IIASA DISTINGUISHED LECTURE SERIES /1

The Role of Models in Determining Policy for Transition to a More Resilient Technological Society

George B. Dantzig

International Institute for Applied Systems Analysis

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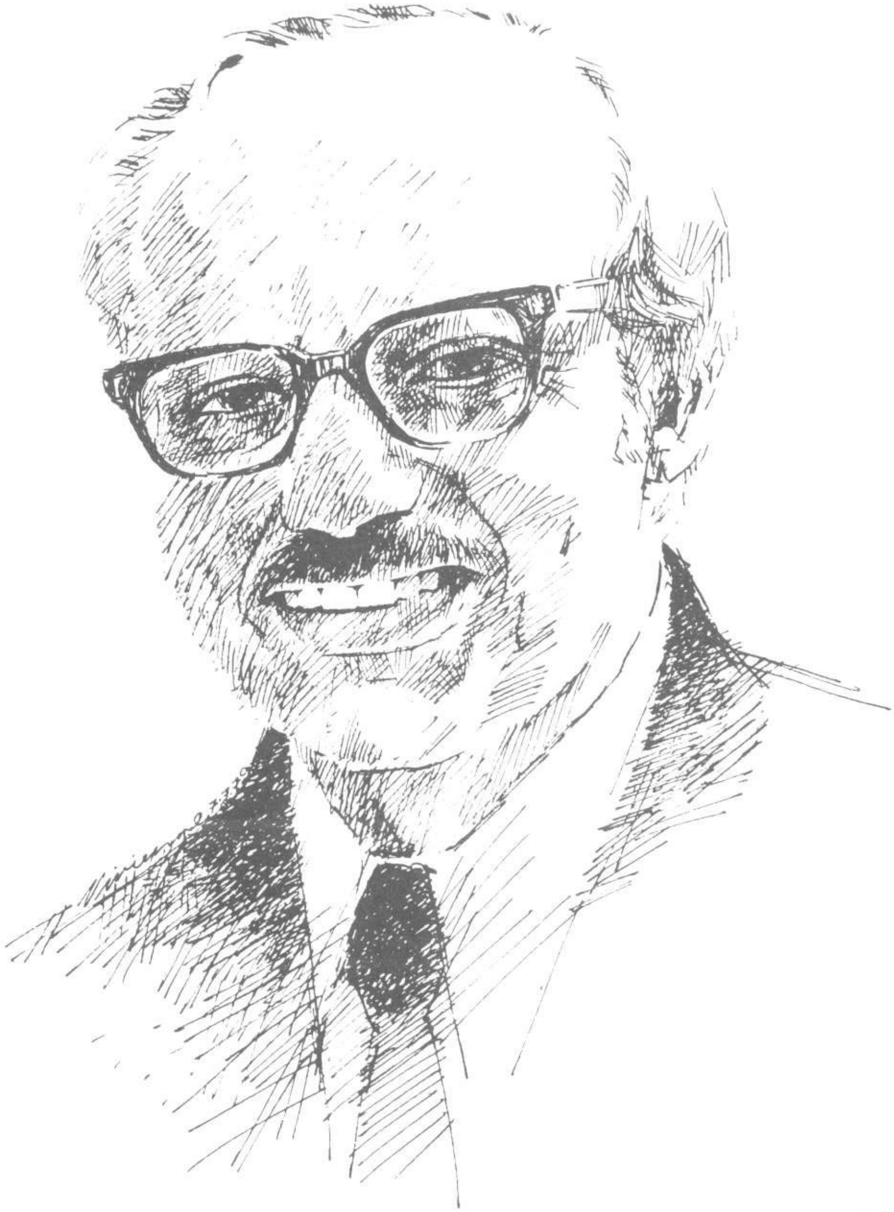

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GEORGE B. DANTZIG

International Institute for Applied Systems Analysis
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INTRODUCTION

Roger E. Levien, Director
International Institute for Applied Systems Analysis

In 1976 the U.S. National Academy of Sciences received a contribution to be used for

> ...the furthering of research, in an international setting, and addressed to the methods and concepts of systems analysis broadly conceived.... ...to support research, or the presentation and discussion of research, bearing on problems of an interdisciplinary, international and world-wide character, both with regard to the individuals participating in the research or its discussion, and to the problems of world society to which the findings are hoped to be applicable.

The National Academy of Sciences felt that an activity benefiting the International Institute for Applied Systems Analysis (IIASA) would be consistent with the intentions of the gift.

After consideration, the Institute proposed that the gift to the Academy be used to sponsor an IIASA Distinguished Lectureship, which would be an annual event intended to "further research in the methods and concepts of systems analysis broadly conceived" and to strengthen IIASA's role as a forum for presentation, exchange, and discussion of such research, with an emphasis on the international and interdisciplinary character of systems analysis.

The Academy accepted this proposal, and planning was initiated to select an appropriate speaker to initiate the Lectureship. Deliberations among the research staff and leadership led to the choice of Professor George Dantzig. In retrospect, the selection seems to have been inevitable, for Professor Dantzig's work exemplifies the ideal of methodological advancement combined with applicability toward which IIASA strives.

Professor Dantzig is perhaps best known as the inventor in 1947 of the simplex method of solving linear programs, which in conjunction with the high-speed digital computer has made possible the solution of complex optimization and planning problems in fields as diverse as petroleum refining and manpower planning, farm management and machine scheduling, water resources planning, and transport system operations. Furthermore, as the brief biography at the back of this book attests, he has contributed significantly over the past three decades to the further development of mathematical programming, which has proven to be a methodology of fundamental importance to applied systems analysis throughout the world.

Professor Dantzig has at the same time always been deeply engaged in the application of mathematics to practical problems. Beginning with the work during World War II on the scheduling of large enterprises, his career has spanned such problem areas as petroleum and gas distribution, milk production and distribution, medical diagnosis, chemical equilibrium analysis, and ecology. Today his efforts are devoted to energy policy planning.

There is another, more personal, reason that we felt George Dantzig was the best person to initiate IIASA's Distinguished Lectureship: he began IIASA's work on methodology. During the first months of the Institute's scientific activity in 1973 and 1974, Professor Dantzig established the Methodology Project and, with it, the tradition, which continues today, of a close collaboration between the methodologists and those working on applied problems. The standards of excellence that he brought to the Institute have remained as guides to the work of what has become our System and Decision Sciences Area. And his personal warmth and willingness to help have served as a model for subsequent leaders.

It is thus particularly fitting that the first IIASA Distinguished Lecture has been presented by Professor George Dantzig, recipient of the U.S. National Medal of Science, member of the U.S. National Academy of Sciences, and IIASA alumnus.

THE ROLE OF MODELS IN DETERMINING POLICY FOR TRANSITION TO A MORE RESILIENT TECHNOLOGICAL SOCIETY

George B. Dantzig

THE THREAT TO SURVIVAL

Harrison Brown, in his new book, *Learning How To Live in a Technological Society*, says

> Historians of the future may well look back upon the thirty-five year interval between 1973 and 2008 as the most critical of human history. We must face the fact that we are well into a period in which enormous world forces are converging rapidly and threatening to engulf us all. Indeed those forces may well destroy, perhaps forever, our ability to create a world community in which all people have the opportunity of leading free, abundant and even creative lives, divorced from the traditional scourges of hunger, deprivation and war.

Why does Brown select 1973 as the starting point? "Because that marks the year when a major critical resource, crude oil, was first used ...as a major weapon of war." The convergent forces he speaks of are rapid growth of population and affluence; increasing demands for food, energy, and raw materials; decreasing quality of the resource base; changing environment, including climate; rapid technological change; the growing gap between the rich and poor nations; the increasing danger of nuclear war that hangs over all humanity; the rivalry of the superpowers; and the

This paper was prepared while the author was on sabbatical leave from Stanford University; he was with the Institute for Advanced Study of Behavioral Sciences, Stanford, California, from January to June 1979 and the International Institute for Applied Systems Analysis, Laxenburg, Austria, in June and July 1979.

increasing vulnerability of complex industrial societies to disruption by a combination of internal and external pressures.

Modern technological societies are confronted by this vast array of problems. They are interlocked, one with another, forming a vast web. The solution to any one problem will not necessarily ease the functioning of the whole – indeed, it can often make things worse. This is true because the modern technological world is incredibly complex, interconnected, and interdependent.

WHAT IS MEANT BY THE STATEMENT: "MODERN TECHNOLOGY IS COMPLEX"?

It is not easy to paint a picture of just how complex modern technology is. One way to start is to list the activities of a small town. By using the classified section of the telephone directory, I can list a few activities of the town of Richmond, California. Here are those that begin with the letters *Br*: Bridge Builders, Bridge Tables, Broadcasting Stations, Brochures, Brokers, Bronze, Brushes, Brooches, Brakes, Brandies, Brazing, Bricks, Brick Stain, Bric-a-Brac. I counted over 6,000 activities in all.

Another way to see the diversity of the material side of life is to look at a catalog of electronic supply items that are for sale. There are thousands upon thousands of different kinds of resistors, condensors, vacuum tubes, transistors, cables, sockets, knobs, switches, dials, circuit boards, cabinets. Look up the number of different items listed in a chemical supply catalog or a Sears, Roebuck catalog, and again the number of different items runs into many thousands. A modern university can have a hundred different departments. The United States Government has nearly 2,000 different kinds of offices in San Francisco alone, each presumably carrying out a different function for the public good. So far we have spoken only of diversity, but complexity has other dimensions.

The Leontief input–output model of the national economy of the United States classifies industries into about 400 major types and requires data for each of these industries about how much it shipped (or received) from every other industry. The resulting 400 × 400 table contains 160,000 numbers. Each region of the country has such an input–output table, and there are many regions. Each number in an input–output table expresses a dependency of one industry upon another; the transactions between regions and industries represent further dependencies; there are a great number of cross combinations. Countries depend on each other in the same way.

There are also *time* dependencies: facilities are built and maintained for future use; material is stockpiled for future use; people are trained for future jobs. There are *locational* dependencies as well: men, material, and facilities are moved to new locations, not only on the surface of the globe but below and above.

While we may easily understand the ins and outs of each small part of this vast web of activities, the problem is how to track all the interactions at once. We know that the powerful forces of population growth, shortages of raw materials, food, energy, growing affluence, and so on, are rapidly reshaping this complexity. There is a fear, based on reasons that I will deal with below, that the structure that interconnects these activities may not hold up very well under these stresses. We see the possibility of all kinds of system failures if we let the changes go on uncontrolled. Is there some way to come to grips with this complexity, to steer and reshape it into a more resilient, less interdependent economic system?

The greatest hope, in my opinion, for coming to grips with the dynamics of change in our complex technological society in these critical years ahead, lies in the use of mathematical models and computers. This use of models is not *the* solution, but without them, there may be no good way to plan a smooth transition.

WHAT ARE MODELS?

The term "models" requires some definition. In its crudest form, a "model" of a system, whether it be a biological system or an economy, is viewed as a black box whose inner workings are a mystery; it is possible, however, to observe the various inputs into it or outputs from it. One describes the system mathematically by a system of differential equations or finite difference equations, usually linear. One adjusts the unknown coefficients of the models and other parameters (such as time delays) so that a good fit to the historically observed inputs and outputs is obtained.

I call models of this sort *models of ignorance* because they assume that nothing is known about the inner workings of the system. Even though such knowledge exists, it is sometimes convenient to act as if one didn't have it: I recently heard a talk about an automobile engine being modeled in this way. These crude models of ignorance have been remarkably successful in practice; indeed, much of control theory uses this approach.

Econometric models are more sophisticated versions of this type of model. The differential equations are no longer linear but are nonlinear functional forms whose solutions make more sense over a wider range of inputs. Such models should perform better than models of total ignorance, but there are those who would question whether they do.

Another class of models makes use of simultaneous equations. The Leontief input–output matrix is a good example of this sort. The economy is represented (as noted earlier) by about 400 industries that produce 400 different types of goods. Each industry is represented by a column of the matrix; this column is the vector of inputs required to produce one unit of output. Given the levels of production of various industries, one can multiply these by the input–output matrix to compute the net output of goods available to the consumer sector. Conversely, given the net output of industry, one can multiply it by the *inverse* of the input–output matrix to compute the production levels necessary to produce this output in the real world.

I should like now to turn to a third type of model. These are *alternative* processes. For example, in the energy sector, there are a number of different ways to produce electricity. The third class of model, the *linear program*, allows for such alternatives. As in the Leontief model, the columns of the matrix of coefficients represent the inputs and outputs of various goods associated with a unit level of an activity (a process). There are now more columns than rows because alternative processes are allowed. As in the real world, there is now freedom to do things in different ways, and it is necessary to use objective functions to select among the alternatives.

The dynamics of growth in a finite world have been studied by Forrester and Meadows using models of the finite difference equation type. Other global models use a mixture of approaches and vary greatly in level of detail. (Global models have attracted great attention and concern because of their prophecies of worldwide shortages of food and energy.)

The Leontief and linear programming models are often called "bottom-up" because they attempt to build a representation of the system from known (or hypothesized) workings of its various detailed component parts. For example, a refinery is represented as a collection of chemical processes in various tanks and pipes that transform the outputs of one process into the inputs of another. Each process has a known mathematical description, and the power of the model is that it is able to simulate the complexity of the system as a whole by keeping track of the transformations going on within a part and by accounting for the flow between parts.

There are two ways in which models are used:

1. To simulate an existing system and to predict how it will change over time.
2. To model a variety of possible future systems with the idea of selecting a future that is more attractive than the others according to some specified criterion and then to spell out broad policies that appear necessary to bring this future about. (Actually, models of this type can do much more. It is possible to find a solution that is "best," i.e., one that maximizes the criterion function.)

A policy may be simply a statement: "We should build two central solar power stations in Arizona by the year 1990." Usually, we use the term more broadly, to mean a consistent policy – a program of actions that are consistent with one another and mutually self-supporting.

Both kinds of models work with very aggregated representations of reality. The state of the nation or of the world is boiled down to a few hundred numbers. The number of relations between various activities is boiled down to a few thousand. As a result policies are also expressed in very aggregated terms. Even so, policy makers often complain that the answers provided by the models are too detailed. Unfortunately, the nature of complexity is that it is complex. Because politicians and the public demand simple answers to complex issues, the search goes on to find ways of expressing policies in simple terms. Recently, my group at Stanford has been asked by the U.S. Department of Energy to work on a project originated by James Schlesinger, the U.S. Secretary of Energy, called "Model Simplification." Our approach is to set up a hierarchy of submodels, each of which supplies summary-type information to the next higher echelon.

Before discussing the use of models, let us return to the subject of *why* models are needed.

MODERN TECHNOLOGICAL SOCIETIES ARE FRAGILE

Industrial society is a complex interconnected system composed of mines, factories, farms, transportation and communication networks, power grids, and water and sanitary systems that support our homes, shops, hospitals, schools, and recreational facilities. The failure of any major component can jeopardize the life of the whole, much as can a failure of a single critical organ of the human body.

Industrial society is like a busy highway – the slightest disruption can cause a monumental traffic jam. One accidental overload of an electric power grid can cause the blackout for days of a whole section of the United States. The fat belly of an operator of a control panel of a nuclear power station can obscure the instruments warning of danger, causing a meltdown of the nuclear core and the scrapping of a billion-dollar reactor. The recent short supply (or rumored short supply) of gasoline in California caused millions of motorists to queue in their cars for hours, disrupting work and damaging the tourist industry. On a still larger scale, economies may go into recession or into boom; inflation can go out of control. Systems have become so complex that they are no longer understood in all their intricacies.

A kind of mystique has grown up about systems. In recent times a number of books have appeared about the "mysterious ways" in which large-scale systems behave; these systems appear to take on a life of their own. The books are humorous, silly, often no more than a collection of clichés. Most people do not take the ideas expressed very seriously, but the system failures that they describe are all too familiar.

John Gall, in his remarkable little book, *General Systemantics*, pronounced "system *antics*," describes the ways of systems:

> Things Aren't Working Very Well
>
> Systems In General Work Poorly Or Not At All
>
> If Anything Can Go Wrong It Will
>
> New Systems Mean New Problems
>
> Large Systems Usually Work In Failure Mode (If At All)
>
> A Large System, Produced By Expanding The Dimensions Of A Smaller System, Does Not Behave Like The Smaller System
>
> When A Fail–Safe System Fails, It Fails By Failing To Fail Safe.

(He likes to capitalize the first letter of words.)

Gall captures the essential difficulty of dealing with complex systems with the following alliterative (possibly) fictitious example:

> Insecticides, introduced to control disease and improve crop yields, turn up in the fat pads of Auks in the Antipodes and in the eggs of Ospreys in the Orkneys resulting in incalculable ecologic damage.

MAKING SYSTEMS LESS FRAGILE

Gall offers only one piece of advice: Don't make systems too tight. Tightness is the result of trying to make systems efficient. *Don't!* Build in redundancy instead. Have many different ways to do the same thing. Systems that are not tight last longer and function better.

Modern technological societies are too fragile – they are designed too tight. Many critical industries and services are now so highly automated and computerized that only a few persons are needed to operate them. They are, for this reason, highly vulnerable to sabotage, strikes, accidental happenings – vulnerable because highly trained operators become bored and are replaced by less well trained operators, who are unable to cope with a real emergency; vulnerable because no one is really in charge; to be more precise, vulnerable because, in fact, bureaucratic regulations are in charge, with only "good soldier Schweik" at the controls, following orders designed to cover the worst case.

We can learn much by studying other complex systems, such as earlier societies or biological systems, that have successfully survived for long periods. Here are some observations about how resilience can be increased:

1. By not placing the system under too severe a strain. Don't operate a system near its capacity.
2. By building redundancies into the system so that when one part is strained, alternative pathways are available that will permit the strain to be relieved.
3. By being prepared to accept risk in order to reap benefit. This could greatly simplify the complexity of parts of the system.

The demand of industrial societies for energy is increasing rapidly. This has greatly increased the strains on almost all the economies of the world. In order to lessen the vulnerability that results, three approaches are being pursued by industrial societies:

1. Lessen the needs for energy.
2. Make greater use of domestic resources.
3. Diversify external sources of imported energy.

Major Changes Are Required to Make our Society Less Fragile

Becoming resilient requires extensive changes in the ways we do things. Self-sufficiency in energy requires using energy sources ranging from trees to uranium ore; it involves the use of sun rays to heat homes; coal and shale and alcohol to generate liquid fuels to run our cars; windmills and geothermal power to light our lights. There is an urgent need to redesign our cities so that they are less vulnerable to electric power outages and to transportation failures; so that they are more convenient, with fewer automobile accidents; and so that green space is conserved.

The coordination necessary to bring about the smooth transition to a more resilient industrial base and urban design is extensive and would have to proceed on a broad front. It is made all the more difficult by various groups who may be opposed to change because they feel that their vital interests will suffer. Indeed this resistance to any proposed changes may be the most difficult stumbling block of all. Only through developing consistent programs of action that clearly demonstrate that the proposed actions are to the advantage of society as a whole can we hope to find ways to convince these diverse groups to cooperate for the common good.

HOW THE PILOT ENERGY/ECONOMIC MODEL CAN BE USED TO DETERMINE POLICY

In order to determine what changes are necessary – i.e., to arrive at a consensus on what actions should be carried out – models can play an essential role. I should like now to illustrate the kinds of consistent plans that can be developed by using the PILOT Energy/Economic Model, which I helped build at the Systems Optimization Laboratory, Operations Research Department, Stanford University. Our research at Stanford is an outgrowth of my contacts with Wolf Häfele and his Energy Project at IIASA. (During the early days of IIASA, 1973-1974, I served as leader of the Methodology Project.)

PILOT addresses the following problem:

Currently, two-thirds of U.S. energy comes from domestic gas and oil. In the next 40 years only one-third can come from this source. Query: How do we effect a smooth transition to new energy sources?

The main linkages of the PILOT model are shown in Figure 1. The "industry" box is a Leontief input–output model of the economy – this part describes the inputs into each industry from other industries in order to produce a product. The "detailed energy" box describes a large variety of processes (nuclear, solar, oil, gas, coal, and so on) that convert raw

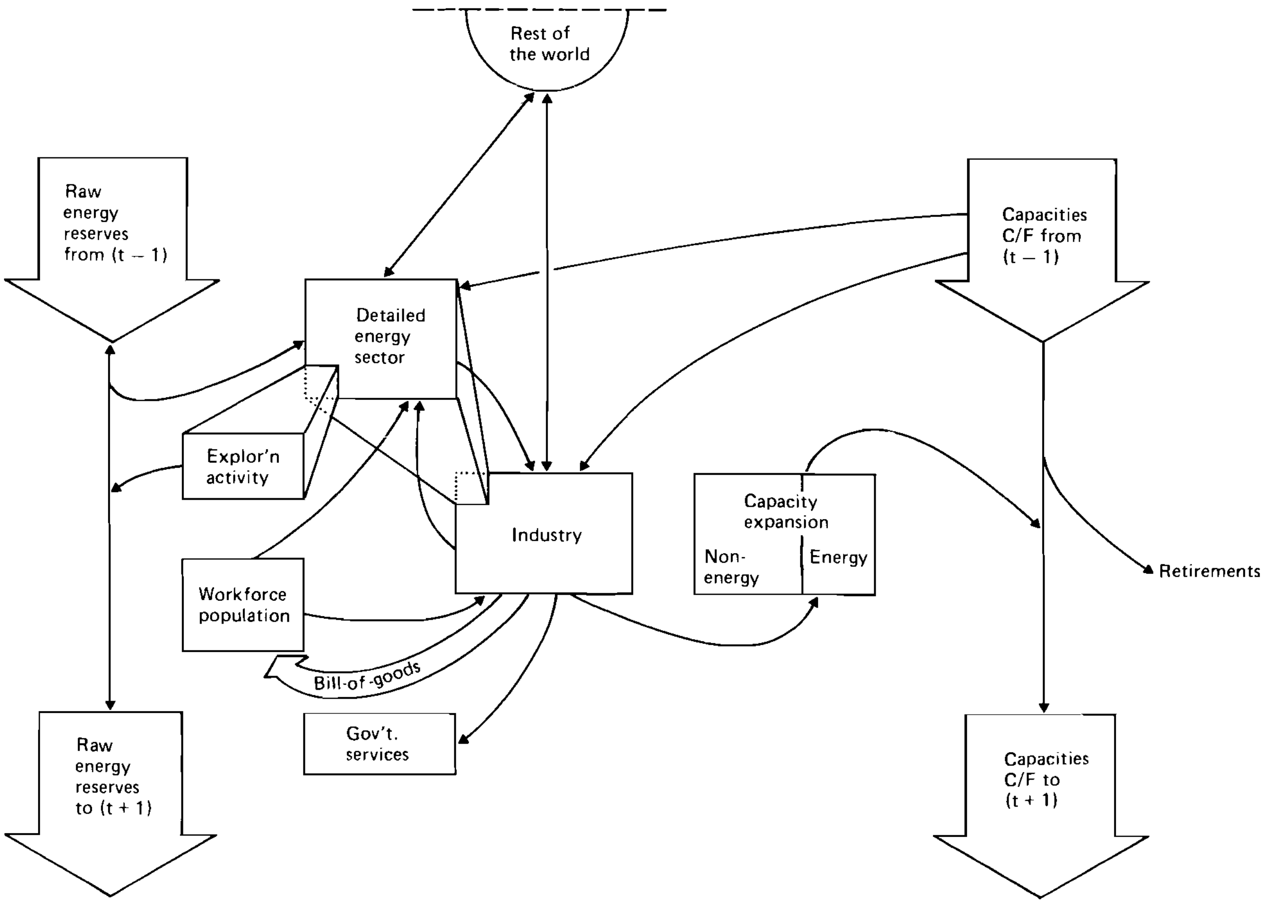

FIGURE 1 A schematic representation of the main linkages in the PILOT model.

source energy into more usable forms. The model is dynamic. Reserves of oil and gas are kept track of over time. Exploration for new oil and gas enlarges these reserves; oil consumption reduces them. The capacity of industrial facilities is expanded as required over time by drawing on products in competition with the products used by the final consumer. Consumers, in turn, provide industry with a workforce. To acquire foreign oil, industry must produce products for export. The relations dealing with the balance of payments between nations are represented by the "rest of the world" box.

PILOT belongs to the second class of models described earlier. It lays out a possible future for the United States. It is a linear programming model consisting of 800 linear equations in 2,000 non-negative variables representing the levels of activity of various processes over the next 40 to 100 years. The objective of the model is to maximize the future standard of living of the population. Figure 2 shows one of many pages of output of the model: the sources of energy that should be developed.

Figure 3, drawn from another study using the PILOT system, shows dramatically that major changes are required in the way we heat our homes.

The objective to be maximized in the PILOT model, as mentioned above, is a function that represents the "standard of living." This is defined as the discounted sum (over the period of the study) of the Gross National Consumption. Figure 4 shows that the availability of primary energy can make a big difference in the average income level. By 2005 the average income could be $6,000 (in 1967 dollars) per person if there is abundant primary energy available; it would be only 65 percent of this if primary energy is in short supply.

The PILOT Energy/Economic Model is one of many models currently being used by the Department of Energy of the United States and by the Electric Power Research Institute (EPRI) to study the long-range aspects of the energy transition problem. It is also one of many that have been used by the Energy Modeling Forum to study various energy issues. I should like to say a few words about this forum.

THE ROLE OF THE ENERGY MODELING FORUM IN DETERMINING POLICY

The Energy Modeling Forum (EMF) (with headquarters at Stanford University) supported by EPRI and other groups, is an important new way to bring policy makers and model makers together. The modus operandi

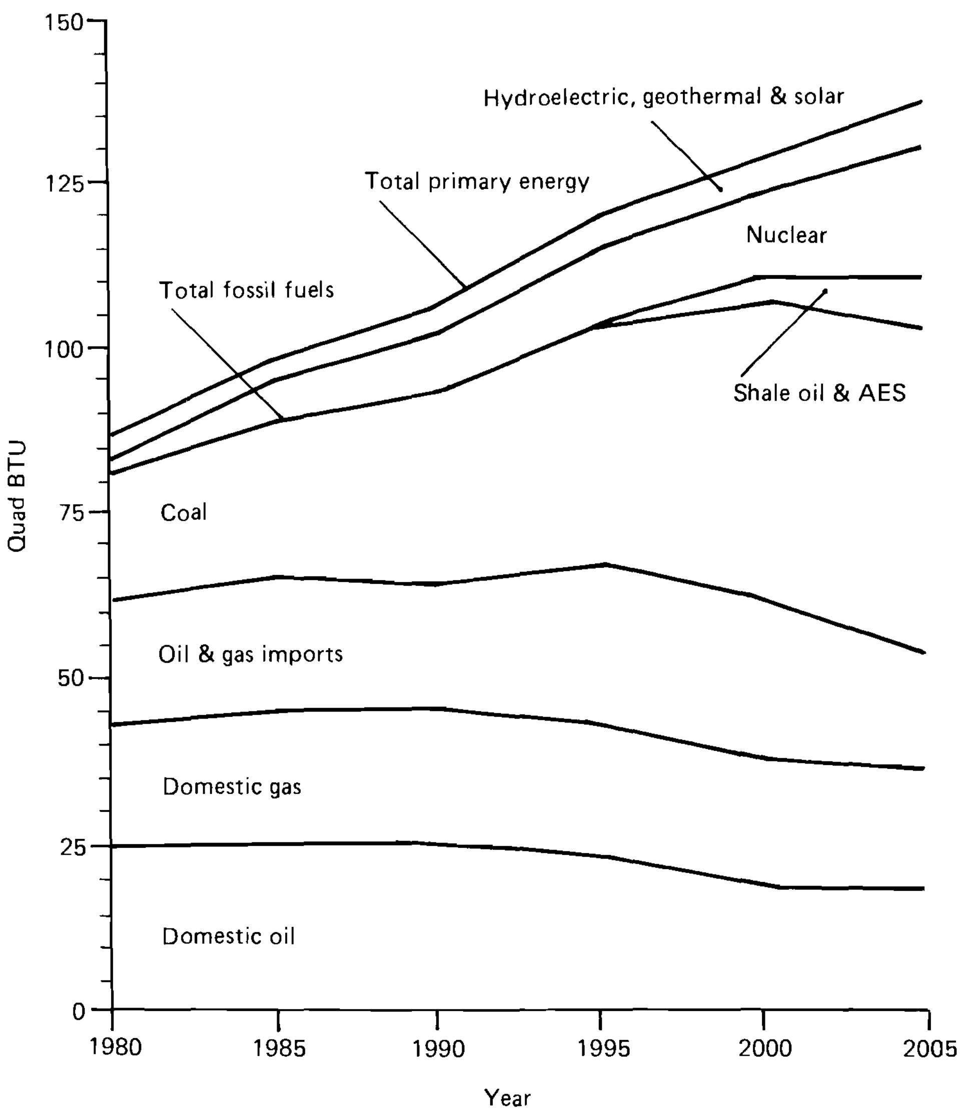

FIGURE 2 Consumption of primary energy (PILOT model).

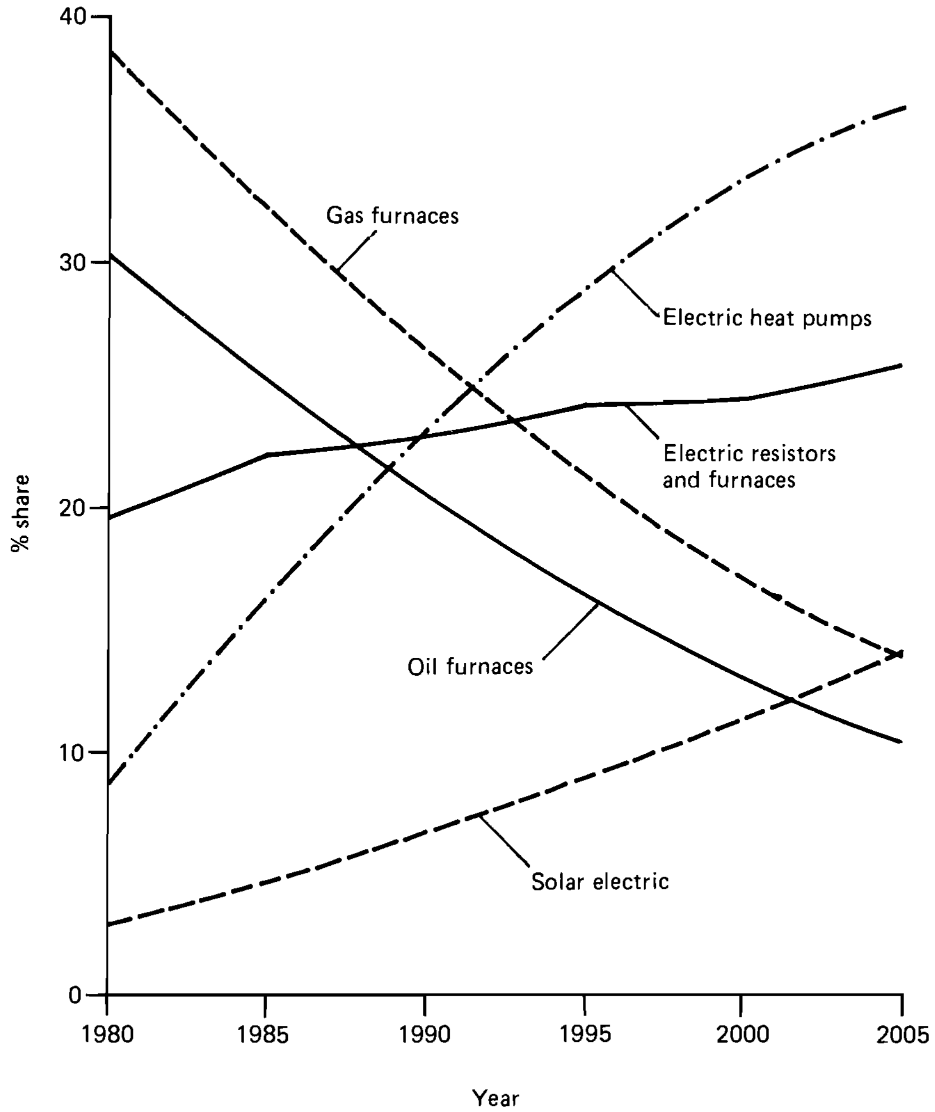

FIGURE 3 PILOT model output. Share of space heating demand by energy system (percent of end-use demand).

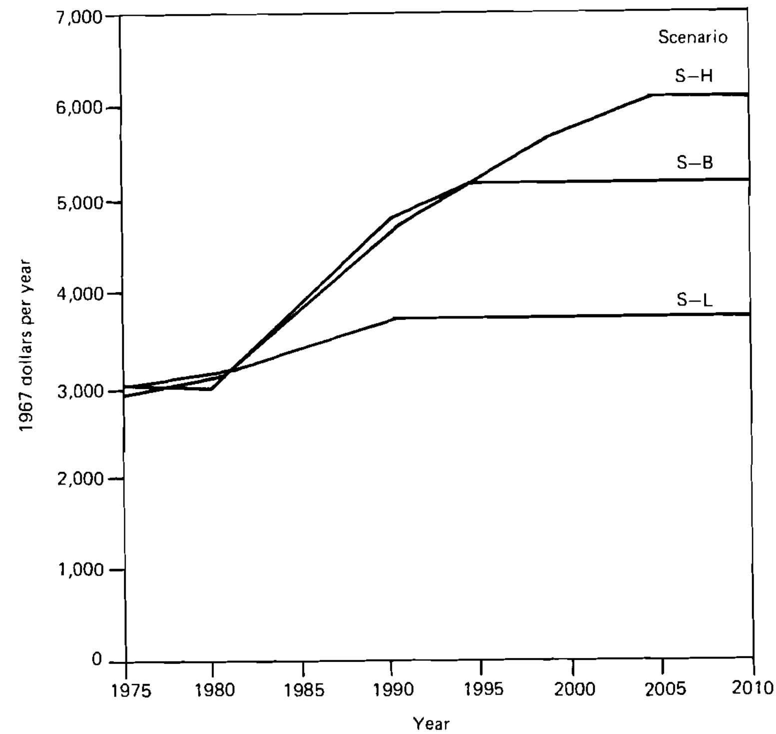

FIGURE 4 Comparison of U.S. per capita consumption of goods and services attained under PILOT base case, high availability, and low availability of primary energy.

of EMF is first to select an issue related to energy; next to get agreement on source data, basic assumptions, and scenarios; finally, different groups that have developed models (using different methods) are invited to run their models in competition with each other. The results are compared. As many as eight models can compete. Differences in results can be very instructive. The Forum has done much to build up confidence in energy/economic models and to learn about their strengths and weaknesses. These exercises have helped to bring about a consensus among academics, industrialists, and government officials about what the nature of the transition to new energy sources is and what form it is likely to take or should take.

THE USE OF SCENARIOS TO TEST THE RESILIENCE OF THE SOLUTION

Typically, energy models are run under a variety of scenario assumptions to take into account the effects of conservation and the uncertainties about the availability of new technologies, foreign energy imports, domestic reserves, and so on. Some attempt is made in this process to arrive at a future energy technology profile that will be able to supply energy even when various unplanned and unhappy events (as represented by scenario cases) occur. Nevertheless, much work needs to be done to arrive at solutions that, if implemented, would yield the kind of resilient industrial structure that Harrison Brown believes is necessary if modern society is to survive.

EDUCATING POLICY MAKERS TO USE MODELS

The problem of the growing disparity between rich and poor nations, the problem of changing the nature of our industries so that they will be less vulnerable, the problem of transition to new technologies as traditional sources of resource supply disappear, the problem of changing and reworking the design of our cities, all can benefit from the advanced use of models since such use can result in balanced and consistent plans of action. We live in rapidly changing times, and the time has come to demonstrate to policy makers and politicians that their respective countries – and the world – can no longer allow them to make policy about complex systems (such as the economy or the environment) without the use of such models. The Energy Modeling Forum and the International Institute for Applied Systems Analysis are part of this educational process.

Much work needs to be done, however, to educate policy makers, as can be seen from a recent survey of key personnel in Washington, D.C., involved in policy making. The following is a paraphrase of some of the answers received about their opinions of modeling and analysis:

> "A good Assistant Secretary knows when to use a number. He knows when a number is good and knows where and to whom to go to get a good number."

> "Staff people (of a senator) are not influenced by models, except if they conform to a point of view that they wish to promote."

> "Senators are advocates. Few if any of them know anything about the technical details modeling folk talk about. They don't talk the same language."

> "PIES (the main planning model of the Department of Energy) is irrelevant to anything we do around here. No one and I mean no one, takes it or any other model seriously."

"At best, a senator has a 6-year time frame, but we are asked to look at analysis with a 25-year horizon, or more. That is ridiculous."

"We need discrete and simple answers, and no model is going to give you that."

"The only influence of impact that modeling has is on the incomes of the modelers."

The situation with regard to use of models for policy analysis, however, is not as gloomy as these answers seem to indicate.

For example, John Weyant in a 1979 EMF study, "Quantitative Models in Energy Policy," has made an analysis of two important energy policy debates before the 94th Congress. In his paper, the extensive use of models in these instances is documented and analyzed to identify conditions that seem to have led to the success or failure of modeling tools. Another survey, this time of federally funded modeling projects, concluded that no more than one-third of the models developed achieved their avowed purpose of direct application to policy problems. I regard a score of one-third as very good indeed!

Another example. In 1978 the State of Texas took steps to acquire from the U.S. Department of Energy the PIES model with the purpose of making their own analysis of what U.S. energy policy should be. This is the first instance I know of in which two rival political groups have been using models to advance their own positions. In my opinion, this may be the most important single event in the effort to bring about the acceptance of models as the principal tool for analyzing complex issues.

SUMMARY

As Harrison Brown has said, the period 1973 to 2008 is a critical one for modern, technically oriented societies. He believes that our present society is structured too tightly and is fragile and vulnerable to world forces of growing population, diminishing resources, rising affluence, differences between rich and poor nations, accidents, strikes, sabotage, and so on. Our society may not survive unless it undergoes, with all deliberate speed, changes that will make it less fragile, less vulnerable.

The world, and in particular each country, should act now. IIASA could take responsibility for the global aspects. Because of the complexity of the economic, environmental, and political systems, I doubt that a smooth transition can be effected without the extensive use of models to represent this complexity in order to develop consistent programs of action – that is, to develop policies that, if implemented, could lead to a more resilient, less vulnerable economic system with a greater promise of the good life for all.

The methodology for using models and computers for formulation of policy exists and has been tested. Their use by policy makers so far has been very limited (at least in the United States). If we accept the thesis that the danger of collapse of our society is very real because our technology is designed too tight, then I feel that it is important that models assume a key role in developing plans for moving smoothly to a more resilient technological society.

Time may be running short.

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GEORGE B. DANTZIG

Professor Dantzig received his early training in mathematics at the University of Maryland, the University of Michigan, and the University of California at Berkeley, earning a doctorate in 1946. He worked on quantitative planning methods at the headquarters of the U.S. Air Force from 1946 to 1952, and at the Rand Corporation from 1952 to 1960, when he moved to the University of California at Berkeley to become chairman of the Operations Research Center. At Stanford University since 1966, he holds the C.A. Criley Chair in Operations Research and Computer Science.

From 1973 to 1974, while on leave from Stanford, he was the first head of the Methodology Project at the International Institute for Applied Systems Analysis.

In 1947 he introduced the concept of an objective function into quantitative planning, formulated a linear program containing such an objective function, and developed the simplex method of finding the optimal value of the objective function and the conditions that would produce it, a method that is still in wide use today. Since then he has made many contributions to the theory and use of linear programs and to such allied fields as input–output economics and network flow, and his contributions to these fields and their many arenas of application is continuing.

He is a Fellow of the Econometric Society and of the Institute of Mathematical Statistics and a past president of both The Institute of Management Sciences and the Mathematical Programming Society. He holds honorary doctorates from the Technion in Haifa, Israel, the Linkoeping University in Sweden, the University of Maryland, and Yale

University. He has received the von Neumann Theory Prize of the Operations Research Society of America and The Institute of Management Sciences, and the Numerical Analysis and Applied Mathematics Prize of the National Academy of Sciences. He was elected to the National Academy of Sciences in 1971 and to the American Academy of Arts and Sciences in 1975. He received the 1975 U.S. National Medal of Science.