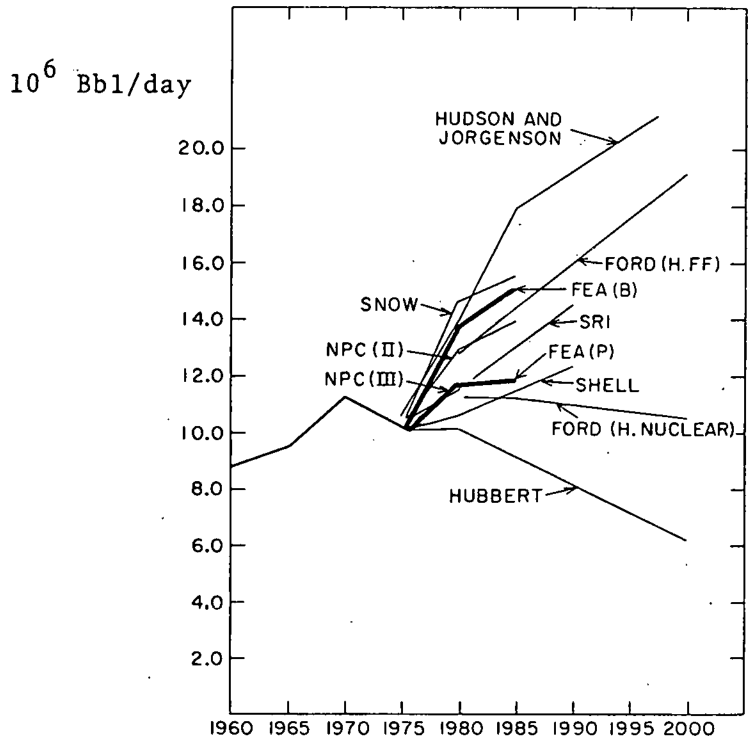

Figure V.1. Domestic oil supply projections. Source: Future Oil Supply to the Northeast United States, BNL Report 50557, p. 30.

Key:

FEA (B): Business as Usual (1976)[13]

FEA (P): Pessimistic (1976)[13]

FORD: Ford Foundation Energy Policy Project (1974)[2]

Hubbert: (1971)[20]

Hudson & Jorgenson: (1974)[22]

NPC: National Petroleum Council (1972)[23]

SHELL: Shell Oil Co. (1974)

SNOW: David G. Snow (1974)

SRI: Standard Research Institute (1972)

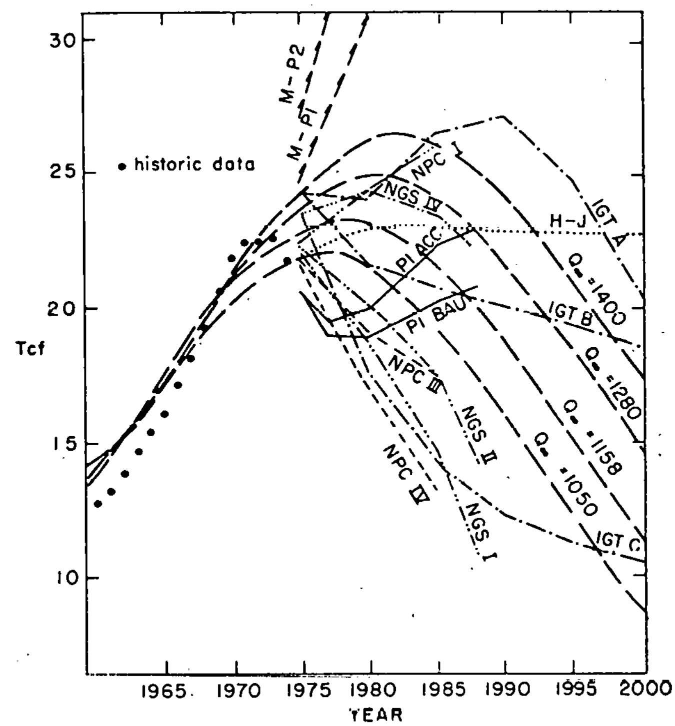

Figure V.2. Natural gas supply projections.
Source: **Future Natural Gas Supply to the Northeast**, BNL Report 50558, p. 24.

Key:

M-P1, P2	:	MacAvoy & Pindyck (1973)[31]
H-J	:	Hudson & Jorgenson (1974)[22]
PI BAU, ACC	:	Project Independence (1974)[12]
NPC I-IV	:	National Petroleum Council (1973)[33]
IGT A,B,C	:	Institute of Gas Technology (1974)[30]
NGS I-IV	:	Federal Power Commission (1972)[14]

Discussions of these supply projections are presented in References 6 and 27. Also, a comprehensive survey of energy supply models developed before 1973 is contained in a March 1973 report of Decision Sciences Corporation.[29]

C. Projections from Long Term Supply Curves

Even if price elasticities of supply are fairly elastic, they will decrease over the longer term as the domestic resource base approaches exhaustion. This is evident in the supply curves used in the Stanford Research Institute Energy Model.[39] Figure V.3 shows the long run marginal cost curves used in the model which are a function of cumulative production from July 1, 1975. Marginal costs for natural gas and crude oil eventually increase dramatically, whereas those for coal, shale oil and nuclear fuel do not. Although these supply functions are very useful in parametric model studies, they must be used with care in forecasting the future price paths of oil and gas because of the many assumptions that are embedded in them. These assumptions include:

- Constant 1975 technology,
- Constant relative prices for the factors of production,
- Exclusion of lease bonus payments and other economic rent,
- A given set of public regulations and policies.

Given the present state-of-the-art in modelling and forecasting, it is desirable to make a *range* of long term

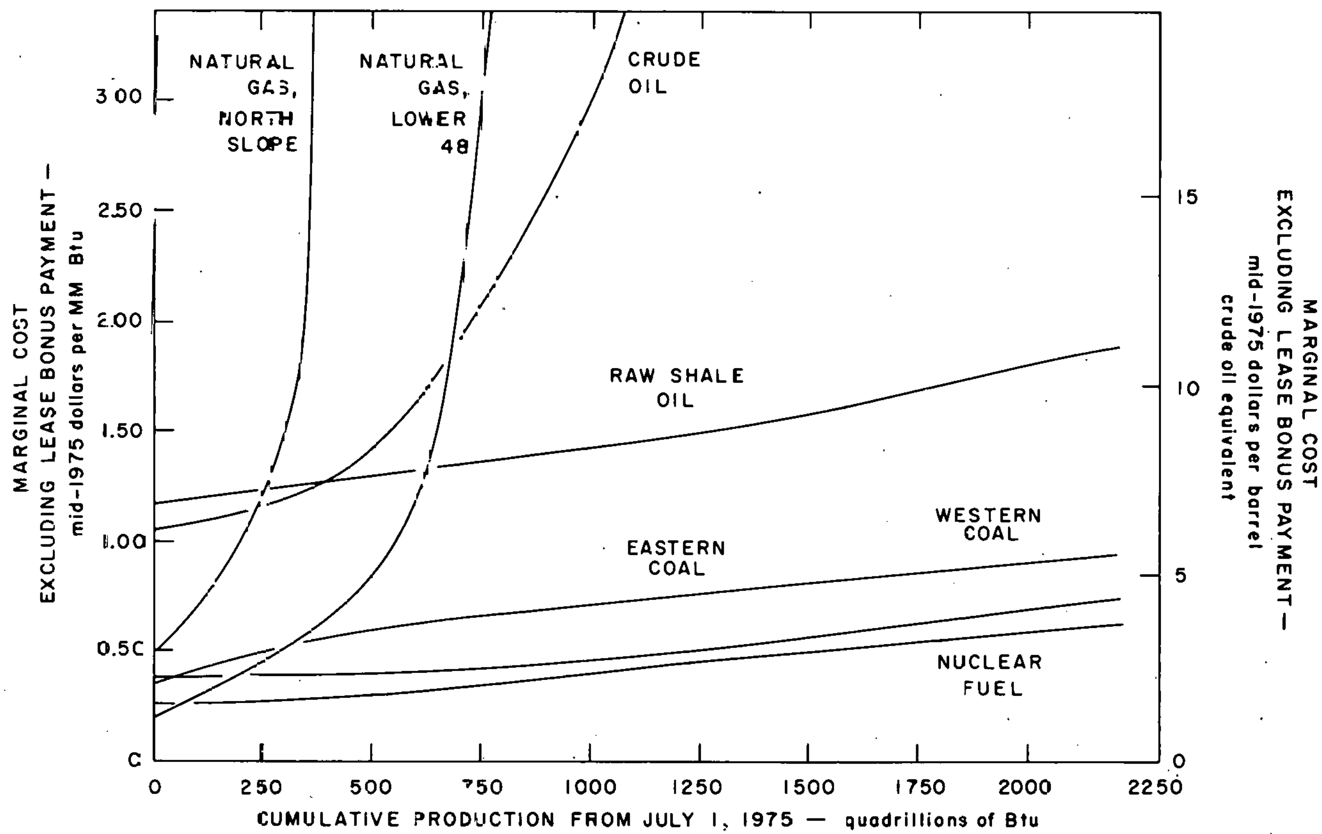

Figure V.3. Resource marginal cost curves. Source: Stanford Research Institute, A Western Regional Energy Development Study: Economics, Volume II-SRI Energy Model Data Base, November 1976.

supply projections based upon sets of alternative assumptions. The uncertainty about the future level of many important parameters is too large to permit estimation of single supply functions. Projection techniques should include estimates of the future costs of discovery and extraction, the ultimate resource base, market clearing prices and other relevant policy parameters such as federal leasing policy and regulations.

D. Projections for Synthetic Fuels

In addition to supply projections for domestic oil and gas, information about substitute energy forms becomes important. When and at what cost will production of synthetic liquid and gaseous fuels be commercially feasible? This question is important even if foreign oil and gas is available to the U.S. well into the 21st Century because the availability of synthetic technology can provide an upper bound on the actual market prices of crude oil and natural gas.

ERDA expects successful development and construction of commercial size synthetic plants (gas and liquids from coal, liquids from shale) before the year 2000. This is within the time framework over which our domestic oil and gas resources are expected to last; so attention will be focused on the expected cost of synthetic fuels, assuming successful development of the technology.

SRI cost estimates are shown in Figure V.4 along with the coal cost upon which they are based.[39] They include only production costs, omitting marketing and distribution expenses. Syncrude from coal estimates are 6.7 to 8.4 times the cost of coal on a BTU basis. High BTU gas from coal estimates range from 9.8 times the cost of coal with the Lurgi process down to 5.6 times the cost of coal with advanced technology. These costs bracket those for syncrude from coal, and all are estimated to be less than the cost of producing syncrude from shale - 11.3 times the cost of coal on a BTU basis.

The set of ERDA cost estimates[53] for the year 1985 are shown in Figure V.5. The projected costs of high BTU gas (5.6 times the cost of coal) and syncrude from shale are much lower. Furthermore, the ERDA estimate includes the cost of refining whereas the SRI estimate does not.

All of these estimates are very uncertain because commercial technology has not yet been proven. A more comprehensive analysis of projected changes in the relative prices of all fuel forms will be the subject of a future issue paper.

Synthetic fuel and oil shale are characterized by considerable environmental and socioeconomic effects.

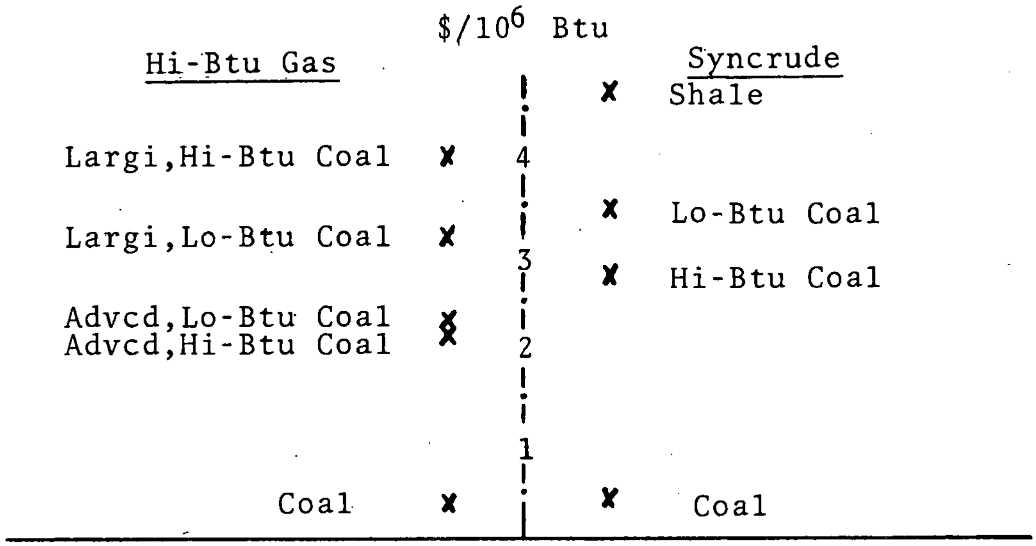

Figure V.4. SRI synthetic fuel costs in the 1980's (1975 $).

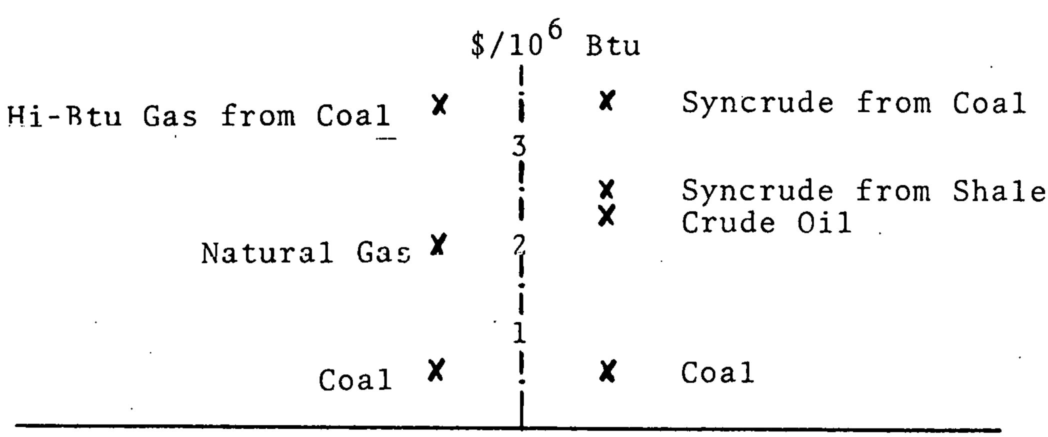

Figure V.5. ERDA synthetic fuel costs in 1985 (1975 $).

For this reason they may be limited to a role of partial substitution. Like the direct use of coal, they contribute to the CO_2 problem which will loom larger until a definitive answer is found. Finally, synfuel and oil shale advocates have a long history of cost underestimation. These considerations must be incorporated in an analysis of the mutual level of backstop costs for these fuels. The potential price of synthetic fuels and the role they may play as fuel substitutes is crucial to conservation planning. A continuing effort should be directed to obtaining information on likely costs of synfuels and other new technology candidates.

E. Effects of Energy Conservation on Supply Projections

National policy is currently shifting toward a greater emphasis on energy conservation. Given the response that has occurred since the oil embargo and the large remaining potential for reducing energy consumption, this will lead to substantial decreases in growth rates for oil and gas demand from historic levels. The greater the impact of conservation, the longer our domestic resources will last and, probably, the lower their future price paths.

If final consumers of energy choose their stock of energy using capital equipment on the basis of future as well as current energy prices, estimates of the future price paths of oil and gas are crucial for capital stock decisions - decisions which will determine future energy consumption over an extended period of time. Greater success in achieving energy conservation will reduce the rate of price increase faced by these decision makers. The extent to which price expectations play a role in today's capital stock decisions is an important one which deserves more attention.

Another important conservation action that will extend our domestic resource base will be successful technology for using renewable resources, such as solar direct heating and cooling. Although there is widespread expectation that oil and gas prices will continue to increase over the foreseeable future, it is important to note that there are certain factors within an energy conservation framework which will work against or at least limit such increases.

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VI. MODELS PROJECTING WORLD OIL PRICES

A. The Role of Models

Many models of resource extraction are in existence. Some of these are models of the quantity of resource discovered as a function of previous discoveries and search costs; others treat resource extraction as a function of previous resource findings and extraction cost; and still others treat resource extraction in response to energy price.

Another class of models has attempted to examine the future price of resources given various supply and demand assumptions. A subset of such models have been directed to examining the effect of the OPEC oil cartel on world oil prices. These are discussed below. These supply and demand models can be classified as static or dynamic and as simulation or optimization. All of them are long run equilibrium and all but one assume that there is a producers' cartel. All of the models address one or more of the following issues:

1. How rational are the OPEC price policies and can the prices be maintained?
2. Is OPEC inherently stable and how do various pricing rules affect stability?
3. Can the future course of world oil prices be projected with any confidence?

B. General Conclusions of the Models

A brief statement of the general price conclusions of each model is stated below. The prices used in most of these models are those of late 1973 and 1974. Thus, $7.00 or $9.00 per barrel of oil is about the same in real terms as $13.00 per barrel currently. Most models indicate that over a wide range of conditions the optimal or preferred strategy for OPEC pricing is to maintain or slightly decrease real prices for the next fifteen or twenty years. Most assume fairly low backstop technology costs (50% higher than current prices). Higher backstop technology costs would change the conclusions and suggest constant or rising prices.

Static Models. The Kennedy model[26] shows that OPEC revenue is maximized at prices between $3.50 and $7.00 per bbl (1973 prices) with low supply elasticity and unitary elasticity of demand. With higher non-OPEC supply and/or demand elasticities, OPEC's maximum net revenue is lower at higher oil prices.

The Levy model[28] assumes Saudi Arabia, Kuwait, and Abu Dhabi act as residual suppliers. The conclusion is that if demand growth is below historical levels, highest returns to residual suppliers come at prices below current levels. At historical rates of demand growth, highest returns would come from current price levels.

The FEA model (PIES)[11] has two versions:

1. One version assumes all OPEC members restrict output proportionately. This results in a tremendous surplus capacity if price is to be held at $9 per bbl (1973 prices).
2. A second version allows six members to be revenue maximizers while the remaining countries would be residual suppliers. The surplus capacity of the residual suppliers must be 52% to maintain $9.00 per bbl oil.

Dynamic Models. Prices in dynamic models always climb to the level of the backstop technology. This usually happens between 2000 and 2025. The price movements discussed below for each model hold over the next couple of decades. For most of the models, the near term (20 year) price response assumes the existence of backstop technologies at costs about 50% higher than cartel prices. One might interpret the models as saying that stable cartel price solutions will occur at prices somewhat below backstop technologies and that the less OPEC acts monolithically, the higher the demand elasticity, and the higher the non-OPEC supply elasticity, the lower will be the price at which the cartel can maintain stability. Not surprisingly, one might make the above statements on the basis of logic without recourse to models; but it is comforting that the models support these conclusions over a wide range of policy options and parametric variations.

The Blitzer *et al.* model[4] has two versions. In one version, assuming a monolithic OPEC, the authors present a small number from "thousands" of parametric runs. These runs as well as the results from the second version which treats Saudi Arabia, Kuwait, and Abu Dhabi as residual suppliers indicate that the strategy yielding greatest stability and returns to the residual suppliers is output maximization at constant or declining prices.

The Kalymon model[25] also has two versions, each of which has sub-versions. The first of these is an optimization version for a monolithic OPEC and three alternative sets of residual suppliers. In all runs the optimal solution calls for an immediate price decrease followed by a slow continous price increase to the backstop price. In all cases prices would drop from $10 to $7-8.50 and then slowly rise to the backstop price of $15 between 2027 (monolithic OPEC) and 2053 (Saudi Arabia/Kuwait/ Abu Dhabi/Neutral Zone). In the second version - a simulation at initial prices of $7.00, $8.50 and $10,00, with a monolithic OPEC - Saudi Arabia would be indifferent but Iran and the other members would prefer $10. Therefore, $10 would probably hold. With Saudi Arabia or Saudi Arabia/Iran as residual producers, the stable price level would probably be at $8.50 although $7.00 would also maximize revenue.

Gately and Kyle[16] have produced a model that incorporates price expectations in the actions of oil suppliers. The model assumes a monolithic OPEC and has two versions:

1. a dynamic simulation model of specified price policies and pricing strategies and;
2. an optimization model that considers all price paths and selects an optimum for given criteria.

The authors conclude that

> "one rule of thumb pricing strategy that is likely to serve OPEC very well for the for-seeable future, both in terms of yielding high profits and avoiding the dangers of greatly underutilized capacity, is a strategy that is relatively cautious about further price increases."
>
> and
>
> "certain other, more aggressive pricing strategies, will also yield good results for OPEC."

A model by Cremer and Weitzman[8] models profit maximization for a monopolist (Arab Persion Gulf and North African States) faced with supply responses to price for non-OPEC suppliers and world demand response to price. There is no backstop technology. Increasing costs as a function of cumulative extraction according to the Hubbert and Nordhaus analysis are assumed. The authors conclude:

> "...that the recent increase in the price of oil was a once and for all phenomena due to the formation of the cartel and that prices should remain approximately constant during the next twenty years."

After that period, however, prices rise rapdily due to depletion of resources.

The Nordhaus model[34] assumes a competitive world and examines the future of all fuels including synthetic (hydrogen) backstops. His results support the Hotelling-Solow theory of price trajectories for exhaustible resources. An interesting conclusion from the Nordhaus model is that the U.S. will be a major coal exporter after the middle of the next century.

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