A SYSTEM DYNAMICS MODEL FOR NATIONAL ENERGY POLICY PLANNING

Roger F. Naill and Sharon D. Belanger
Applied Energy Services, Inc.
1925 N. Lynn Street
Arlington, VA 22209

INTRODUCTION

The U.S. energy system has been the subject of intense national interest and policy debate over the past two decades. During that time the U.S. has experienced a steady trend toward increased oil imports, two major oil embargoes, oil price shocks, and a series of government policy initiatives designed to reduce its vulnerability to oil supply disruptions: Project Independence, the National Energy Plan, and more recently oil and gas price deregulation.

Understanding the dynamics of the U.S. energy system has been the focus of a decade-long System Dynamics modeling effort which began in 1972 at the Massachusetts Institute of Technology, continued at Dartmouth College, and is now centered at the U.S. Department of Energy (DOE). The analytical focus of that effort is an integrated model of U.S. energy supply and demand called FOSSIL2, which is used to prepare projections for energy policy analysis in the Department of Energy's Office of Policy, Planning and Analysis. This paper describes the conceptual development of the FOSSIL2 model, and its use in analyzing national energy policy issues.

BACKGROUND

The origins of the FOSSIL2 modeling effort can be traced back to the "Limits to Growth" study, a study of global population, economic growth, pollution, resource and agriculture trends conducted at M.I.T. from 1970 to 1972. This study emphasized the finite nature of our global resources, including energy resources. Resource "limits" were projected to constrain world population and economic growth over the next 50 to 100 years. The study resulted in a number of books and publications, including World Dynamics (Forrester 1971), Limits to Growth (Meadows 1972), Toward Global Equilibrium (Meadows 1973), and Dynamics of Growth in a Finite World (Meadows 1974).

To explore in more detail the nature of long-term resource dynamics, a separate study was conducted at M.I.T. in 1972 to explore the life cycle of natural gas (Naill 1973). This study confirmed the hypothesis first theorized in 1950 by a petroleum geologist, M. King Hubbert (Hubbert 1950), that a continuation of the historical decline in oil and gas discoveries per foot of exploratory drilling would eventually cause oil and gas production to peak and decline over time. According to Hubbert's theory, oil and gas production must follow a "life cycle" -- a period of low prices and exponential growth in production, a peaking of production as the effects of resource depletion cause discoveries per foot of exploratory drilling to drop and prices to rise, and a long period of rising costs and decline in production.

Applying this theory of resource "life cycles" to the U.S. energy system led to the recognition that the U.S. is in the midst of a major transition -- a historic shift away from the use of liquid and gas fuels and toward a new mix of energy sources. In fact, the United States has already gone through two major energy transitions in the past 100 years. In the late 1800's there was a shift from wood to coal as the primary U.S. energy source and in the early part of the twentieth century, a shift from coal to oil and gas. In the current transition, the U.S. is shifting away from oil and gas as primary fuels. U.S. consumption of oil and gas peaked in the early 1970's at about 75 percent of total energy use, and now has started to decline.

Yet something different is happening in the current energy transition. In each of the two previous transitions, changes in energy use were caused by technological advances that took advantage of new, cheaper energy sources. In each case the new sources -- first coal, then oil and gas -- dominated our energy mix because they were cheaper and more productive than existing sources. Unlike these previous transitions, the current decline in oil and gas use is being "forced" by shortage (depletion of U.S. oil and gas resources and rising production costs) -- not by the development of a better, more abundant resource.

Continued growth in U.S. energy demand, depletion of oil and gas resources, and long delays in the implementation of alternative energy sources raised the probability of a significant "energy gap" between demand and domestic energy production, as shown in Figure 1. The United States must rely on imported energy -- primarily oil -- to balance supply and demand during the transition period. The consequence of heavy dependence on oil imports is to make the United States vulnerable to oil import disruptions and price shocks. The policy issue of energy security (oil import dependence and vulnerability) has been the focus of a number of major policy initiatives over the past decade.[1] Increased dependence on oil imports is therefore a symptom of the U.S. energy transition problem.

THE MODEL

The transition problem shown in Figure 1 was the dynamic hypothesis for a series of System Dynamics models built between 1976 and 1980 under contract to the U.S. Government (the models were called COAL2 (Naill 1977), FOSSIL1 (SDG 1977) and FOSSIL2 (EEA 1980)). These models share a basic structure and behavior and are progressively more complicated versions of each other, and so will be described here as one model (called FOSSIL2).

Figure 2 illustrates the basic dynamic mechanism of the energy transition problem -- the depletion of oil and gas, and the feedback effect of rising costs of oil and gas production on energy supply and demand. As conventional resources are depleted, both the costs and the prices of oil and gas rise. On the demand side, price increases encourage consumers to conserve energy and shift away from oil and gas toward other fuels -- for example, gas, coal, and electricity. On the supply side, rising prices stimulates more oil and gas exploration and development, but at the same time encourages producers to develop alternative sources of oil and gas, or to invest in other sources.

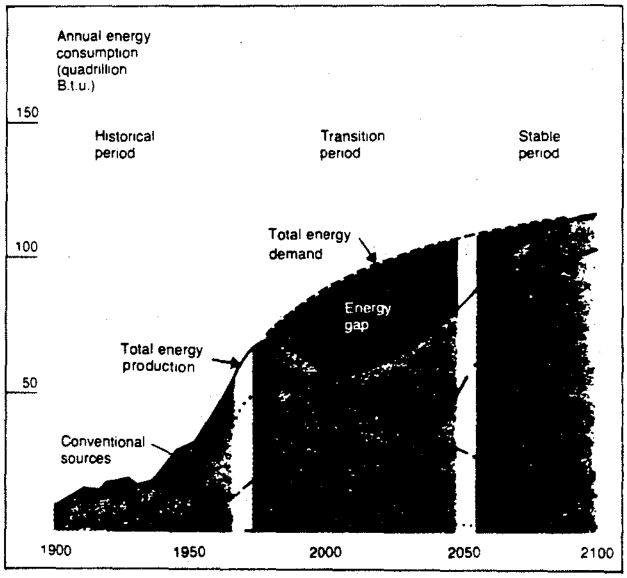
Figure 2 also shows the basic interactions between energy producers and consumers included in the FOSSIL2 model. In the demand sector, energy consumers make a decision to utilize oil, gas, coal, or electricity based on both price and availability of the fuels. Energy producers, in turn, choose to invest in the production technology that maximizes the industry's rate of return (or minimizes the average cost of production), subject to environmental constraints (for example, SO_2 restrictions or water availability) or market limitations (for example, low-Btu gas can satisfy only a fraction of final gas demand because it is uneconomic to transport long distances through existing pipelines).

Both end-use investment decisions and energy producers' investment decisions accumulate through time because they become embedded in capital equipment, and the existing capital stock determines the net demand and production capacity for each fuel. If an imbalance develops between demand and capacity, then energy prices adjust through market forces to restore the balance (unless prices are regulated).

Although energy price variations tend to balance energy supply and demand over time, several dynamic features of the energy system make the current energy imbalance unusually difficult to resolve:

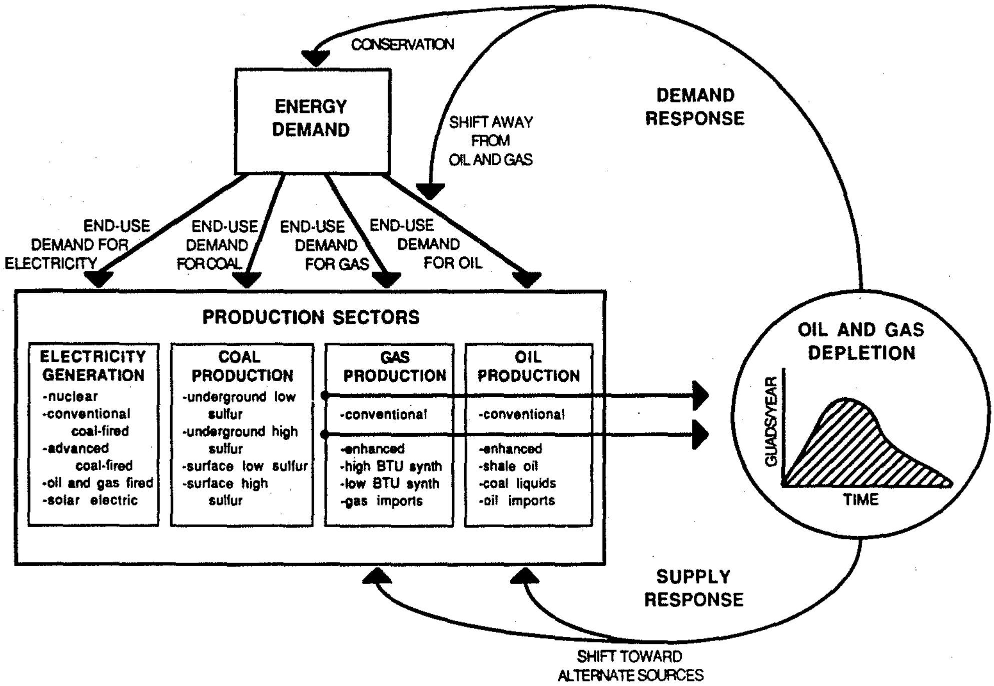
1. Expensive alternatives: In past energy transitions, new energy sources were both cheaper and more convenient than their predecessors (as in the previous transitions from wood to coal and

FIGURE 1: THE UNITED STATES ENERGY TRANSITION PROBLEM



Source: Naill, Managing the Energy Transition, p.5

FIGURE 2: BASIC MECHANISMS OF THE ENERGY TRANSITION



from coal to oil and gas). In the current transition, there is no cheap, convenient alternative to oil and gas.

2. Continued growth: As the economy grows, so will energy demand. Continued energy demand growth exacerbates the transition problem by creating increasing needs for dwindling oil and gas resources.
3. Adjustment delays: Full adjustment of the energy system to changes in the price and availability of oil and gas can take fifteen to thirty years. Energy users cannot change consumption patterns quickly, even in the face of rapid price increases. Energy producers need time to develop viable alternatives to conventional sources of oil and gas -- new enhanced recovery techniques, shale oil, or synthetic fuels from coal.

The resolution of the energy transition problem requires some difficult decisions by both public and government policymakers. Tradeoffs must be made between higher prices and decreased availability, between adverse environmental impacts and increased domestic production, and between increased political vulnerability and increased government intervention. The FOSSIL2 model structure is designed to quantify these tradeoffs.

ENERGY POLICY ANALYSIS

In April of 1977, the Carter Administration White House staff produced a document called The National Energy Plan. At this point in history, there was agreement that the United States faced an "energy crisis." World oil prices had quadrupled in 1973-74, making the U.S. realize that OPEC posed a real economic and political threat. The combined effects of regulated natural gas prices and an abnormally cold winter had caused shortages of natural gas in some parts of the country in 1975. But there was a realization that supply interruptions and shortages were symptoms of the underlying imbalance of energy demand and supply:

> "This invisible crisis arises from the pressure of growing demand on finite resources of oil and gas. Over time, economic growth and increases in population add large increments to an already large base of consumption. However, the resources from which the demand must be satisfied are limited."NEP 1977, p.9

The 1977 National Energy Plan proposed a number of major policy initiatives to reduce U.S. dependence on oil and gas. These included policies meant to:

- o increase energy conservation and fuel efficiency;
- o raise the price of oil and natural gas;
- o encourage the conversion to coal;
- o promote limited development of nuclear power; and
- o stimulate the long-term development of renewable sources.

Included in the Plan were many policy initiatives that later became law as a part of the National Energy Act of 1978 (for example, fuel efficiency standards and a "gas guzzler" tax for automobiles, residential conservation tax credits, the Public Utilities Regulatory Policy Act or PURPA, a "windfall" profits tax on oil, and expansion of the Strategic Petroleum Reserve), as well as some proposals that never became law (a standby gasoline tax of up to 50 cents per gallon).

Immediately after this Plan's publication, the House Subcomittee on Energy and Power requested the Dartmouth System Dynamics Group to evaluate the plan using the FOSSIL1 model. A report titled "Evaluation of the National Energy Plan" (Naill and Backus 1977) was prepared in June, 1977 and used as the basis for testimony before the Subcommittee in hearings about the Plan that summer. This analysis concluded that the Plan was primarily an energy conservation strategy and did not fully recognize the severity of the long-term energy problem. The analysis projected that the Plan would likely meet its goal of reducing energy demand, but would fall short on its other goals -- particularly its goal of reducing oil imports. This analysis concluded that additional policies that accelerated supply -- primarily decontrol of oil and gas prices -- were needed.

Soon after this analysis was published, one of its authors was hired to head the Office of Analytical Services in the newly-formed U.S. Department of Energy. A major part of his responsibilities was to prepare projections in support of future National Energy Plans, which were mandated by Congress to be updated every two years. To prepare these projections, the FOSSIL1 model was implemented in-house at the Department of Energy and modified extensively to allow it to analyze national energy policy issues. The new version of the model, call FOSSIL2, is still used at the Department of Energy. In the second National Energy Plan (published in 1979) and in every subsequent plan, the FOSSIL2 model has been used to prepare energy projections and analyze policies.

The second National Energy Plan was prepared under the Carter Administration in 1979. This plan emphasized supply-side policy initiatives that complemented the largely demand-oriented policies of the first National Energy Plan. These policies included a proposal to decontrol oil prices (coupled with a "windfall" profits tax on oil revenues), a $3/barrel tax credit for shale oil, and additional solar energy tax credits. The FOSSIL2 model was used to analyze the net effect of this combination of programs on oil imports, as shown in Table 1. These policy initiatives were projected to reduce oil imports by about 2 million barrels per day in 1990, mostly due to the effects of oil decontrol. Although oil decontrol was proposed in 1979 in this Plan by President Carter, it was not enacted until the spring of 1981 under President Ronald Reagan.

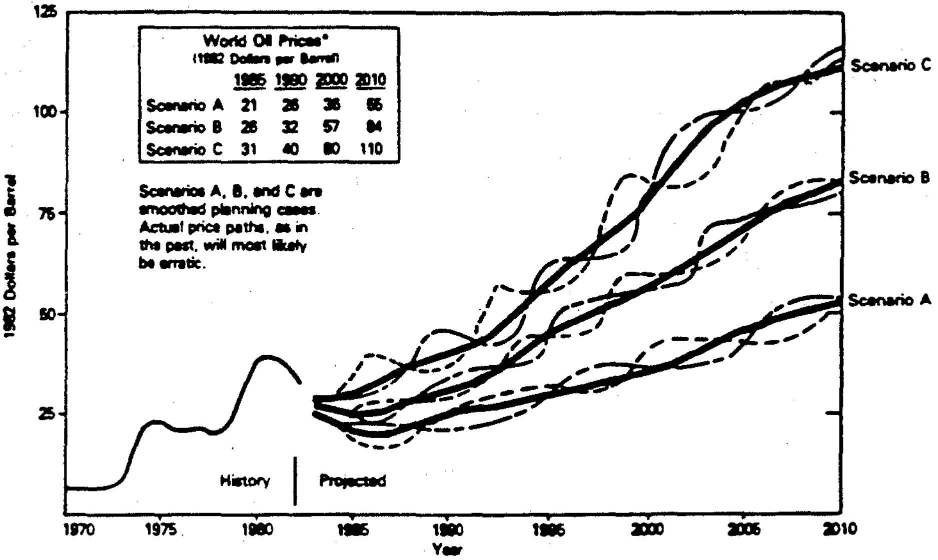
Energy policymaking under the Reagan Administration took a totally different approach from the Carter Administration. The cornerstone of the Reagan Administration's energy policy was reliance on markets -- not the government -- to solve our energy problems. President Reagan moved quickly to decontrol oil price in 1981 and consistently supported proposals to decontrol natural gas prices.

Policy analysis under Reagan, therefore, focused on projecting what would likely happen if energy markets were allowed to adjust to unforeseen conditions. The behavior of the world oil market was therefore of particular importance. To better understand the likely future behavior of this market under different scenarios and assumptions, the Department of Energy developed a world oil supply and demand model (WOIL) in 1981. When linked with the FOSSIL2 model, this model allowed policymakers at DOE to test policies affecting the combined U.S. and world energy markets.

An example of how this model was used, taken from the third National Energy Plan in 1983, is shown in Figure 3. The 1983 National Energy Policy Plan developed three world oil price scenarios from different assumptions about economic growth, OPEC behavior, non-OPEC oil supply, and other factors. In this study, world oil prices were projected to range between 36 and 80 dollars per barrel in the year 2000 (in 1982 dollars). In subsequent projections, (NEP 4 and 5), the projected level of world oil prices dropped dramatically, as energy markets have proved more "elastic" than previously thought possible. This surprising responsiveness of energy markets to price encouraged policy makers to rely on market-oriented solutions to energy problems, rather than regulatory fixes.

A more recent application of the FOSSIL2 model has been its use to analyze the effectiveness of energy policies designed to mitigate the "Greenhouse Effect." The use of fossil fuels for energy produces about 40 percent of the CO_2 added to the atmosphere each year. In 1989 the Department of Energy began a major study of policy initiatives to reduce greenhouse gases, using the FOSSIL2 model. The model structure will be modified to add emissions data to track projected greenhouse gas emissions from the U.S. energy system. The model will then be used to test the effectiveness of alternative policy options designed to reduce greenhouse gases. A report is expected to be produced at the end of 1989.

FIGURE 3: NEPP-1983 WORLD OIL PRICE SCENARIOS



*U.S. Refiner Acquisition Cost of Crude Oil Imports

Source: U.S. Department of Energy, Energy Projections to the Year 2010 A Technical Report in Support of the National Energy Policy Plan, October 1983, p.6.

CONCLUSION

The history of the FOSSIL2 model represents one of the real success stories of System Dynamics modeling. Since the implementation of the model at the Department of Energy in 1978, the model has been used regularly as a tool for national energy policy analysis. What factors contributed to this success?

First, energy was (and still is) a good problem area to apply the System Dynamics methodology. The U.S. and world energy systems have many of the properties that can be described easily in System Dynamics models: for example, nonlinearities (such as resource depletion), stocks and flows (of resources and capital), feedback loops, dynamic behavior, and the need for energy policy analysis. This makes the System Dynamics methodology a good choice for analyzing energy markets.

Second, the modelers found themselves at the right place and the right time for implementing the model. The model was developed in the late 1970's, when there was great interest in national energy planning and not much formal computer modeling had been done. The model's development was timely in that there was a great deal of interest in the policy issues that the model could address (primarily, the long-term behavior of U.S. oil imports). For example, the Department of Energy was formed in 1981, and this new Cabinet-level agency had a specific need for national energy projections and policy analyses.

Third, a specific need for the model evolved. Congress passed legislation in 1980 requiring the newly-formed Department of Energy to prepare long-term projections of U.S. energy supply and demand, and to submit them every two years in a report called the National Energy Plan. The FOSSIL2 model was developed to meet the specific needs of this legislative requirement.

Finally, as is often the case in any modeling project, the successful implementation of the model was helped by the background and interests of the people (both clients and modelers) involved. In the case of the FOSSIL2 model, the original developer of the model took a job at the newly-formed Department of Energy's Office of Policy and Evaluation, which became the major user of the model. Working from inside the organization, it was relatively easy to adapt and use the model for policy analysis. While all of these factors (good problem area, timeliness, need for the model, and personal contacts) were important, it is this author's opinion that the personal contacts were the most important factor in implementing the FOSSIL2 model successfully.

TABLE 1

IMPORT REDUCTIONS FROM POLICY OPTIONS IN THE SECOND NATIONAL ENERGY PLAN[1]

(Thousand Barrels per Day)

Proposed Action	1985	1990
Oil Decontrol and Tax[2]	950-1,130	1,400-2,100
Shale Oil Tax Credit	0-50	100-200
Solar Initiatives	50-70	100-140
Total Savings[3]	1,000-1,250	1,700-2,300

1 Range of savings represents uncertainty due to world oil prices

2 Savings compared to a base case that assumes continued controls on domestic oil prices

3 Columns may not sum to totals due to rounding.

Source: NEP2 1979, p. 157.

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Notes

1 See, for example, Federal Energy Administration, Project Independence, Washington, D.C.: U.S. Government Printing Office Stock No. 4118-0029, 1974; the White House, The National Energy Plan; U.S. Department of Energy, Energy Security, a Report to the President of the United States, March 1987.

2 For a description of Least Cost. see A. Lovins, "Energy Strategy: The Road Not Taken," Foreign Affairs, Vol. 55, October 1976, pp 65-96, or R. W. Sant, D. W. Bakke, R. F. Naill, Creating Abundance: America's Least Cost Energy Strategy, New York: McGraw-Hill, 1984.