FOSSIL1: A POLICY ANALYSIS MODEL OF THE U.S. ENERGY TRANSITION

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ABSTRACT

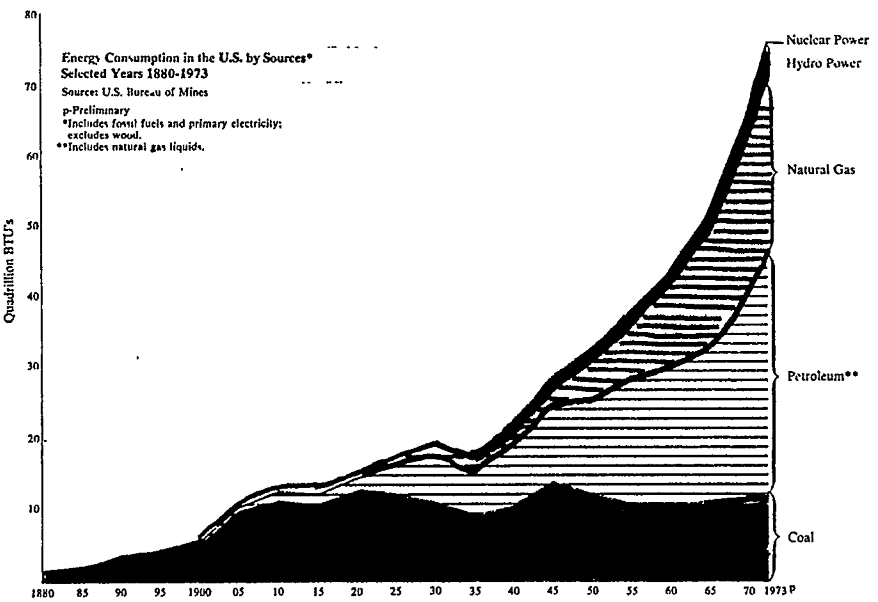
Over the past four years the Dartmouth System Dynamics Group has developed a dynamic simulation model to aid in the analysis and design of United States energy policy. The model, titled FOSSIL1, simulates the interactions between energy prices, financial markets, resource depletion, government regulation, changing technologies, and consumer behavior that determine future patterns of energy production and consumption. The model is specifically tailored to allow the user to examine the effects of new energy policy on the behavior of the U.S. energy system. This paper will briefly outline the problem addressed by FOSSIL1, the structural characteristics of the model, and a demonstration of its application to energy policy analysis.

I. THE U.S. ENERGY TRANSITION PROBLEM

United States energy consumption has grown at an average of 3% annually for the past seventy years and at 3.5% over the past twenty five years. As shown in Illustration 1, this extraordinary period of sustained growth has been accomplished almost entirely through increased consumption of petroleum and natural gas. Oil and gas usage grew from negligible amounts in 1900 to over 75% of gross U.S. energy inputs in 1974. But domestic production of these two fuels has been declining since 1970, and there are no prospects for a significant upturn in production rates. The recent reappraisal of the nation's oil and gas resources by the U.S. Geological Survey (2) and the National Academy of Sciences (3) led the Energy Research and Development Administration (ERDA) to conclude that current production rates will be "difficult to maintain" despite the expected contribution from offshore and Alaskan deposits. (4)

ILLUSTRATION 1

U.S. Energy Consumption, 1880-1973 (1)

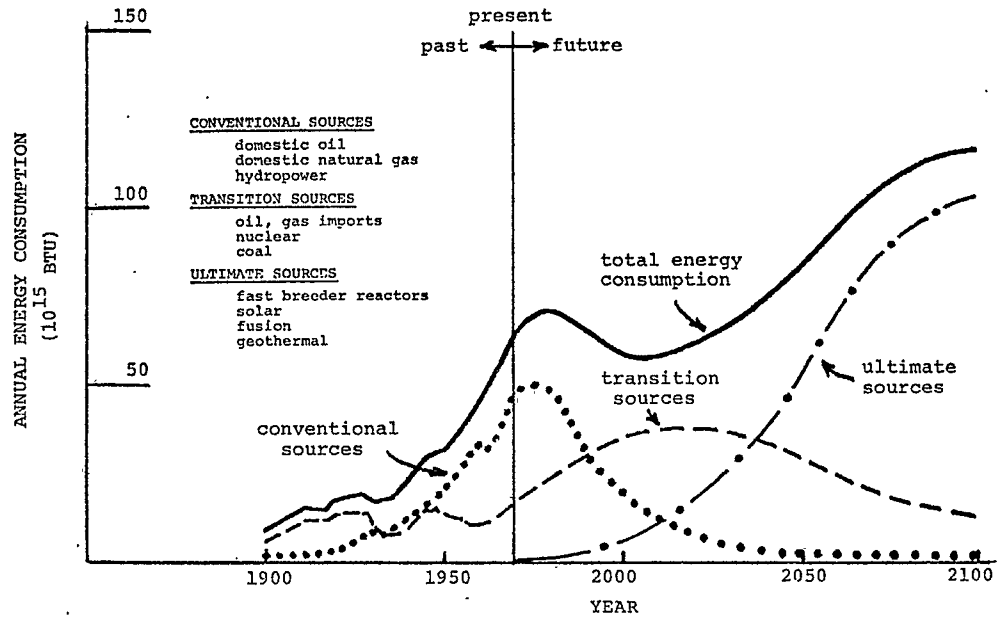


Ultimate energy sources such as nuclear fusion, solar, wind, ocean thermal gradient, bioconversion, and geothermal are the most desirable alternatives to oil and gas in the far future. But they probably will be unable to provide more than 10 to 20 percent of the nation's energy demand by the year 2000. The massive social and economic changes implied by a nationwide transition to ultimate sources may not permit them to carry the bulk of the country's energy burden before 2050.

The extent of the problem posed by the expected decrease in domestic oil and gas production, combined with the slow increase in production from ultimate sources, depends heavily on future energy demand. Clearly any reduction in the historical rate of demand growth would help alleviate the U.S. energy problem. Yet even the "zero growth" scenario of the Ford Foundation Energy Policy Project assumed that consumption would grow to levels one-third

ILLUSTRATION 2

The U.S. Energy Transition Problem



A possible scenario for U.S. energy: poorly managed transition to ultimate energy sources. The evolution of the U.S. energy system will likely consist of three phases: a growth period with major dependence on conventional sources consisting of coal, oil, gas and hydropower; a transition period, with major shifts to dependence on nuclear power and coal; and a period of stable demand, with primary dependence on ultimate sources such as solar power, fusion, bioconversion, and geothermal energy. Without careful planning of transition sources, the U.S. could suffer a serious energy gap during the transition period.

above those of 1975 before it stabilized. The 1975 ERDA National Energy Plan projects at least a doubling of energy consumption by the year 2000.

Continued demand growth, depletion of oil and gas resources, and long delays in the implementation of ultimate energy sources raises the possibility of a significant "energy gap" between the energy demanded at prevailing prices and the energy available from domestic sources, as shown in the hypothetical projection in Illustration 2. In this scenario the U.S. must resort to massive energy imports to balance supply and demand during the transition period.

To counter the trend toward imports, the federal government is currently considering the following proposals:

-mandatory conservation measures
-oil import quotas or tariffs
-decontrol of oil and gas prices
-accelerated development of nuclear power
-weaker air quality standards
-accelerated synthetic fuels research and development
-federal loan guarantees or price supports for synthetic fuels commercialization
-rate reform for electric utilities
-federal subsidies for coal development.

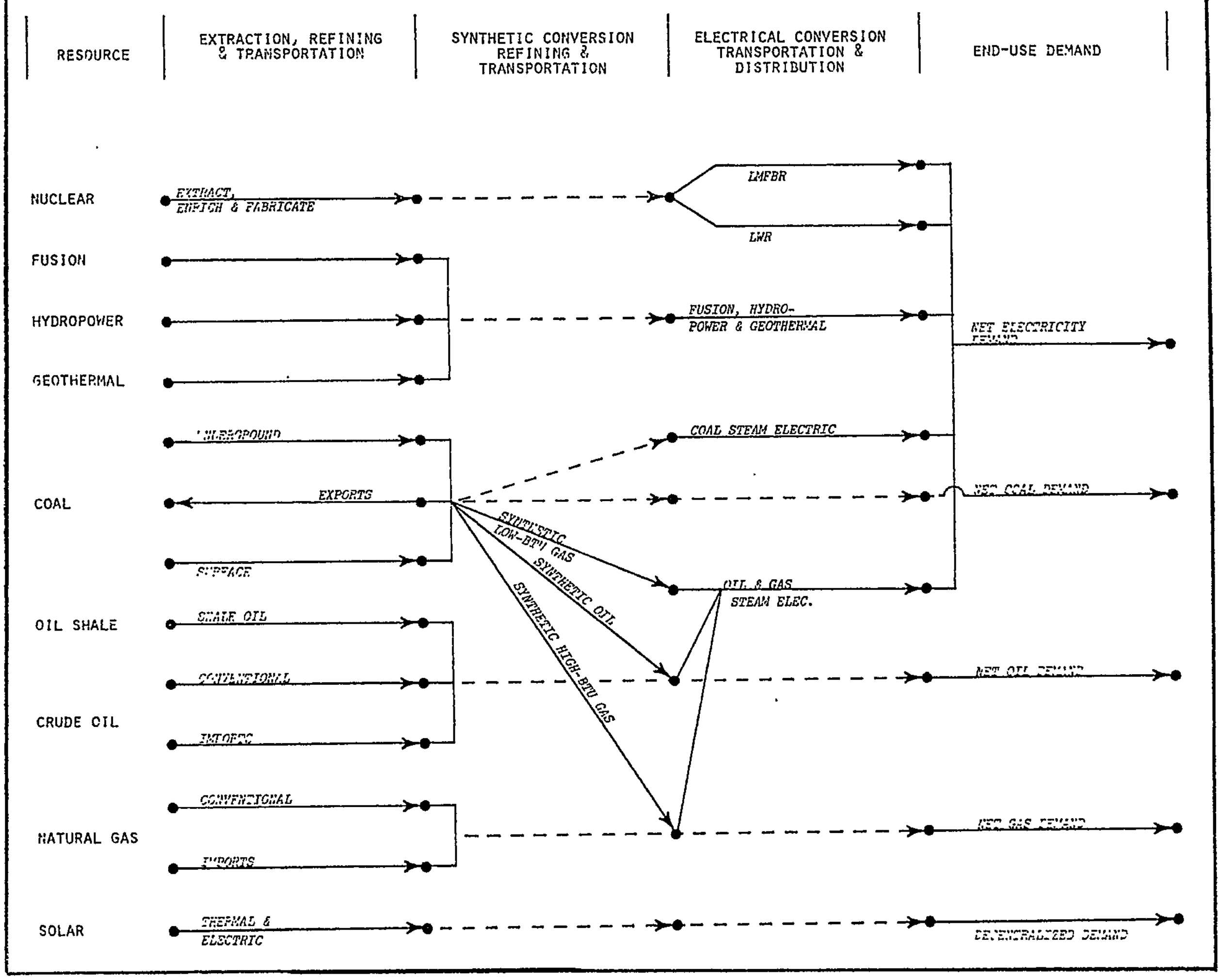
In each case, government policymakers must determine whether federal intervention is warranted. To analyze the long-term impact of federal policy on the U.S. energy system, a system dynamics model, entitled FOSSIL1, has been constructed under the sponsorship of ERDA Fossil Energy. This model emphasizes the long-term, delayed causal mechanisms that determine the production and consumption of energy over time.

II. FOSSIL1 MODEL STRUCTURE

The flow of U.S. energy from primary resources to satisfaction of end-use demand represented in the FOSSIL1 model is illustrated in Illustration 3. From this perspective, the U.S. energy system converts and processes primary energy into

ILLUSTRATION 3

FOSSIL1 Energy Flow Network



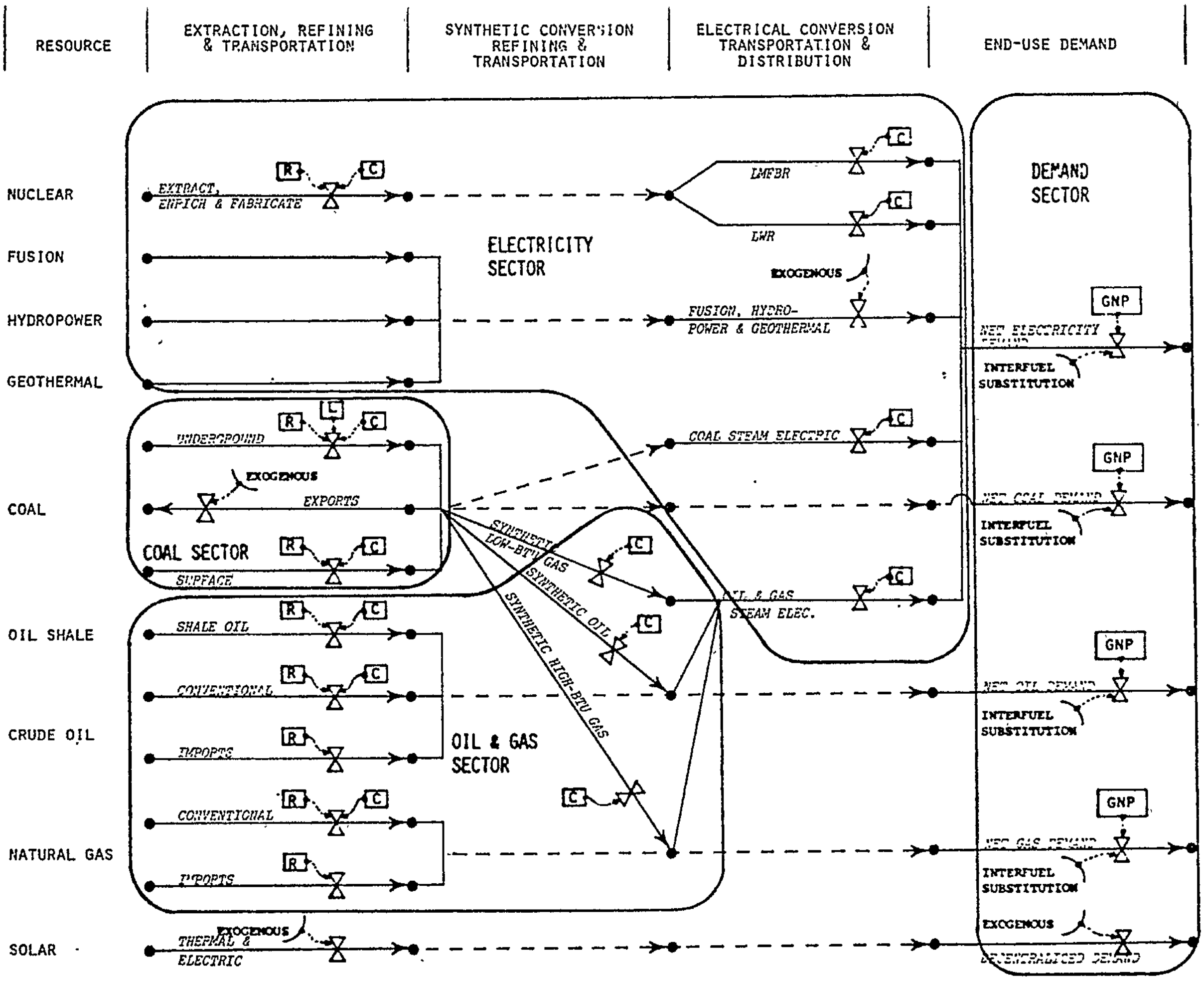
three products: electricity, coal, oil and gas. At each stage of conversion (synthetic fuels or electrical conversion) considerable energy is lost, and therefore the net energy delivered to the customer is considerably less than the primary energy extracted (82% in 1974). (5)

Each of the solid arrows in the network flow diagram of Illustration 3 represent energy flow rates (measured in BTUs per year in FOSSIL1). Illustration 4 shows that each energy flow can be thought of as controlled by a valve represented by ⧗ in the diagram). The end-use demand valves have been steadily opening at an aggregate rate of about 3% per year for the past 25 years, due primarily to the expansion of GNP. Increasing end-use demands for energy have necessitated a rise in production and conversion of primary energy resources over history. Ideally, domestic flows from resources to demand are balanced, and there is little need for imports as an energy input. If balancing energy demand and supply were as simple as adjusting a valve, there would be little talk of a domestic energy crisis.

Although policy makers attempt to control the energy "valves" shown in Illustration 4, their influence on energy flow rates is at best an indirect one. Energy flows are determined primarily by physical constraints: for example, the availability of labor, capital, and resources (represented by L, C, and R in Illustration 4. Each of the energy flows is constrained by a "production function" in the FOSSIL1 model relating resource extraction outputs, synthetic conversion outputs, and electrical conversion outputs to labor, capital, or resource inputs. These

ILLUSTRATION 4

Energy Flow Constraints in FOSSIL1



inputs are called levels (or state variables), and are the basic building blocks of the FOSSIL1 model. Illustration 4 indicates the primary constraints (or levels) considered for each energy flow rate (⧗) included in the FOSSIL1 model.

It is easy to visualize a "snapshot" of the system shown in Illustration 4 at any point in time: energy capital, labor, and resources are constant, allowing a fixed energy flow rate through each of the valves. Yet over long periods of time (50 to 75 years), the availability of energy resources, capital, and labor can change in important ways: oil and gas resources are depleted, energy investment decisions and capital availability can shift rapidly, and underground coal labor may become scarce. The FOSSIL1 model focuses on those factors that control the dynamic behavior of the levels (□) in Illustration 4. The structure of the FOSSIL1 model mimics the complex interaction of geologic, economic, environmental, technological factors, and government policies that affect the availability of the primary factors of energy production (and demand) through time. Table 1 shows all of the forty-one levels which exist in the five major sectors of FOSSIL1.

III. FOSSIL1 STRUCTURAL PROPERTIES

The FOSSIL1 model contains the following structural properties:

- resource depletion
- price feedback
- financial constraints
- environmental constraints
- physical and behavioral lags
- new technology development

TABLE 1

Level of Disaggregation in FOSSIL1

Demand (1 level)	Oil (10 levels)	Gas (11 levels)	Coal (10 levels)	Electricity (9 levels)
1. GNP	1. Conventional oil capital	1. Conventional gas capital	1. Surface capital	1. Oil and gas utility capital
	2. Conventional oil reserves	2. Conventional gas reserves	2. Low sulfur surface reserves	2. Coal utility capital with SO_2 emissions control
	3. Coal liquids capital	3. High BTU synthetic gas capital	3. High sulfur surface reserves	3. Coal utility capital without SO_2 emissions control
	4. Shale oil capital	4. Low BTU synthetic gas capital	4. Underground capital	4. Nuclear utility converter reactor capital
	5. Shale oil reserves	5. World gas reserves	5. Low sulfur underground reserves	5. Nuclear utility breeder reactor capital
	6. World oil reserves	6. LNG import capital	6. High sulfur underground reserves	6. Uranium reserves
	7. Refinery distribution capital	7. Enhanced gas recovery capital	7. Underground labor supply	7. Long-term utility debt
	8. Long-term oil debt	8. Enhanced gas recovery reserves	8. Long-term coal debt	8. Utility equity
	9. Oil equity	9. Gas utility capital	9. Coal equity	9. Book value of utility capital
	10. Book value of oil capital	10. Long-term gas debt	10. Book value of coal capital	
		11. Gas equity		
		12. Book value of gas capital		

In FOSSIL1 oil, gas, coal, oil shale, and uranium are depletable resources. The cost of extracting these non-renewable resources depends upon their relative geological scarcity. The model mirrors the standard business practice of extracting the most accessible and cheapest resources first. Consequently, as a resource is depleted in the model the cost of extraction increases.

A price increase in the model and the real world regulates the consumption of energy resources. Both net demand and the fuel mix is adjusted by this price feedback. Higher prices will cause a dampening of demand and consumption will tend to switch to a cheaper energy resource. These reactions to higher prices, however, are not immediate. Financial constraints, environmental constraints, and physical and behavioral lags impede the transition from one energy source to another.

Financial constraints in the model are due to federal price regulation and the slow response of investors to changes in the business climate. Government price regulation limits the return on investment. As a result, a scarce energy resource such as oil, gas, and electricity would be undervalued in the marketplace. Such an undervaluation of resources discourages investment and conservation. In the nonregulated sectors such as coal, higher prices and its attendant higher rate of return does not immediately result in a larger investment in the industry. Investors are slow to respond because they want to be sure that a higher (or lower) rate of return is a persistent trend and not a quirk of that particular year.

Environmental constraints impede the energy transition by either limiting the rate of return through higher costs and/or by precluding an investment possibility. Incorporated in the FOSSIL1 model are the effects of sulfur dioxide emissions and regulations, mine health and safety legislation, Western water availability, and strip mining regulations.

Even if energy investments are available in a period of energy scarcity, physical and behavioral lags hinder the ability of the system to respond rapidly. For example, once an investment is made, three to ten years must pass before that investment results in a physical plant. In FOSSIL1 three years are necessary to open a strip mine, five years for an underground mine, six years to build a fossil-fired electric utility plant, and ten years to construct a nuclear plant. On the demand side, ten years are required to replace and upgrade inefficient end-use capital.

Finally, the FOSSIL1 model contains the dynamics of developing new technologies. It does so by showing how changes in the date of commercial availability, energy conversion efficiency, and capital cost affect the rate of a technology's market penetration. FOSSIL1 can test, for example, the impact of research and development on the U.S. energy future of the

following technologies:
- oil shale
- coal liquifaction
- coal gasification
- breeder reactors.

IV. A DEMONSTRATION OF ENERGY POLICY ANALYSIS WITH FOSSIL1

The dominant issue in the current debate is how to shrink oil imports to a level that reduces the country's vulnerability to a new oil embargo. The federal government is currently considering the following proposals designed to reduce imports:
- mandatory conservation measures
- oil import quotas or tariffs
- decontrol of oil and gas prices
- accelerated development of nuclear power
- weaker air quoality standards
- accelerated synthetic fuels research and development
- federal loan guarantees or price supports for commercialization of synthetic fuels
- rate reform for electric utilities
- federal subsidies for coal development.

In each case, government policy makers must determine whether federal intervention is warranted. Even though imports would be reduced, the financial and environmental costs of intervention could be so great that the country might be better off to accept high oil imports as a fact of life, with perhaps less freedom of action for the U.S. in its foreign policy.

To aid policy makers in assessing the need for federal intervention in the normal workings of the energy system, a *reference projection* of the FOSSIL1 model is developed. The reference projection estimates the likely behavior of energy demand and the contribution of oil and gas, synthetic fuels, coal, nuclear power, and imports to U.S. energy supply from 1950 to the year 2000, given no new federal incentives. Illustration 5 shows the FOSSIL1 reference projection.

Table 2 lists the energy policy options that can be examined with the FOSSIL1 model. To test a policy change in FOSSIL1, the proposed legislation, program, or decision rule must be translated into a change in the reference model structure or parameters. For example, in order to test the impact of ERDA's research and development program, the commercialization year, energy conversion efficiency and plant cost parameters for the various synthetics technologies are altered in FOSSIL1. Table 3 shows improvments in these parameters that ERDA expects as a result of its Fossil Energy RD&D program. (Note: this paper was prepared months in advance of presentation and therefore may not reflect current ERDA thinking.) With this change in place, the FOSSIL1 model then maps out a new behavior of the system, including the direct effects on synthetic fuels investment and production, and all the indirect effects on conventional oil and gas production, imports, electricity generation, coal production, and energy

ILLUSTRATION 5

FOSSIL1 Reference Projection (Preliminary Results)

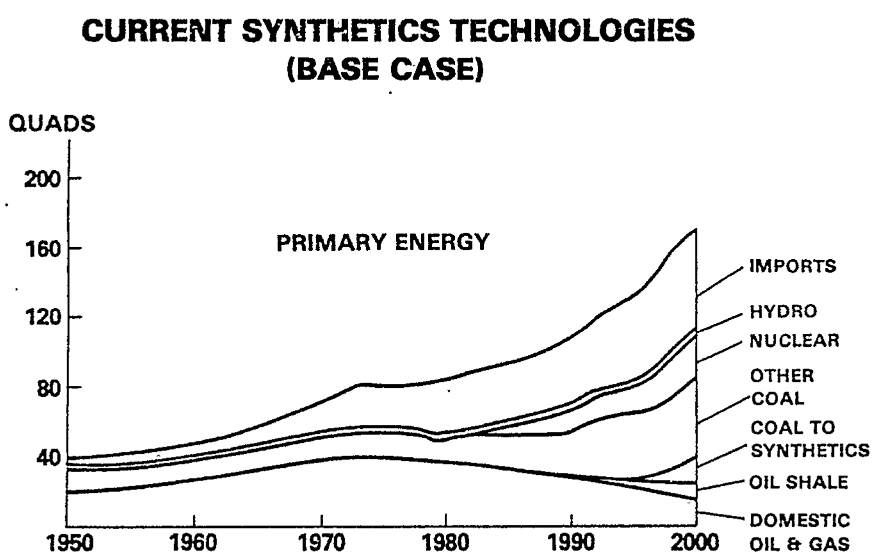


TABLE 2

FOSSIL 1 POLICY OPTIONS

RESOURCE EXTRACTION REFINING, TRANSPORTATION	SYNTHETIC CONVERSION REFINING, TRANSPORTATION	ELECTRICITY CONVERSION, TRANSPORTATION, DISTRIBUTION	END-USE DEMAND
NUCLEAR FUEL SUBSIDIES	ACCELERATED R&D IN: IN-SITU OIL SHALE LOW-BTU GAS HIGH-BTU GAS COAL LIQUEFACTION	UTILITY RATE RELIEF	CONSERVATION POLICIES ("TECHNICAL FIX")
OIL IMPORT QUOTAS, EMBARGOES		UTILITY LOAD MANAGEMENT	ZERO ENERGY GROWTH
FOREIGN OIL TARIFFS		REDUCTION OF NUCLEAR SITING AND PLANNING LEAD TIME	SHIFT IN THE COMPOSITION OF GNP TO LESS ENERGY-INTENSIVE OUTPUT
		ACCELERATED R&D IN BREEDER REACTOR TECHNOLOGY	
ENHANCED OIL OR GAS RECOVERY	ACCELERATED COMMERCIALIZATION INCENTIVES (PRICE OR LOAN GUARANTEES) FOR: OIL FROM SHALE LOW-BTU GAS HIGH-BTU GAS COAL LIQUEFACTION		INTENSIVE ELECTRIFICATION
OIL OR GAS PRICE DEREGULATION		RELAXATION OF SO_2 STANDARDS	ACCELERATED COAL USE IN INDUSTRY
OIL SHALE WATER MANAGEMENT		ACCELERATED DEVELOPMENT AND IMPLEMENTATION OF COAL COMBUSTION TECHNOLOGIES: STACK GAS SCRUBBERS FLUIDIZED BED COMBUSTION SOLVENT REFINED COAL MHD	
OIL SHALE ENVIRONMENTAL STANDARDS	CHOICE OF CONVERSION PROCESS FOR R&D FUNDING		
1969 COAL MINE HEALTH & SAFETY ACT		NUCLEAR MORATORIUM	
BAN ON SURFACE MINING			
SURFACE MINING RESTRICTIONS (STEEP SLOPE)			
FEDERAL SURFACE COAL RECLAMATION STANDARDS			
SURFACE-MINED COAL TAX			

TABLE 3

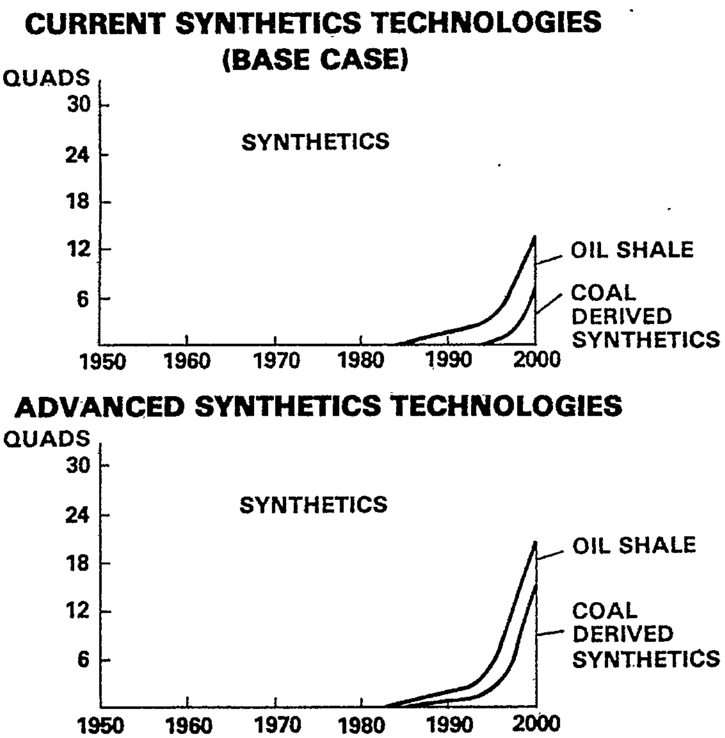
MODEL CHANGES REQUIRED TO IMPLEMENT ADVANCED RD&D PROGRAM

FUEL FORM	NOMINAL PLANT SIZE	TECHNOLOGY	STATUS OF TECHNOLOGY	MODEL CHANGES		
				COMMERCIALIZATION YEAR	ENERGY CONVERSION EFFICIENCY	PLANT COSTS (1975 $ x 10^6)
LOW BTU GAS	250 mmSCFD	LURGI	CURRENT	1975	.65	420
		LURGI	ADVANCED	1975	.65	420
HIGH BTU GAS	250 mmSCFD	LURGI	CURRENT	1975	.55	592
		SYNTHANE	ADVANCED	1984	.62	406
COAL LIQUIDS	50 mBPD	-	CURRENT	-	-	-
		SYNTHOIL	ADVANCED	1985	.64	533
SHALE OIL	50 mBPD	SURFACE RETORT	CURRENT	1958	-	560
		SURFACE RETORT	ADVANCED	1958	-	560

demand. Illustration 6 compares the projected production of synthetics in the base case of no federal research and development with the projected synthetics production due to the present ERDA research and development program. Because the model focuses only on the long-term, dynamic properties of the energy system, many effects outside the model's boundary (such as the policy's impact on inflation, GNP growth, or unemployment) will not show up in the FOSSIL1 model output. For this reason the results of the FOSSIL1 model policy analysis must be considered in conjunction with analyses that explicitly examine other aspects of a proposed policy change.

ILLUSTRATION 6

Comparison of FOSSIL1 Base Case and ERDA Fossil Energy Program Impact (Preliminary Results)



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4. Ibid., p.S-2.