APPENDIX C
Energy Projections

Introduction

The future availability and price of natural resources are crucial variables in long-range projections of world economic development. Energy supply and demand in particular affect not only industrial production but also agriculture, transportation, and general living conditions. As a result, the findings and conclusions of these five global modeling studies are significantly influenced by their treatment of the global energy system and their assumptions about future energy trends. Some of the models do not address energy specifically, or in detail, and others merely assume that energy will not be a constraint within their restricted time horizons.

In general, those models that include a finite resource stock tend to show that depletion will raise prices, slow production, and dampen global economic growth; in short, resource constraints make them susceptible to economic collapse. Even the most optimistic findings, however, suggest that the world faces a difficult transition away from dependence on oil. Coal, nuclear, and solar power are offered as the principal alternatives for the future energy system. The accuracy and reliability of these projections are also influenced by their assumptions about population and economic growth, potential technological progress in extraction and conservation, the potential for substitution and alternative sources, and the future political and economic behavior of both producers and consumers.

Purposes, Structures, and Findings

World 3

Although The *Limits to Growth* is sometimes said to have "predicted" the energy crisis of the 1970's, the World 3 model itself does not specifically address future trends in energy supply and demand. The purpose of the model is to describe the world as a general system rather than to predict its parts in detail, so energy resources—petroleum, natural gas, and coal—are lumped together with 16 other raw materials (primarily metals) in a single category called "nonrenewable resources." The authors cite U.S. Government estimates showing total reserves of individual resources ranging from 7 to 5,100 years, but they assume that,on average, there are about 250 years worth of nonrenewable resources at 1970 consumption levels. They also assume, however, that the quantity of resources consumed per capita is a fixed function of average income per capita, and that continued population and economic growth will lead to a 4-percent growth rate in total world resource consumption. Consequently, this 250-year reserve would be completely used up by about 2040 if growth continues unabated. In addition, the model assumes that the cost of obtaining resources will rise dramatically once 50 percent of the reserves have been depleted, due to declining resource quality and increasing transportation costs.

The standard run of World 3 demonstrates the consequences of this combination of assumptions for the behavior of the nonrenewable resource sector and for the entire world system (fig. C-1). Rising population, combined with rising industrial production per capita, results in the rapid depletion of resources and an equally rapid increase in the costs of obtaining the resources. As more and more capital is diverted from agricultural and industrial production to the obtaining of raw materials, per capita food and industrial output alike begin to decline. This leads eventually to mass starvation and the collapse of the world economic system,

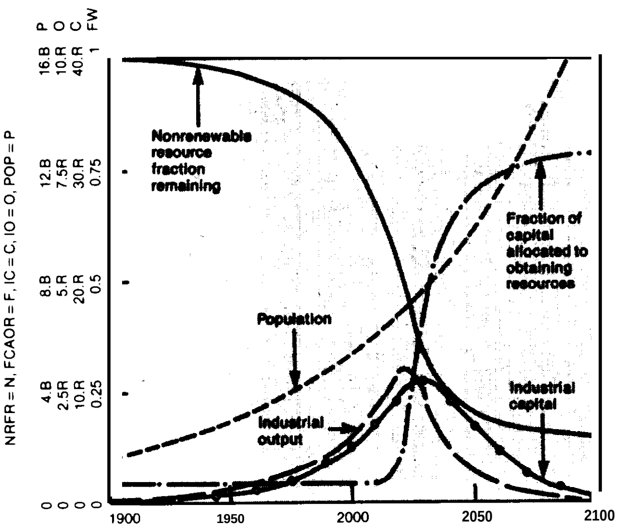
Sensitivity tests conducted by the authors of World 3 indicate that the general behavior of the nonrenewable resource sector and of the integrated world system are not particularly sensitive to their assumptions about resource reserves, consumption rates, or extraction costs.

- If reserves are set at twice their initial value, the collapse is delayed by only 15 years (fig. C-2).
- A tenfold increase in initial reserves will eliminate resources as a constraint to growth—at least before 2 100—but the general behavior of the world system remains unchanged. In this case, persistent pollution causes a decline in production followed by starvation and a decline in population (fig. C-3).
- Improved extraction technologies, by reducing the short-term cost of obtaining virgin materials, would eliminate the economic incentives for conservation and substitution. These technologies could delay the collapse a few years, but they would cause a faster depletion of resources and a sharper eventual decline in industrial output (fig. C-4).
- Improved conservation technologies, sufficient to reduce per capita consumption by a factor of four, allow much higher industrial output and postpones its decline for about 40 years, but they cannot prevent eventual collapse (fig. C-5).

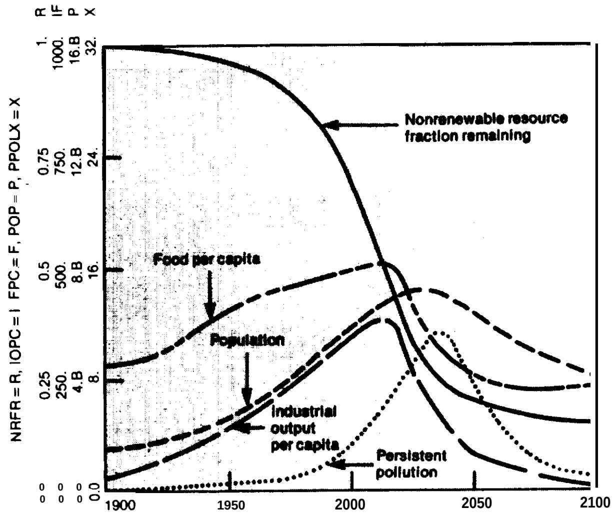
The only model run that succeeds in postponing the collapse beyond 2100 is based on the combination of

[1]The following material is based in part on the draft working paper, "The Role of Energy in the Global System)" by Paul Werbos, Office of Energy Information Validation, Energy Information Administration, U.S. Department of Energy.

Figure C-1.—Impact of Resource Depletion on the Nonrenewable Resource Sector and Integrated Model, World 3 Standard Run



Run 5-1: standard run for the nonrenewable resource sector.

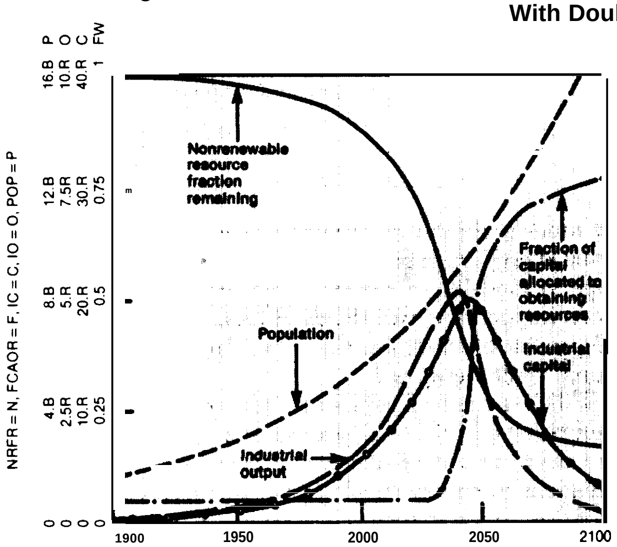


Run 7-6A: World 3 reference run.

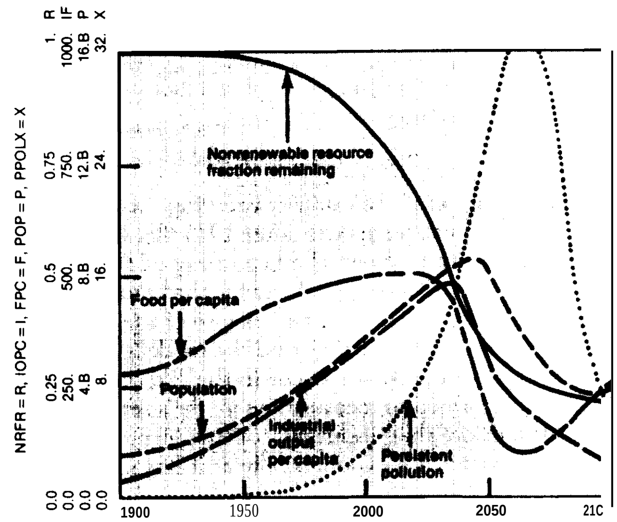
This is the World 3 reference run, to be compared with the sensitivity and policy tests that follow. Both population POP and industrial output per capita IOPC grow beyond sustainable levels and subsequently decline. The cause of their decline is traceable to the depletion of nonrenewable resources.

SOURCE: *Dynamics of Growth in a Finite World.*

Figure C-2.— Behavior of the Nonrenewable Resource Sector and Integrated World 3 Model With Doubled Reserves



Run 5-2: behavior of the sector with double the initial value of nonrenewable resources.

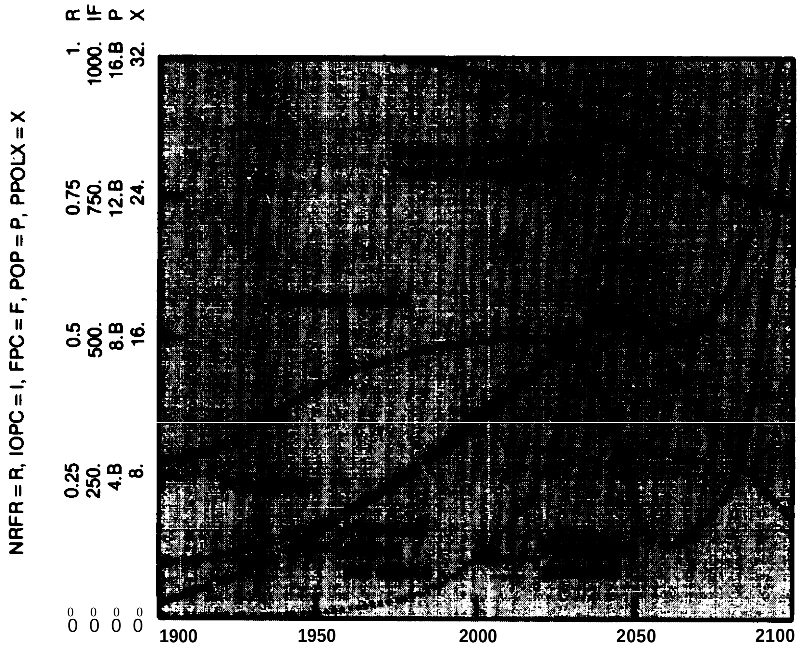


Run 7-7: sensitivity of the initial value of nonrenewable resources to a doubling of NRI.

To test the sensitivity of the reference run to an error in the estimate of initial nonrenewable resources, NRI is doubled. As a result, industrialization continues for an additional 15 years until growth is again halted by the effects of resource depletion.

SOURCE: *Dynamics of Growth in a Finite World.*

Figure C-3.—Behavior of the World 3 Model When Initial Resource Reserves Are increased Tenfold



Run 7-8: sensitivity of the initial value of nonrenewable resources to a tenfold increase in NRI.

The initial value of nonrenewable resources NRI is increased by a factor of 10, to a value well outside its most likely range. Under this optimistic assumption, the effects of nonrenewable resource depletion are no longer a constraint to growth. Note that there is no dynamic difference in this run between setting resources at 10 times their reference value or assuming an infinite value of resources. However, population and capital continue to grow until constrained by the rising level of pollution.

SOURCE: *Dynamics of Growth in* a *Finite World.*

cost-reducing and resource-conserving technologies with zero population growth after 1975 (fig. C-6). Even this run, however, shows the beginning of the characteristic rise in the amount of capital that must be allocated to obtain resources—the collapse of the economic system, although delayed beyond the model's time horizon, will undoubtedly still occur in the 22d century. No test was performed to measure the model's sensitivity to the assumption that industrial output per capita will continue to increase exponentially as it has in the past.

World Integrated Model (WIM)

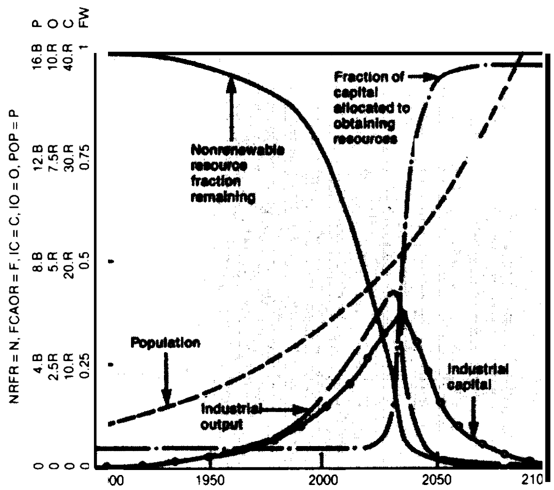
WIM is both more detailed and more flexible in its treatment of energy resources than World 3, and it has been used extensively for testing alternative energy futures. WIM specifically represents both the supply and the demand for five different energy sources—oil, gas, coal, hydroelectric, and nuclear—within each of its 10 or more geographical regions.[2] The model also represents energy trade between regions, a significant advantage in modeling a world system where some 110 nations import over two-thirds of their energy needs and 90 percent of all oil supplies move through the international trade network.[3]

WIM's structural equations reflect the assumption that rising oil prices will lead to both conservation and the development of alternative sources of energy. Investment in energy development is partially controlled by price, which in turn is determined by supply and demand. The model also assumes that oil will cover a declining portion of total world energy demand after

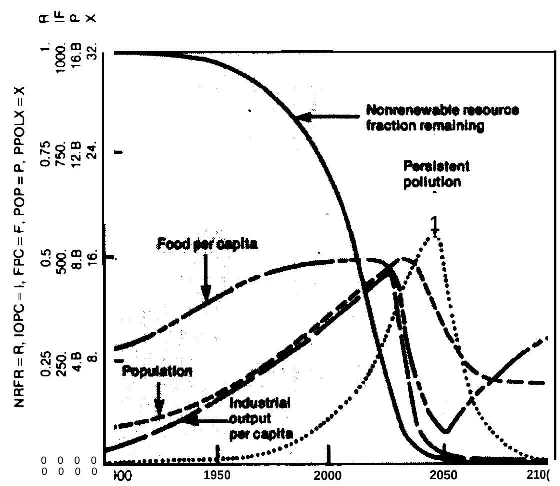
[2] The fifth category, "nuclear energy," also includes solar energy and other capital-intensive alternatives. Source: Command and Control Technical Center (CCTC), Wodd Integrated *Model Multilevel Hierarchical* Theoretic Concepts, CCTC Technical Memorandum TM 197-79 (Washington, D. C.: U.S. Defense Communications Agency, June 15, 1979), pp. 2-17.

[3] M. D. Mesarovic and E. Pestel, Mankind at *the Turning Point* (New York: Dutton, 1974), p. 180.

Figure C-4.– Impact of Cost-Reducing Extraction Technologies on the Nonrenewable Resource Sector and Integrated World 3-Model



Run 5-3: the **effects of cost. reducing technologies on the behavior of the nonrenewable resource sector**

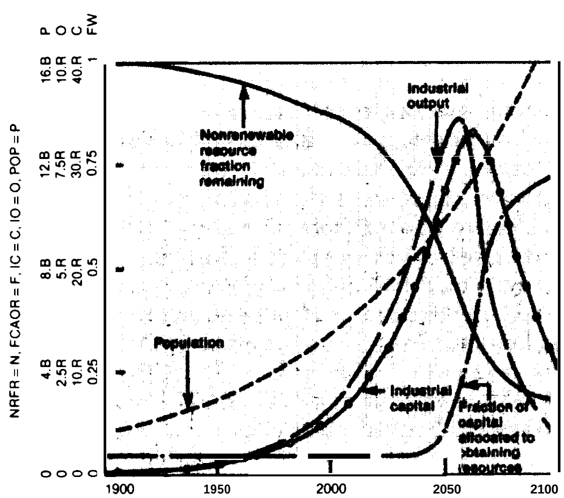


Run 7-12: improved resource exploration and extraction technologies.

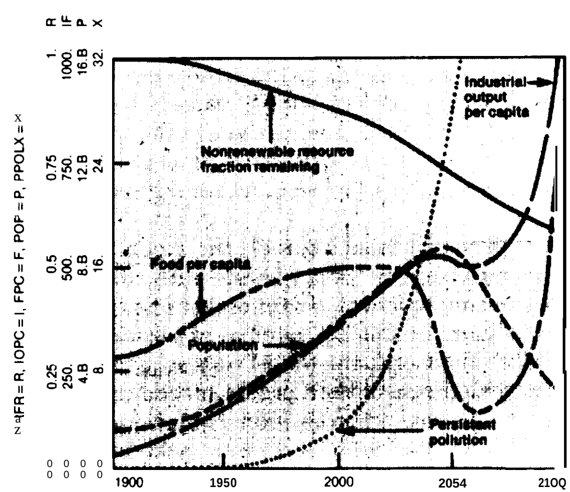
The implementation of improved resource exploration and extraction technologies in 1975 is modeled by lowering the capital cost of obtaining resources for Industrial production. This policy allows industrial production to continue growing for a few more years than in the reference run, but it is ineffective in avoiding the effects of resource depletion.

SOURCE: *Dynamics of Growth in a Finite World.*

Figure C-5.–impact of Resource. Conserving Technologies on the Nonrenewable Resource Sector and Integrated World 3 Model



Run 5-4: the effects of resource-conserving technologies on the behavior of the nonrenewable resource sector.

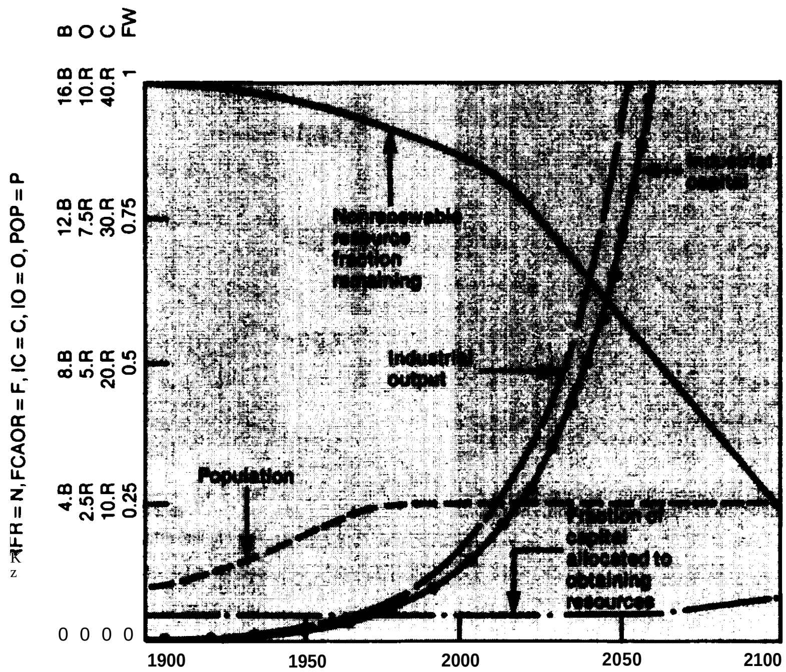


Run 7-13: recycling technologies.

The advances in resource exploration and extraction technologies of Run 7-12 are supplemented by an improvement in recycling technologies that reduces per **capita resource usage by a factor of eight in 1975. That policy removes the constraining effects of resource depletion and allows population and capital growth to continue until checked by persistent pollution**

SOURCE: *Dynamics of Growth in a Finite World.*

Figure C-6.—Combined Impacts of Zero Population Growth, Resource Conservation, and Improved Extraction Technologies on the Behavior of the World 3 Nonrenewable Resource Sector



Run 5-5: the effects of zero population growth and advanced technological policies on the behavior of the nonrenewable resource sector.

SOURCE: Dynamics of *Growth in a Finitefe World.*

1990, and that substitution between energy sources will be based largely on cross-price elasticities, Consequently, although oil and oil substitutes are the most binding resources in WIM, energy supply appears to be constrained less by absolute scarcity than by the speed with which substitutes can be developed—energy is an economic and engineering problem, rather than a physical one.[4]

For use as a policymaking tool, the model provides "scenario variables" or "policy levers" with which users can test the consequences of nonmarket pricing behavior by producers or shifting patterns of substitution by consumers.[5] In general, the model runs suggest that cooperation would benefit both producers and consumers and would also ease the transition away from oil, and that continued long-term economic growth may be possible under either of two alternatives: the rapid and widespread deployment of breeder reactors; or the construction of vast "solar farms" and hydrogen plants in the deserts of the Middle East.

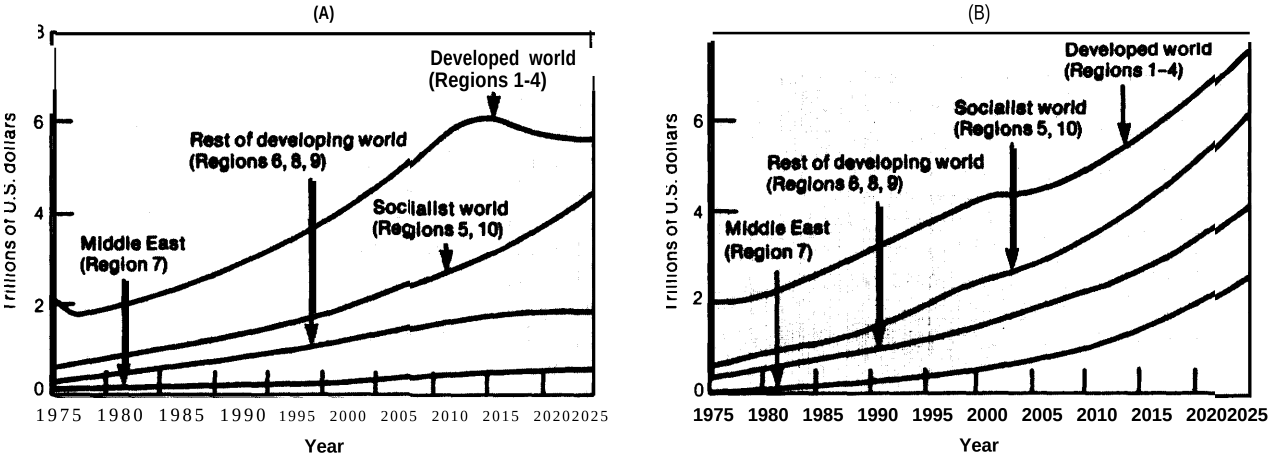
The world oil crisis is a major focus of the many scenarios reported in Mankind at the Turning Point. In the first pair of computer runs, the model was used to demonstrate the long-term economic benefits of an "optimal" oil pricing policy (fig. C-7). Continuation of low oil prices would encourage overexploitation and rapid depletion, discourage the development of substitutes, and lead to major dislocations in the developed regions when reserves are exhausted. Both exporters and importers would fare better under an "optimal price scenario, " in which the real price of oil rises 3 percent annually until it reaches an optimal level (about 50 percent above the initial price of $13.50/barrel, as determined in a separate analysis), at which level it stabilizes thereafter. Optimal oil pricing is assumed in a second set of computer runs that indicates that both exporters and the developed regions benefit under scenarios in which the flow of oil from the Middle East is unimpeded and international energy trade is "governed solely by the economic forces without undue interference from the political level" (fig. C-8).[6] All of these runs, however, project a transient world oil deficit between

[4] P. VanderWerf, "Energy, " in The *Global* 2000 Report to the *President* (Washington, D. C.: Council on Environmental Quality and Department of State, 1980), vol. 2, p. 618.

[5] CCTC, op. cit., pp. 2-17.

[6] Mesarovic and Pestel, op. cit., p. 112.

Figure C-7.—Comparison of Long-Term World Development for World integrated Model "Fixed Low Oil Price" Scenario and World integrated Model "Optimal Oil Price" Scenario



Cheap energy in the form of oil has been a prime fuel for the unprecedented growth of the world economy in the 1950's and 1960's. The dramatic increase in oil prices in **1973 was viewed as a catastrophe. However, computer analysis of our world system model indicates that the continuation of what amounts to overexploitation of oil, spurred by an unreasonably low price, would lead to major dislocations because of the exhaustion of reserves and the lack of motivation to develop substitutes in time. Pursuance of short term objectives would lead to major dislocations in the long run (see A). A much more beneficial development for all concerned results from the "optimal price scenario" in which the price is gradually increased up to the "optimum" level. Such a policy would bring in the substitutes in a more regular fashion while prolonging the reserves. Both exporting and importing regions would fare better (see B). it is only by taking a global and long term view that such a course of development, most beneficial to all concerned, can be identified.**

SOURCE: *Mankind at the Turning Point.*

1997 and 2002 and a severe, persistent deficit beginning around 2020; substitutes or alternative sources would be necessary after that date.

One possible energy future, based on nuclear power, has been proposed by some technological optimists. Tests using the WIM "fast-nuclear scenario" raise questions about the short-term feasibility and long-term consequences of this alternative. After testing short-term scenarios based on Herman Kahn's The Next Two Hundred Years, the authors conclude that:

> It is impossible to design any energy program in Western Europe or Japan which could, over a ten-year period, reduce energy demand and increase production of energy from non-petroleum sources sufficiently to compensate for the loss of the Persian Gulf by 1987. The Hudson report statement regarding the ease of adjustment to a quick disappearance of oil reserves is therefore erroneous.[7]

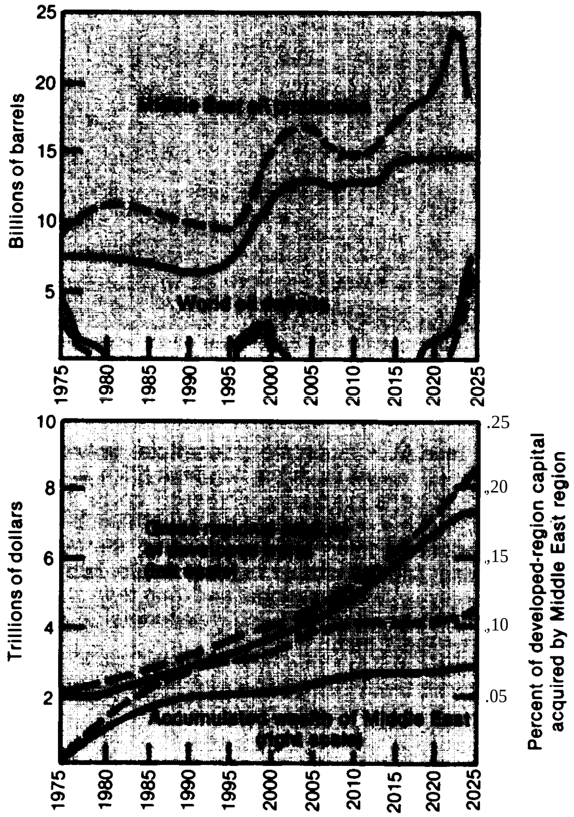
Other WIM tests indicate that the longer term feasibility of the nuclear option is just as questionable. The U.S. Atomic Energy Commission estimated in the early 1970's that nuclear energy would provide 30 percent of the developed world's energy needs by 2000, based on higher demand growth than is now expected. By extrapolating from this figure, the authors found that by 2025 nuclear power would have to provide 60 percent and by 2075 almost 100 percent of **all** energy needs (see fig. C-9). The social, economic, and security impacts of such a course would be enormous: sole reliance on fission nuclear power would require 24,000 fast-breeder reactors worldwide by 2075, which in turn would require the construction of 4 reactors per week for a century and the eventual construction of about 2 reactors per day just to replace reactors that have reached the end of their 30-year lifespans, at a cost of $2 trillion per year for replacements alone (see fig. C-10).[8] This scenario would also require the energy sector to process and transport 33 million pounds of plutonium each year; only 10 pounds of this element are needed to construct a nuclear bomb.

Mankind at the Turning Point concludes that an energy future based on nuclear power would be a "Faustian bargain," but this conclusion involves several important assumptions. For one thing, fusion as well as fission could provide the growing nuclear share of energy

[7] B. Hughes and M.D. Mesarovic, "Testing the Hudson Institute Scenarios" (Washington, D. C.: U.S. Association for the Club of Rome, September 1979), mimeograph, p. 22.

[8] Mesarovic and Pestel, op. cit., pp. 132-1 M

Figure C-8.—Comparison of Middle East Oii Production, World Oil Deficits, Developed=Worid Gross Regional Product. and Middle East Accumulated ‘Wealth Under Two World integrated Model Scenarios



Solid line: Middle East withholds oil, Imposes ultimate ceiling of 14 billion bbl/yr.
Dotted line: Production and trade governed solely by economic factors.

SOURCE: *Mankind at the Turning Point,*

supply, although fusion power on such a scale would involve similar financial and engineering problems and (at present) even greater technical problems. Another significant factor is the assumed rate of growth for energy demand, which seems unrealistically high in view of subsequent events; in updated projections, higher energy prices and slower demand growth would make the nuclear share—whether fission or fusion-substantially smaller. The authors prefer an energy future that places mid-term reliance on coal and coal-derived synfuels, combined with long-term development of huge “solar energy farms” in the present oil-producing regions. This alternative has not been tested with the model, but it too would involve massive capital and engineering requirements, even with slower energy demand growth. Because of its technical uncertainties (see below), and because it is not based on explicit analysis with WIM, this solar alternative remains speculative.

Latin American World Model (LAWM)

LAWM assumes the nuclear-energy future that WIM rejects, but unlike the other global models it contains no representation of energy or any other resource. The structure of LAWM is based on the assumption that, “for the foreseeable future, the environment and its natural resources will not impose barriers of absolute physical limits” on the satisfaction of basic human needs.[9] The authors base this assumption on two studies conducted independently of the model itself: a survey of currently known reserves of fossil fuels, which found enough oil and gas to last 100 years, and enough coal to last 400 years, at present consumption levels;[10] and an analysis of future production costs for energy, which found that:

> . . . the so-called energy crisis . . . is of a conjunctural character, such as others of similar importance that occurred in the past. And it may be perceived that the main reactions of the system will be to establish a new equilibrium, which, generally speaking, in the long term will not differ from the previously observed trends. ’[11]

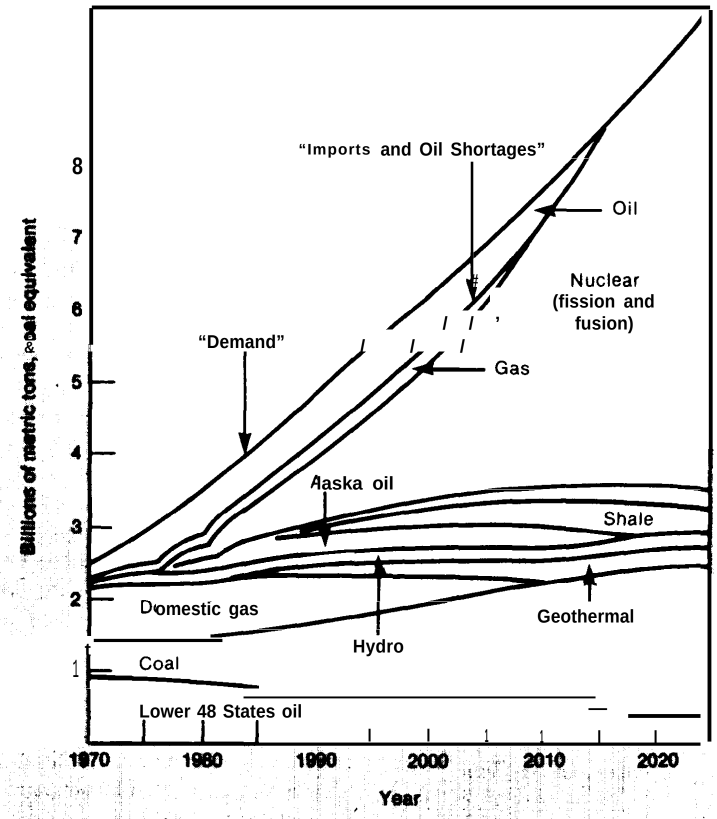
The latter conclusion appears inconsistent with the authors’ own reserve estimates, which represent slightly more oil and gas but considerably less coal than those used in World 3 and WIM, However, the authors assert that “the most important fuels for the future are nuclear fuels.” They cite predictions that nuclear power will generate 50 percent of the world’s electricity by 2000, and, although their own estimate of uranium oxide reserves reflects only 33 years supply even at 1970 levels, they suggest that “a small increase in the price or an advance in technology” will make it economical to extract vast amounts of uranium from granite or seawater.[12] The model itself, however, does not reflect the capital costs or potential technical bottlenecks involved in this nuclear scenario.

United Nations Input-Output World Model (UN IOWM)

The central concern of UNIOWM is to reduce the income gap between the rich and poor nations before the year 2000. In order to determine whether U.N. development targets are consistent with the availability of nonrenewable resources, the model projects the levels of production and world trade in six metals and three en-

‘A. O. Herrera, et al., Catastrophe or *New Society? A Latin American World Model* (Ottawa: International Development Research Centre, 1976), p. 8.
[10]Ibid., pp. 32-33.
[11]Ibid., p. 34.
[12]1 bid., p. 33.

Figure C:9.- Projected U.S. Energy Supply Distribution for World Integrated Model "Fast-Nuclear" scenario



In the conditions of continued growth, it is important to look over a sufficiently long period of time in the future in order to assess the consequences of selecting one of the available alternatives. The graph in the figure gives projections made by the U.S. Atomic Energy Commission of energy demands in the United States from 1975 up to the year 2000 and how this demand could be met if the decision is made in favor of relying on nuclear energy production. The full impact of such a decision can be seen only when the projection is extended over a sufficiently long period of time. By the year 2025 sole reliance on nuclear power would require more than 50 major nuclear installations, on the average, in every State of the union.

SOURCE: *Mankind at the Turning Point.*

ergy sources (oil, gas, and coal) that would be required to support its relatively high rates of population and economic growth. Its major conclusion:

> The problem of the supply of mineral resources for accelerated development is not a problem of absolute scarcity in the present century but, at worst, a problem of exploiting less productive and more costly deposits . . . and of intensive exploration for new deposits . . . .[13]

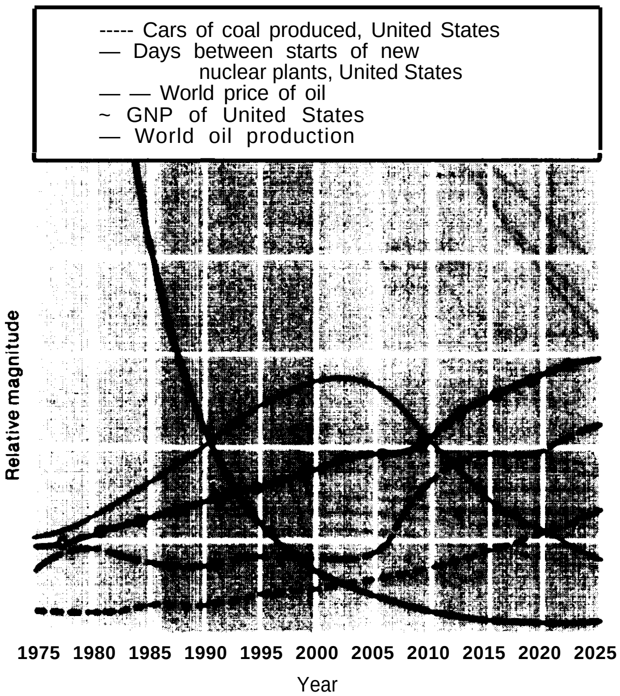
Reserves and prices are determined independently of the model itself, and the amount of each resource required for expansion in each economic sector is adjusted for assumptions about increased efficiency due to technology. Most of these technical assumptions are not reported, although the model does assume 55-percent recycling of all materials, worldwide, by 2000.[14] The model also assumes that all nations will rapidly develop domestic reserves, but that extraction costs will rise as high-grade deposits are exhausted.

The authors project that 77 percent of the world's known petroleum reserves will be depleted by 2000, but their confidence about future energy supplies rests on the world's plentiful reserves of coal, which they "conservatively" estimate at 9 trillion metric tons (roughly the same as World 3). The model assumes "autonomous

[13] W. Leontief, A. Carter, and P. Petri, *The Future of the World Economy: A United Nations Study* (New York: Oxford, 1977), p. 11; emphasis added.

[14] Ibid., pp. 5, 45.

Figure C-10.– Long-Term Consequences of U.S. Energy Self-Sufficiency Under World integrated Model "Fast-Nuclear's Scenario



SOURCE: Systems Research Center, Case Western Reserve University.

substitution" between energy sources, but it does not rely on cross-price elasticities nor does it compute prices endogenously. For example, it assumes that shale oil and gasified coal will replace petroleum and natural gas in North America before 2000, but it also assumes that the price of coal will decline despite a sevenfold increase in the price of natural gas.[15] In addition, UNIOWM assumes a growing substitution of nuclear for conventional fuels in the utility sector, although this assumption is not reported in the documentation.[16]

In all of its many scenarios, UNIOWM projects a tremendous increase in world consumption of minerals and energy between 1970 and 2000. The global demand for petroleum is projected to increase 5.2 times, natural gas 4.5 times, and coal 5.0 times 1970 levels. Rapid industrialization in the developing regions causes them to more than double their share of world energy consumption. The Middle East remains the major net exporter of petroleum, with output projected to rise almost eightfold—a projection that now appears unrealistic in view of subsequent OPEC production decisions, Non-OPEC developing regions, along with Western Europe and Japan, become increasingly dependent on imported petroleum; but the U.S. oil deficit disappears after 1990, apparently due to the development of shale oil and a sudden doubling of domestic coal consumption in the 1990's. Despite anticipated advances in mining technology and industrial efficiency, the percentage of capital stock used in resource extraction increases steadily in all regions, just as it did in World 3.

In the standard scenario, based on the U.N.'S International Development Strategy, the real price of natural gas increases by 656 percent and that of petroleum by 225 percent over the 1970-2000 period; but the price of coal—the most plentiful energy resource—actually declines by 14 percent in constant dollars.[17] In a second scenario based on "more generous" resource endowments, production and consumption levels change very little and extraction costs, although they rise later, are just as high by 2000. The most significant impact of higher reserve estimates is on trade deficits: this scenario reduces the balance-of-payments deficit of the developed regions by 50 percent, but the non-OPEC developing regions, after being better off in 1990, have accumulated greater debts by 2000 than they do in the standard, "conservative" scenario.

In a later policy test conducted for the U.S. Department of Commerce, UNIOWM indicates that aggressive fossil-fuel conservation in developing regions could reduce LDC trade deficits and thereby remove the main economic constraint to Third World development .18 Such a course would also increase LDC capital requirements and (implicitly) would require an even greater nuclear share to provide adequate energy for continued industrial expansion. In general, the authors find energy to be an economic rather than a physical problem, at least until 2000: internal reform in the LDCS and the creation of a "new international economic order" are the necessary conditions for accelerated development in this century, although the model's restricted time horizon prevents it from examining the sustainability of such growth in the next century.

Global 2000

The energy projections in the Global 2000 Report include a variety of short-term and midterm forecasts, based on different methodologies and assumptions, whose purpose is "to define a range of credible futures against which alternative policy options can be tested."19 The report's estimates of total world reserves

[15] Ibid., p. 65.
[16] A. Carter, private communication, April 1981.

[17] Leontief, Carter, and Petri, op. cit., p. 65, table 61; these projections, like those for production, appear unrealistic in view of subsequent events.
[18] A. P. Carter and A. K. Sire, "An Energy Conservation Scenario for the World Model," prepared for the Bureau of International and Economic Policy, U.S. Department of Commerce, November 1977, p. 2.
[19] J. Pearson, et al., "Energy Projections," in *The Global 2000 Report to the President* (Washington, D. C.: U.S. Council on Environmental Quality and Department of State, 1980), vol. 2, p. 173.

of fuel minerals come from figures prepared by the World Energy Conference, the Congressional Research Service, and the U.S. Geological Survey; but these reserve estimates are not used as inputs to the production or consumption forecasts, The short-term projections (1975-90) were prepared by the Department of Energy's Energy Information Administration (EIA) soon after its creation in late 1977, using two similar computer models: the Project Independence Evaluation System (PIES) for U.S. figures, and the International Energy Evaluation System (IEES) for global figures. The forecasts made for the Global 2000 study use the study's low, medium, and high growth-rate assumptions for population and GNP, but the energy projections were not used as inputs for other sectors; in essence, "GNP is implicitly treated as independent of the energy market."[20]

Both PIES and IEES are equilibrium market simulations, in which producers compete to satisfy short-term world demand and the entire global energy system is assumed to act in such a way as to minimize total costs without regard for the future value of the resources. As a result, both models assume that unlimited world oil supplies will be available at prices (determined outside the models) that rise from $13/barrel in 1978 to $23/barrel in 1990. The models contain detailed representations of the OECD countries and the major fuels, but they contain no representation of resource depletion or political factors and only simplified demand equations for the growing LDC market. The models assume that coal and nuclear will substitute for oil in response to price elasticity, but they impose no limit on the creation of new generating capacity in the utility sector. (The number of new generating plants is determined by expert judgment rather than price, a procedure that may be reasonable for forecasts through 1990: the lead time for developing new productive capacity is so long that current investment plans are a good guide to what will happen in the next 10 years.)

EIA was unwilling to extend its IEES forecasts beyond 1990, and Global 2000's midrange energy projections (1985-2000) are based instead on four different studies representing diverse philosophical and methodological approaches, as well as different assumptions about future demand growth and fuel substitution (see fig. C-1 1):

- the Workshop on Alternative Energy Strategies study, based on estimates from independent national experts, predicts global supply-demand "gaps" of 15 million to 20 million barrels of oil per day by 2000 and examines the consequences of choosing either nuclear or coal as the major replacement;
- the World Energy Conference study, after examining different assumptions about world oil reserves and recovery rates, predicts that global production will peak at a ceiling of 82 million to 104 million barrels per day around 1990, and emphasizes coal and hydropower as replacements when oil supply falls short of demand;
- the Stanford Research Institute (SRI) model of the U.S. energy market through 2020 (see below), which foresees a relatively plentiful energy supply based on coal but assumes perfect consumer foresight about future shortages and prices; and
- a Brookhaven National Laboratory/Dale Jorgenson Associates study of the U.S. energy market, which emphasizes conservation and coal as well as the development of nuclear and renewable sources.

In general, to the degree that these diverse projections can be compared, Global 2000 suggests that a rapid increase in the supply of energy will be needed through the end of the century, even with a declining rate of economic growth. Demand growth will be moderated only by price increases, and significantly higher oil prices will be needed to encourage substitution. Because petroleum production capacity is increasing more slowly than demand, a supply-constrained market is likely before 1990. Furthermore, because the rate of petroleum reserve additions is falling, world production is likely to peak between 1990 and 2010 and gradually decline thereafter. As a result, "a world transition away from petroleum dependence must take place, but there is still much uncertainty as to how this transition will occur."[21]

The findings suggest a considerable potential for coal and natural gas beyond 2000, but the short-term projections indicate that nuclear power will expand far faster than any other source, particularly if oil prices continue to increase. The potential contribution of solar and other renewable sources is rather limited at best. However, there does appear to be a substantial long-term potential for "aggressive, conservation-induced reductions in energy consumption."[22] The alternative energy systems examined in the different studies indicate that options do exist, however limited, and that current decisions about the future fuel mix will have increasingly significant impacts after 2000.

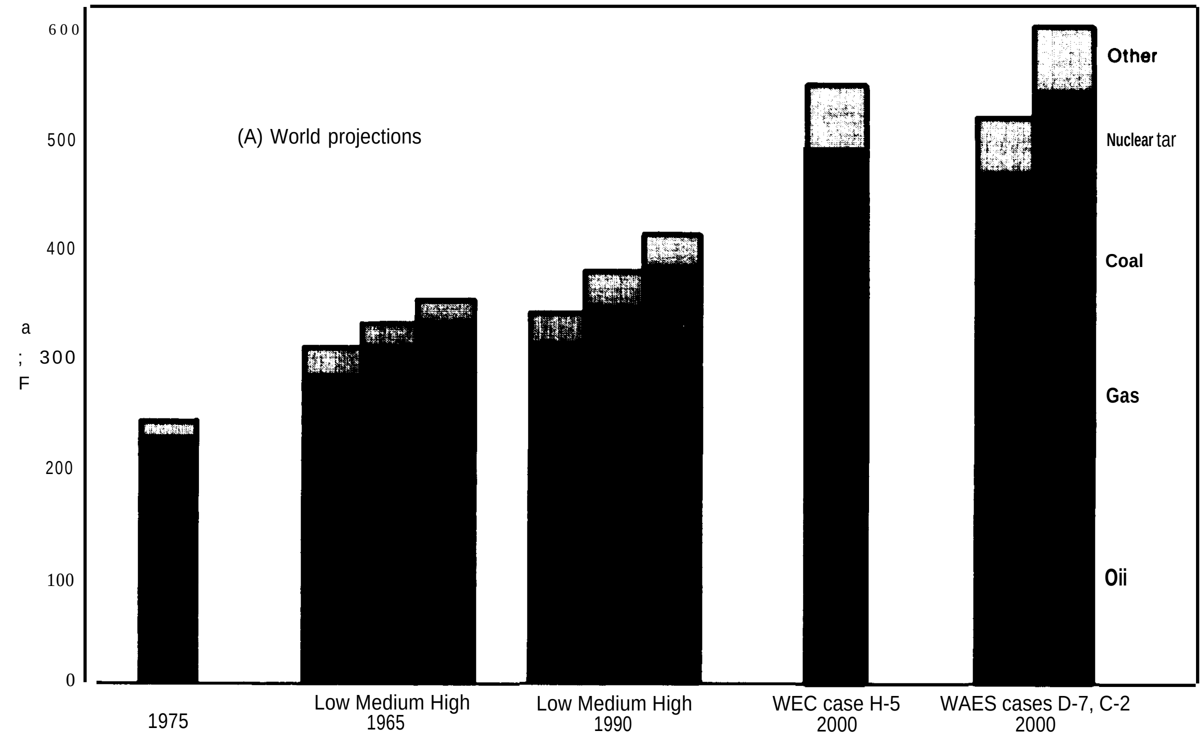
Other Energy Projections

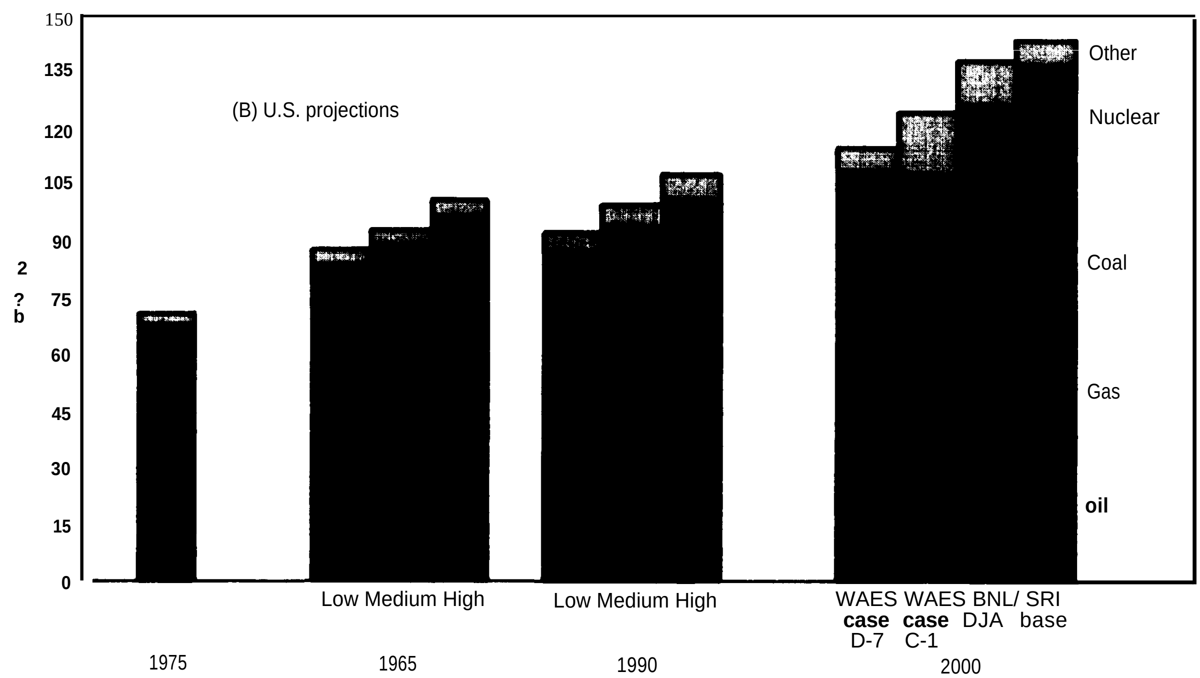
Concurrently with its PIES/IEES short-term global projections, EIA also produced a set of long-term (1978-2020) energy projections for the United States using the Long-term Energy Analysis Program (LEAP), an up-

[20] VanderWerf, op. cit., vol. 2, p. 571.

[21] *The Global 2000 Report to the President*, vol. 1, p. 27.
[22] Pearson, et al., op. cit., p. 161.

Figure C-II.–Comparisons of Global 2000 Projections of World and U.S. Energy Consumption and Supply Mix, 1975-2000





SOURCE: *The Global 2000* ***Report*** *to the President.*

dated version of the SRI -energy model (see above) .23 This forecast, which was not reported in the Global 2000 Report, describes the energy requirements for continued economic growth in the United States during a transition from oil to coal and nuclear power. It assumes the rapid development of shale oil and synfuels to replace oil imports, as well as an ambitious level of energy conservation: a 48-percent reduction in the energy-consumption-to-GNP ratio, based on improvements considered possible on the basis of known technologies, with almost no increase in residential consumption and most of the demand growth coming in the industrial sector. It also assumes that the rate of real GNP growth will decline to 2.4 percent by 1995. Despite these assumptions, the SRI model's projections would require U.S. coal production to triple by 2000 and reach 5 times present levels by 2020; nuclear power would increase eightfold by 2000 and reach 16 times present levels by 2020. This vast expansion is required partly to satisfy growing industrial demand, but primarily because coal and nuclear must grow from 23 percent of primary energy to 72 percent in order to replace depleted U.S. oil and gas. (This energy supply mix corresponds roughly to the "fast-nuclear scenario" that was tested with WIM; see figs. C-9 and C-10, above).

EIA's Office of Energy Information Validation has conducted an evaluation of this 1978 forecast, and their report cites a number of factors that might modify these projections :[24]

- statistical studies of U.S. oil reserves suggest that there may be only half as much domestic oil available as previously estimated by the U.S. Geological Survey and assumed in the forecast;
- recent studies show that the actual costs for shale oil and synfuels may be two to four times greater than earlier engineering estimates, and that there are severe physical constraints on the development of a massive synfuels industry;
- the forecast assumes that extraction costs for coal and uranium will not increase significantly over time due to depletion or scale, and that environmental consideration will not impede the development of these industries;
- the forecast does not address the capabilities of the relevant industries and therefore fails to consider potential bottlenecks and constraints, including the need to build up the U.S. railroad system, a potential shortage of engineers and deep-seam miners, the risk aversion and capital constraints of potential consumers, and the potential efforts of State governments to prevent rapid expansion in the West; and
- more recent data, and more realistic technical assumptions, suggest that electric cars can capture 50 percent of the U.S. personal-transportation market by 2000—despite optimistic oil prices and moderate consumer prejudice—if automobile companies can acquire enough capital to keep up with the potential market.

These and other problems are discussed in more recent forecasts by EIA, which continues to refine, validate, and expand its energy modeling capability; but despite a number of structural changes in the models, the 1980 forecasts are based on many of the same assumptions as the Global 2000 projections.[25] Midterm global energy projections (1975-95) now come from an improved version of the IEES model that incorporates the annual oil production capacity forecasts provided by DOE's Office of International Affairs and the oil price forecasts generated by the Oil Market Simulation (OMS) Model. OMS assumes that OPEC will raise oil prices only when world demand requires them to use almost all of their annual production capacity, and it also reflects lower rates of economic growth. Oil prices are projected to reach $50/barrel in constant mid-1979 dollars by 1995, with almost no increase in oil consumption between now and then. This projection assumes, however, that all OECD nations will reach their official conservation targets and that higher prices will lead to further substitution away from oil. Coal is projected to provide a slightly larger share of total energy demand; nuclear projections are lower due to lower estimates of the speed with which new reactors will be built.

Long-term U.S. energy projections (1975-2030) now come from LEAP, a descendent of the SRI model that EIA used in 1978. LEAP still assumes an unlimited supply of oil imports, at the OMS/IEES world price, but it predicts that the United States will require far fewer imports over the next 40 years. This is due in part to conservation and in part to massive deployment of shale oil and synfuels: U.S. oil consumption is cut in half between 1978 and 2020; and of the remaining demand for liquid fuels, coal-based synthetics provide 50 percent, shale oil 27 percent, and conventional oil only 23 percent. This assumes that the goals of the Synthetic Fuels Corp. (1.5 million barrels per day by 1990 and 3.0 million by 1995) will be met or exceeded, and that, there will be virtually no constraints on the expansion of the synfuels industry after 1995. This projection also accepts with little modification the current engineering estimates of synfuel costs; sensitivity tests, using capital costs twice as high as these estimates, lead to an in-

[23]Energy Information Administration, *Annual Report to Congress 1978* (Washington, D. C.: Department of Energy, 1979), vol. 3.

[24]Office of Energy Information Validation, *Analysis Quality Report: 1978 Long-Term Forecasts and Methodology* (Washington, D. C.: Energy Information Administration, 1981).

[25]Energy Information Administration, 1980 *Annual Report to Congress* (Washington, D, C.: Department of Energy, 1981), 1,01, 3.

crease in U.S. oil imports through 2020. LEAP also assumes an upper limit to the net contribution of renewable energy sources (hydro, wind, biomass, small-scale solar, etc.) of about 6 percent of U.S. demand in 2020.[26]

Strengths and Weakness of Energy Projection Techniques

All of these models are generalized analytic tools that can accommodate a variety of assumptions and serve a variety of applications. Some of them have features that limit their usefulness in examining the future of the global energy system, but these features were usually appropriate to the models' original purposes. World 3, for instance, was intended to give a generalized description of the long-term behavior of the entire global system except agricultural land; as a result, it treats energy only as part of a highly aggregated "nonrenewable resources" sector and makes no specific projections of energy supplies or prices. LAWM explicitly excludes all resource constraints except agricultural land; it assumes that energy and other resources will be available and concentrates instead on how they should be allocated in order to satisfy basic human needs. UNIOWM and Global 2000, because of their shorter time horizons and the absence of resource depletion in their structures, are ill-suited for examining the long-term effects of resource depletion. In addition, UNIOWM concerns itself primarily with development targets and trade balances—although it treats the energy sector in detail, it does little more than tabulate resources as they are consumed in meeting those goals. Global 2000's IEES projections represents major producers and consumers of oil in detail, but they contain considerably less detail for other fuels or for the rapidly growing Third World market. Furthermore, Global 2000's energy projections do not interact with other sectors and therefore do not reflect competing demands for energy resources. WIM strikes a balance between detail and generality, and its policy levers provide more flexibility than the other models for testing alternative energy futures and different producer and consumer behavior. Because of its complexity and lack of documentation, however, the value of WIM's conclusions may not have been fully tested or understood.

Factors Affecting the Accuracy and Reliability of Energy Projections

These differences in purpose and technique have an influence on the projections generated by the different models, but the accuracy and reliability of these projections are also affected by a number of factors and uncertainties on which there is presently little general agreement or understanding. Among these factors are the following:

- total resource reserves and future prices;
- population and GNP growth rates;
- conservation;
- Third World energy choices;
- development bottlenecks; and
- future energy breakthroughs.

Total Resource Reserves and Future Prices

Table C-1 shows the estimates of total world reserves of conventional energy resources on which the different models are based. There is little agreement among the models on the size of these reserves or, how they should be measured, and even less agreement on the costs of extracting them. In general, however, those models that consider prices show that lower grades and unconventional sources will become available as prices rise. Extraction cost will be higher for these low-grade deposits, however, and recovery rates will be significantly lower. Consequently, a steadily larger percentage of capital will have to be allocated to obtaining resources, leaving less capital for investment in other sectors. Improvements in extraction and processing technologies might modify this trend, but recent studies have shown that capital costs for shale oil and coal synfuels are likely to be higher rather than lower than previously estimated.

Several of the models predict an energy future based on abundant reserves of coal, but estimated total reserves of coal have increased little since 1913, when they were estimated at 8,000 billion metric tons.[27] Of the 9,000 billion metric tons now generally agreed upon, 50 percent or less is recoverable with current techniques, and two-thirds are reserves claimed by the U.S.S.R. that some experts treat with skepticism. Until recently, however, there has been little incentive for further exploration; new deposits may soon be discovered due to renewed interest in coal.

[26] For further assessment of the technologies and assumptions involved in these projections, see the following OTA reports and technical memoranda: *Nuclear Proliferation and Safeguards*, OTA-E-48 (June 1977); *Gas Potential From Devonian Shales of the Appalachian Basin*, OTA-E-57 (November 1977); *Enhanced Oil Recovery Potential in the United States*, OTA-E-59 (January 1978); *A Technology Assessment of Coal Slurry Pipelines*, OTA-E-60 (March 1978); *Application of Solar Technology to Today's Energy Requirements*, OTA-E-66 (June 1978); *The Direct Use of Coal: Prospects and Problems of Production and Combu.men*, OTA-E-86 (April 1979); *Gasahol: A Technical Memorandum*, OTA-TM-E-1 (September 1979); *The Future of Liquefied Natural Gas Imports*, OTA-E-110 (July 1980); *Energy From Biological Processes*, OTA-E-124 (July 1980); *Wodd Petroleum Availability 1984) -2(3(XI: A Technical Memorandum*, OTA-TM-E-5 (October 1980); *Nuclear Powerplant Standardization: Light Water Reactors*, OTA-E-1 34 (April 1981).

[27] H. S. D. Cole (ed.), *Models of Doom: A Critique of the Limits to Growth* (New York: Universe Books, 1973), p. 98; on the other hand, these reserves have seemed so large relative to expected demand that there has been little incentive for increased exploration.

Table C-l .—Energy Resource Reserves as Described by Five GLobaL Modeling Studies

Global model	Year	Petroleum (billions of barrels)	Natural gas (trillions of ft)	Coal (billions of metric tons)	Uranium oxide (millions of metric tons)
World 3	1972	630 ident[a] 1,200 hyp/spec[b]	1,000 ident 10,000 hyp/spec	8,600 ident 6,600 hyp/spec	N/A
WIM	1974	667 proven	285 proven 2,300 ultimate[c]	4,200 recoverable 8,400 total[d]	Implicitly unlimited
LAWM	1976	1,800 total	103 total	9,640 total	0.76 @ $10/lb; practically unlimited @ $20/lb
UNIOWM	1977	1,555 total	N/A	9,080 total	NIA
Global 2000 ......, ...	1978	646 proven 2,100 total	2,520 proven 5,984 hyp/spec	786 proven 12,682 total	1.661 @ $10-$35/lb 2.794 additional at higher prices

N/A = not available.
[a]Identified reserves include both proven and inferred reserves, including deposits that are currently subeconomic.
[b]Hypothetical resources include undiscovered deposits in known districts; speculative resources include undiscovered deposits in districts not presently known to contain deposits.
[c]Ultimately recoverable reserves; total reserves greater.
[d]Assuming that 50 percent of total is recoverable.

SOURCE: Office of Technology Assessment.

The rate at which new petroleum reserves are being discovered, on the other hand, appears to be falling. In addition, many geologists are pessimistic about the prospects for discovering vast new reserves of natural gas at greater depths than have been explored thus far.

There is as yet no indication of diminishing returns in uranium exploration. Current reserves (including speculative reserves at much higher prices) represent less than 50 years of total world energy supplies at current consumption levels (assuming the use of conventional nuclear reactors), although with breeder reactors these reserves would last far longer. Technologies for extracting huge amounts of uranium from granite or seawater remain speculative, and DOE has at times taken the position that uranium is scarce enough to justify the deployment of the breeder reactor.[28]

Finally, none of the models deals with potential reserves of lithium. Despite the LAWM team's confidence that fusion power will solve the world's long-term energy problems, successful development and widespread deployment of this technology remains speculative (see below).

Population and GNP Growth Rates

Appendix A shows that there is general agreement among the projections of world population in 2000, however much the projections differ in the longer term. There is far less agreement among the models on future rates of economic growth. Both factors influence the energy projections, although the effect of GNP projections is somewhat greater.

The standard run of World 3 assumes that population will continue to grow exponentially. It also assumes that the recent rate of world economic growth, 1.7 percent per year measured in real GNP per capita, will also continue through 2000. These two factors quickly force the model against its resource limits, and the global economic system collapses sometime after 2010 due to rising extraction costs. Sensitivity tests indicate that policies designed to slow population growth or limit industrial expansion could delay (but not prevent) this collapse. Critics have claimed, however, that World 3 underestimates the ability of the free-market system to anticipate and thereby prevent a possible catastrophe, although they have not explained how it would be possible to prevent such a catastrophe in the absence of specific new energy sources .29

UNIOWM assumes a slightly faster population growth and a much higher growth rate for gross product per capita—3.O percent per year even in its most pessimistic "business as usual" scenario, and as high as 6.0 percent per year for the LDCs in other scenarios. The model does not examine the long-term sustainability of these growth rates, however, and the principal reason why UNIOWM does not predict a catastrophe is that it stops at 2000.

LAWM's population projections are higher still, particularly in the longer term, and its optimization procedures impose high investment rates that lead to economic growth rates of 4.0 percent per year for the devel-

[28]U S, Atomic Energy Commission (USAEC), Proposed *Final Environmental* Statement *Liquid Metal* Fast Breeder Program (Washington,D.C.: National Technical Information Service, 1974).

[29]Cole, op. cit., p. 66

oped regions and up to 6.0 percent for the LDCs through 2000, gradually declining thereafter to 2.0 and 3.0 percent, respectively. These growth rates do not lead to an energy-related catastrophe because LAWM contains no representation of resource availability.

WIM assumes relatively ambitious population control in many of its scenarios. Even so, it shows that population will not stabilize before 2050 under the best of conditions. Economic growth varies considerably among scenarios, but in at least one policy test the economic growth rate (supported by investment aid from developed nations) remains at 7.0 percent in Latin America and 8.2 percent in South Asia through 2025.

Global 2000's short-term projections test three different sets of population and GNP growth assumptions, in order to illustrate a range of possible futures. Economic growth rates are highest for OPEC and medium-income LDCs, somewhat lower for the developed nations, and lowest for the low-income LDCs and Communist bloc. In all cases, economic growth slows significantly after 1985.

Conservation

Total demand for energy can be represented as the product of three variables: population and GNP per capita (see above), and the ratio of energy consumption to GNP. Conservation can reduce this latter ratio (and thus the total demand for oil and energy at any given level of population and GNP per capita) in either of two ways: 1) by improving the efficiency with which energy is used (e.g., through residential insulation or improved industrial machinery); or 2) by improving the way in which the overall energy system matches energy sources with particular end uses (e.g., a large-scale coal or nuclear generator is more appropriate to the energy needs of a major industrial city than to those of a rural village, which might well be better served by a small-scale wind, hydro, or solar source). Biomass, dispersed solar, and other small-scale alternatives can contribute to the second form of conservation, but conservation of conventional fuels will depend primarily on the response of large-scale industrial and utility consumers.

Many economists believe that higher prices are an efficient mechanism for inducing this kind of conservation, and economic models generally assume that demand will fall in response to future price increases to the same degree that it has in the past. For example, pre-embargo studies of energy demand in the United States generally showed little responsiveness to price: when prices were low, other variables (such as the price of automobiles or new capital equipment) are more important to consumers than energy costs. As prices first began to rise rapidly, there was a large initial demand response due to "housekeeping" conservation and other simple measures, but the long-term response was expected to be slower due to the slower conversion to more efficient automobiles and capital equipment.

However, the response to the 1979 oil price hike suggests that long-term elasticity will be greater than many people had expected. Conservation has been greater—and demand growth slower—than was previously foreseen, even when the effects of economic slowdown are eliminated. In addition, some economists claim that economic models based on the United States do not reflect the full global potential for long-term conservation through more efficient capital equipment. JO Other studies, however, have shown that technological progress in some critical industrial sectors requires an increasing use of energy per unit of output .31

The World 3 standard run assumes that resource consumption per capita will continue to be a fixed function of GNP per capita. This assumption implicitly rejects any significant potential for conservation and—although reasonable when the results were published in 1972–it gives the standard run a pessimistic bias that has been contradicted by subsequent events. However, World 3's "recycling" run (fig. C-5) does show that conservation, in combination with improved exploration and extraction technologies, can have a significant impact on resource depletion.

WIM, published after the 1973 embargo and price hikes, does assume some conservation in response to higher prices. In the case of oil, a l. O-percent increase in price is converted into a direct decrease of 0.225 percent in consumption, plus additional decreases due to substitution. The authors conclude, however, that even optimistic assumptions about conservation will not prevent a substantial increase in total energy demand—the world will need to develop alternative sources, either nuclear or solar.[32]

LAWM assumes that the global energy system will make more efficient use of different energy sources in the future, and that technological progress will increase the productivity of the capital goods sector by 1.5 percent per year (a rate that would double the output-to-input ratio in 47 years). For the most part, LAWM's optimism about the availability of energy is based not on conservation but rather on unlimited supplies of nuclear power, including the deployment of fusion technology within 50 years.

UNIOWM also assumes that technological progress will change the energy requirements of every sector. The documentation does not reveal, however, the pre-

[30] R. S. Pindyck, "The Characteristics of Demand for Energy," in J.C. Sawhill (cd.), *Energy Conservation and Public Policy* (Englewood Cliffs, N.J.: Prentice-Hall, 1979), pp. 38, 39.

[31] D.W. Jorgenson and B.M. Fraumeni, "Relative Prices and Technical Change," prepared for AEA Annual Meeting in Denver, Colo., Sept. 5, 1980.

[32] Mesarovic and Pestel, op. *Cit.*, p. 136.

cise value of these assumptions or how sensitive the results are to them.

Global 2000's short-term projections assume energy conservation in response to price ($23/barrel in 1978 dollars by 1990), above and beyond the official conservation targets of various national governments. The midterm projections extrapolate from engineering and economic forecasts for 1995 and result in a final level of conservation—48 percent reduction in the energy-to-GNP ratio by 2020–that indicates the technological limits of what can be achieved. More recent DOE forecasts of conservation are based on higher prices ($50/barrel in 1979 dollars by 1995) and on detailed analyses of specific technological possibilities in every end-use sector, many of them derived from engineering studies conducted by the Oak Ridge National Laboratory. These and other studies, combined with the demand response to the 1979 oil price hikes, suggest that long-term conservation in the 50-percent range is in fact a reasonable expectation.

Third World Energy Choices

None of the models except Global 2000 deal with the firewood crisis, which may have severe social and environmental repercussions in many Third World countries. Industrialization and economic development in these countries will also require electricity, however, and all of the models assume, at least implicitly, that nuclear power will be widely deployed in the future. This common assumption is of political as well as economic interest, particularly in the case of LAWM and UNIOWM. Both of these models represent Third World attempts to chart a future in which the gap between the rich and poor nations is narrowed through local and international efforts to accelerate development and increase industrial output. Nuclear power offers developing nations an alternative to their current dependence on fossil fuels, whether to preserve their domestic resources or to reduce their energy-related trade deficits. There is evidence that, whether or not the United States and other OECD nations finally accept the hazards of nuclear power, many Third World nations are likely to accept them on a very large scale, and very soon, for lack of a credible large-scale alternative.

Business commentators already speak of "the nuclear power boom getting under way in the Third World," including such nations as Mexico, Egypt, Korea, Taiwan, and the People's Republic of China.[33] Conventional enriched-uranium reactors in such countries represent a potentially lucrative market for the U.S. and European nuclear industries. Many Third World governments are also investigating natural-uranium technologies that would allow them to exploit domestic uranium rather than depending on Europe or the United States for expensive enriched fuel. Argentina, Pakistan, India, and South Korea already have operational reactors based on a Canadian natural-uranium, heavy-water system. Mexico's recently published National Energy Program calls for the construction of as many as 16 such reactors to meet a tripling of demand for electricity by 2000, despite that nation's abundant oil and gas reserves .34

The WIM "fast-nuclear" scenario, however, foresees an energy future based not on conventional fission but rather on the more efficient "breeder" reactor, which effectively produces more nuclear fuel than it consumes. As a result, breeder reactors might produce 60 to 100 times as much energy from a pound of uranium as do conventional reactors. Both past U.S. Government studies and current expert opinion suggest that, given the limited size of world uranium reserves (even including speculative reserves), nuclear fission may not be able to provide a large-scale, long-term contribution to the world's energy supply without the widespread use of breeder reactors.[35] Because breeders would also produce large quantities of weapons-grade plutonium, however, their deployment throughout the Third World could also pose a serious threat to domestic and international security.

Development Bottlenecks

Some economists would argue that the world's major energy problem is not finding adequate resources, but rather overcoming the bottlenecks in getting those resources to market. Three of the models considered here —World 3, LAWM, and UNIOWM—implicitly assume that there will be no major bottlenecks in the exploitation of energy resources. Although WIM's authors point out the numbers and speed with which reactors would have to be built for the "fast-nuclear" scenario, they do not report any further analysis of development bottlenecks. DOE's models for Global 2000 involve a serious attempt to address problems of timing where they involve liquid fuels and the transition from oil to coal and nuclear power. However, DOE's own evaluation of the 1978 long-term forecasts points out that the models describe the requiremenrs for U.S. energy independence rather than the capabilities of the relevent industries, as well as making questionable assumptions about investor foresight, extraction costs, and environment constraints (see above). Further consideration of these and other factors suggest both that considerable cooperation between Government and industry may be needed to reduce the impact of these potential bot-

[33] H. Rowen, "Nuclear Reactors: Fear of Losing Export Race," *Washington Post*, May 17, 1981, p. K1.

[34] C. Dickey, "Scenic Mexican Reactor Site Entangles Indians, Unions, Nationalists," *Washington Post*, May 18, 1981, p. A12.

[35] See, for example, USAEC, op. cit.

tlenecks, and that other energy sources and mixes should be examined more carefully.

Future Energy Breakthroughs

Finally, the accuracy and reliability of energy projections will also be affected by the assumptions they make about the successful development and deployment of entirely new energy sources. Some such systems are implicitly assumed by one or more of the models, but others are not foreseen by any of them.

The widespread deployment of fusion technology, for instance, could possibly invalidate the pessimistic assumptions of Limits to Growth if the supply of lithium were large enough or if deuterium-deuterium fusion were developed. The LAWM study bases its exclusion of resource problems in part on the expectation that fusion power will in fact be deployed within 20 to 50 years. Commercial-scale fusion power remains purely speculative at present, however. Although fusion researchers hope that a commercial fusion reactor design might be possible by 1990, until then all claims about engineering problems, capital costs, and net energy production will also remain speculative. In addition, none of the models discusses the potential world reserves of lithium. Other sources, however, have estimated that minable U.S. lithium reserves alone are worth over 160,000 quadrillion Btu prior to conversion losses, or about 640 years total world energy supply at 1976 consumption levels.[36]

The WIM solar scenario envisions a long-term energy future based on centralized solar power in the form of huge "solar farms" in the deserts of the Middle East, to be financed by OPEC oil money.[37] With higher energy prices due to scarcity, the capital costs of such facilities—which the authors estimate at $20 trillion to $50 trillion in 1974 dollars—might become bearable; solar might even prove cheaper than nuclear. Theoretically it would be possible to supply all of the present U.S. demand for electricity from a "farm" of solar cells the size of Massachusetts, but DOE studies claim that there are not enough economically feasible sites in the United States for centralized solar to make more than a marginal contribution to U.S. energy supply in the foreseeable future.[38] On the vast scale foreseen by Mankind at the Turning Point—1 percent of the world's land surface–such facilities would involve scientific, engineering, and planning problems that are beyond the current state of the art. Furthermore, some critics question whether the energy produced by these solar farms would be greater than the total amount of energy involved in building them, maintaining them, and distributing the hydrogen and electricity they would produce, Since this scenario was not subjected to rigorous testing with the model, it remains speculative.

A number of other groups have suggested another alternative: solar-power satellites orbiting in space and beaming power down to earth in the form of microwaves or lasers, The National Aeronautics and Space Administration (NASA) has produced detailed designs for such a system, for which it envisions commercial operation by 2000, or about 20 years before fusion is predicted to become commercial. NASA studies have indicated that marginal costs and net energy production will be comparable to present energy sources, although these findings are highly controversial. DOE claims that potential receiving sites are probably more than adequate to supply several times the present level of U.S. electricity demand, since more energy can be received per acre than with central solar and without necessarily prohibiting agricultural uses of the sites, although the effects of low-level microwave radiation are problematic. Research and development costs for the NASA design, however, would be over $100 billion, and the cost per power station would be somewhat higher than that of conventional fission reactors regardless of the scale of production. An alternative design developed at Princeton University involves less R&D and employs small modular processing units whose cost and performance could be tested prior to any commitment to large-scale deployment. The Princeton design is somewhat riskier than NASA's, but it might be possible to deploy it sooner and to reduce energy costs substantially as the scale increases. This might in turn make it possible to sell energy to the LDCs at prices much lower than would be possible with breeder reactors.[39]

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[36] S. S. Penner (ed.), *Nuclear Energy and Energy Politics* (Reading, Mass.: Addison-Wesley, 1976), p. 562.

[37] Mesarovic and Pestel, op. cit., pp. 139-141.

[38] *Domestic Policy Review of Solar Energy* (Washington, D. C.: Department of Energy, February 1979), table 8; DOE's long-term forecasts therefore assume an a priori limit of less than 1.0 Quad central solar by 2020.

[39] Further discussion and analysis of this technology can be found in the following sources: *Satellite Power System Concept Development and Evaluation Program Reference System Report*, DOE/ER-0023 (Washington, D. C.: U.S. Department of Energy and National Aeronautics and Space Administration, October 1978); The *Solar Power Satellite Concept: The Past Decade and the Next Decade*, NASA/JCS-14898 (Washington, D. C.: National Aeronautics and Space Administration, July 1979); R.A. Herendeen, T. Kary, and J. Rebitzer, "Energy Analysis of the Solar Power Satellite," *Science*, vol. 205 No. 4405, Aug. 3, 1979, pp. 451-454; Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Space Systems Laboratory, *Extraterrestial Processing and Manufacturing of Large Space Systems*, NASA contract CR-161293 (Washington, D. C.: National Aeronautics and Space Administration, September 1979), vol. 3, pp. 47-49; Office of Energy Research, Solar Power Satellite Project Division, ***Program Assessment Report***, DOE/ER-0085 (Washington, D. C.: U.S. Department of Energy, November 1980); and Office of Technology Assessment, U.S. Congress, *Solar Power Satellites*, OTA-E-144, (Washington, D. C.: U.S. Government Printing Office, August 1981).