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Dynamics of an Energy-Economic System Subject to an Energy Substitution Sequence

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Abstract *Cyclic phenomena in global industrial production have been observed by means of different analyses applied to historical data. Independently, logistic trend patterns in primary energy substitution have shown penetrations of similar time periods. These characteristics of industrial society have yet to be linked in a unified manner. In this article, energy interactions among fossil fuel stock resources, environmental flow sources, energy-refining industries, and the economic infrastructure that manufactures goods and services are combined to form an energy-based dynamic systems model of global industrial society. When the model is subjected to inceptions of new energy stock resources of increasing quality, as measured by thermodynamic availability and accessibility, primary energy substitution patterns are generated, as are cyclic patterns in industrial production and unperturbed logistic trends of total energy consumption and production.*

Introduction

Attention to the fundamentals of the basic operation of a society has been renewed recently in an effort to explain the observed, apparent long-wave, cyclic behavior of key indicators of that society. (Kondratieff 1906, Bodger et al. 1986, Futures 1981). Forrester (1976, 1978) and Graham and Senge (1980) presented society as a dynamic system through equation form and feedback loops and have produced results that appear to show long-wave behavior in capital investment, production, and capital stock, and they have related this to long waves observed in innovations. They argue that the central long-wave mechanisms come from the interactions of a capital goods–producing sector and a consumer goods–producing sector.

In contrast, Marchetti (1980) considers society a learning system that behaves in a manner subject to simple physical laws. Political altercations or willful planning appear only as perturbations of continuing trends in primary energy substitutions; they are unerring in their long-term continuance, much like a law of nature. Marchetti suggests that the economic features of a society may be an expression of the physical phenomena that are related to the basic working of the society. In this regard society is characterised by logistic functions without causal explanation, although Marchetti referred to wave behavior for primary energy consumption, innovations, and inventions and to details of the phasing of these waves with respect to each other. Any hypothesis on long-wave phenomena should account for the primary energy substitution patterns. No existing study does this however; the patterns are ignored.

The logistic modeling used by Marchetti has simple governing equations and leads to future predictions that imply new energy sources and new phases of inventions and innovations, penetrating at ever-increasing rates without limit. Recently, Baines and Bodger (1984) considered additional energetic criteria, namely accessibility and availability, as an explanation of a society's patterns of sociotechnical behavior under the physical limitations of the laws of thermodynamics. Quantitative data of New Zealand primary energies showed trends that appeared to be moving away from the continuing logistic penetrations of Marchetti toward a stable, sustainable future characteristic of a damped dynamic system.

The concept that society can be modeled as a dynamic system while being governed by the physical laws of thermodynamics has been discussed by ecologists (Jackson-Davis 1979), and a dynamic energy model for New Zealand society has provided insight into variations in energy parameters, the net production of goods and services, and economic infrastructure under specific changes in the availability of energy sources for that society (Baines and Peet 1986). In this article, dynamic energy modeling is used to produce a conceptual system model that incorporates the penetrations of new forms of primary energy sources, each having successively greater accessibility and availability. Cyclic fluctuations in capital investment in the energy and consumption sectors of society and overall industrial production can be generated by this energy model.

An Energetic Perspective of Dynamic Social Systems

For analyzing the dynamic behavior of an aggregated economic system, it is necessary to define the boundary of the process so as to encompass all economic activity. The energetic perspective of system dynamics classifies real economic systems as open in thermodynamic terms because there is always an exchange of energy and material between the system and the environment (Bett et al. 1975). These exchanges are subject to the laws of thermodynamics, namely that matter and energy cannot be created or destroyed and that perpetually self-maintained processes are an impossibility (i.e., entropy increases when energy is expended).

The absolute outer limits to dynamic, physical activity are defined by energy supply. No social or economic utility can be generated without the consumption of available energy and its consequent entropic degradation. This observation means that the dynamics of the economic process are ultimately constrained by the availability of energy in the environment and its accessibility to economic consumption. When related to physical dimensions, the thermodynamic concept of availability leads directly to consideration of energy concentration and energy quality. The maximum amount of work that a given quantum of energy commodity can yield is directly determined by its available energy content. If available energy is to have any value, however, it must also be accessible (Georgescu-Roegen 1976). The application of economic or energy resources is required to access a stock or flow of available energy resource; that is, it is necessary to use energy to get energy. As a consequence, an accessible energy source must yield more energy than is expended in obtaining that energy.

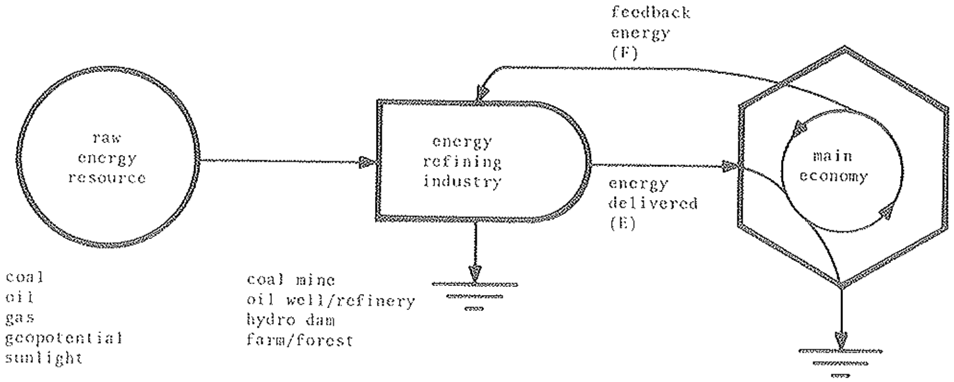


Figure 1. Energy producer-consumer system.

As shown in Figure 1, the concepts of availability and accessibility can be quantified in terms of two energetic parameters, net energy yield (NEY) and energy yield ratio (EYR). Net energy yield is the amount of energy delivered into the mainstream of economic activity less the amount that has been expended in accessing it. The net energy yield of the system in Figure 1, for example, is the energy delivered (E) minus the feedback energy (F). It is the energy that is available to drive work processes in the main economy and thereby to contribute to the production of other goods and services. The energy yield ratio is the numeric ratio of the energy delivered to the economy to the feedback energies required. In the simple example of Figure 1, it is the ratio E:F. The ratio indicates the effectiveness of applying energy resources, both direct and indirect, in a given technology to gain useful energy for application elsewhere in the economy. The higher the ratio, the greater the return on invested resources in terms of energy available to maintain the rest of the economy and to facilitate growth or change. The two parameters net energy yield and energy yield ratio are useful in addressing questions about the process-environment linkage because they quantify flows crossing the boundary from both process and environment.

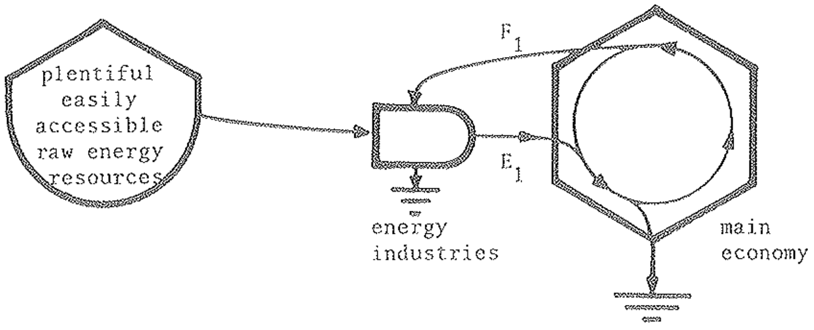
The Fundamentals of an Energy-Economic System

Physical and therefore economic activity depends on the availability and accessibility of energy resources. Growth results from the building of an economic infrastructure that enhances the economy's capacity to exploit the energy resources from the environment. This infrastructure, for capturing, transforming, and distributing energy in a complex of desired usable forms, is only possible because of prior resource depletion.

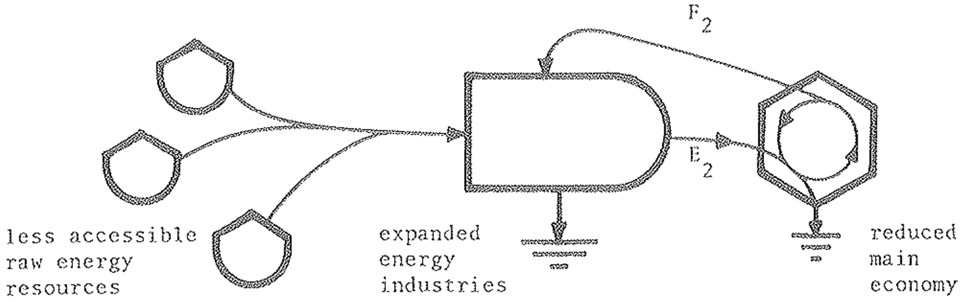
In the early stages of industrial growth (based on stocks of high-quality energy resources such as fossil fuels), high energy yield ratios derived from exploiting the most accessible low-entropy energy and material reserves give rise to rapid growth in net energy yield and commensurately rapid growth in economic infrastructure, economic production, and resource depletion from environmental stocks. This stage is characterized by the positive feedback response leading to exponential growth. Such a pattern of consumption has direct consequences for subsequent process dynamics. While the economic infrastructure is expanding, its associated maintenance-related requirements are also increasing. Continued growth necessarily implies increased levels of maintenance activity in the future and thus increased rates of resource depletion.

Environmental resource depletion begins with exploitation of the most accessible low-entropy stocks. As depletion proceeds, the quality of the available energy stocks and their accessibility change. New technologies may improve accessibility. Energy yield ratios serve to monitor such changes. Low-entropy energy sources can ameliorate the adverse effects of decreasing quality and accessibility in low-entropy material stocks. Nevertheless, in the long run the inevitable impact of any attempt to force a continuation of exponential growth rates in the economic process after the early stages of system growth must be the rapid exhaustion of low-entropy energy stocks.

The effect of such a trend on the total economic system and the energy industries that interface the economic process with the environment is depicted schematically in Figure 2. Figure 2a represents the early stages of industrialized economic development, when energy yield ratios (E1:F1) are high and the interconnected growth of net energy yield and economic infrastructure follows exponential trends (i.e., E1, F1, and the environmental resource depletion rate all follow exponential trends). Exponential growth in the production of goods and services in the main economy requires exponential growth in the supply rate of delivered energy (E1). This, in turn, depends on more or less exponential growth in the infrastructure of the energy industries and the goods and services they consume (F1). If higher-efficiency technologies (as measured in total energy resource



(a) No energy scarcity.



(b) Energy scarcity (relative or absolute)

Figure 2. Dynamic response of an energy-economic system. (a) No energy scarcity. (b) Energy scarcity (relative or absolute).

terms) are developed, F1 may grow for a time at an exponential rate that is slower than that of E1.

A subsequent—and consequent—development is represented in Figure 2b. It results directly from the effect of energy scarcity on the continued goal of exponential growth. As the most accessible energy reserves are exhausted, less accessible reserves must be exploited. In these circumstances, exponential growth in E2 (in terms of quantity at a constant quality) requires even faster exponential growth in the infrastructure of energy industries and their consumption of goods and services (F2). Even if the expectation of exponential growth is set aside in favor of an economic steady state, the effect of declining accessibility is not averted. Simple algebra shows that E2:F2 continually declines (below the highest value of E1:F1), even if E2 = E1 = constant, because F2 is continually increasing (greater than the lowest value of F1).

When energy yield ratios decline to less than unity, net energy yields become negative and an energy source becomes an energy sink. In these circumstances, an absolute environmental limit has been reached. Such an extreme case has probably not happened in mainstream energy supply technologies, although it is not altogether certain whether some nuclear facilities will be net yielders of energy and it has been asserted that some solar technologies are in fact energy sinks.

An Energy-Economic System Subject to an Energy Substitution Sequence

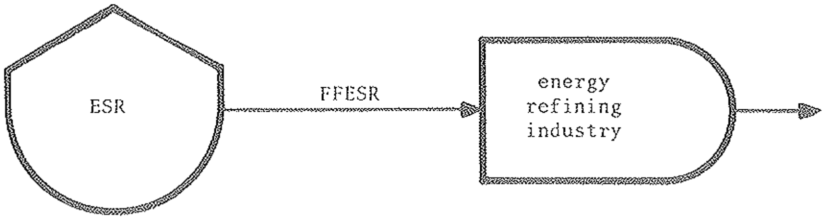
The primary aim of the present investigation was to provide qualitative information about the dynamics of an energy-economic system when that system is subjected to a sequence of energy substitutions.

Model Requirements

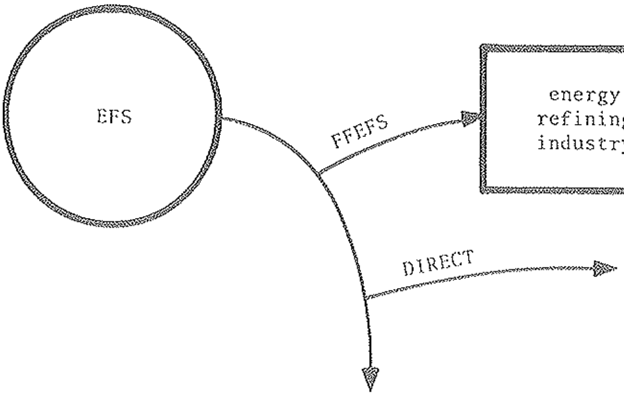
In constructing a model of an energy-economic system, the time span chosen was such that the focus could be the consumption of low-entropy resources from the environment and their use in building and maintaining a socioeconomic infrastructure over a time span long enough to encompass the depletion of stock resources. Thus any long-term changes in the process dynamics could be observed. Short-term fluctuations, such as seasonal changes in the pattern of primary production and variations in the rate and extent of technological changes among different sectors of the economy, are excluded; that is, the model was designed to incorporate any long-term effects of successive short-term fluctuations but not to accommodate the details of each and every fluctuation. What resulted was a picture of the general evolution of the system, illustrating trends and variations in some of the important aggregate parameters over a long period of time.

Model Description

Energy is available in two forms: environmental stock reserves (ESR) such as fossil fuels, which are limited in total amount available; and environmental flow sources (EFS) such as solar radiation and its derivatives, which are practically unlimited in total amount but strictly limited in rate of usage. The flows from these sources, designated DIRECT, FFESR, and FFEFS, respectively, summarize the environmental energy inputs to primary land-based production (agriculture, forestry, and the like) and to energy-refining indus-



(a) Environmental stock reserve (ESR)



(b) Environmental flow source (EFS)

Figure 3. Model representation of energy resources. (a) Environmental stock reserve (ESR). (b) Environmental flow source (EFS).

tries. This is illustrated in Figure 3. Each energy-refining industry is characterized, as shown in Figure 4, by its own economic infrastructure (ECINFR), which provides the necessary feedback energy in the form of factor inputs (FI) to process the flows of energy from the resource stocks or flow source through a workgate, much like a production function. The output of the workgate (E) is the input energy to the remainder of the economic process (see Figure 5), and this in turn attracts energies F as operating feedbacks to the energy-refining industry.

The laws of thermodynamics require both conservation of energy and entropy

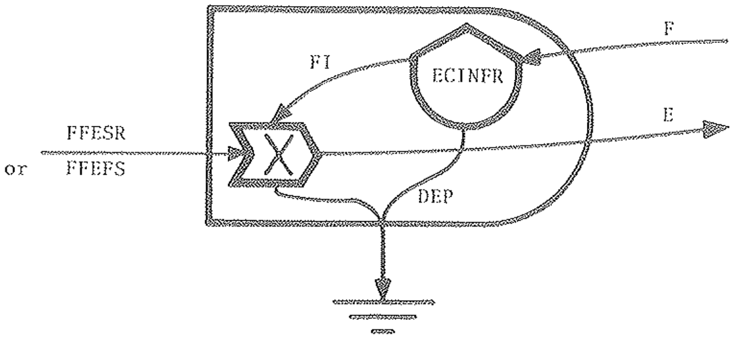


Figure 4. Model representation of the energy-refining industries.

change. As a consequence, there is production of degraded or high-entropy energy from the processing. This degraded energy can deliver no further work and recrosses the boundary as environmental heat, symbolized in Figure 4 by the ground symbol.

The energy-consuming (producer-consumer) sectors of the economic process of society (primary production, capital and consumable goods manufacturing, distribution, government, households, and so forth) are shown in Figure 5. Within the boundary, the process is modeled in a highly aggregated and generalized form. The workgate generates the flow of goods and services required by the economic process (GS) to maintain its existing economic infrastructure (ECINFR) against entropic degradation (DEP) and to facilitate its continued evolution. The economic infrastructure has a twofold role in the dynamics of the process: it generates a demand for consumption of environmental resources and provides the economic factors of production (FP) that are necessary for generating goods and services.

Direct sunlight and the energy flows from the energy-refining industries are the essential inputs to all producer and consumer activity. At this point of consumption, all commercial fuels are aggregated (COMM) to resemble the perceived availability of these concentrated energy forms. Since the industrial revolution, humankind has used concentrated energies both to amplify and to substitute direct solar energy–based activity. An aggregate production function is modeled to reflect this dual role. The energy-refining industries make their own demands of goods and services as capital and operating feedbacks from producer-consumer sectors (F).

The general model components of Figures 3, 4, and 5 are combined in Figure 6 to

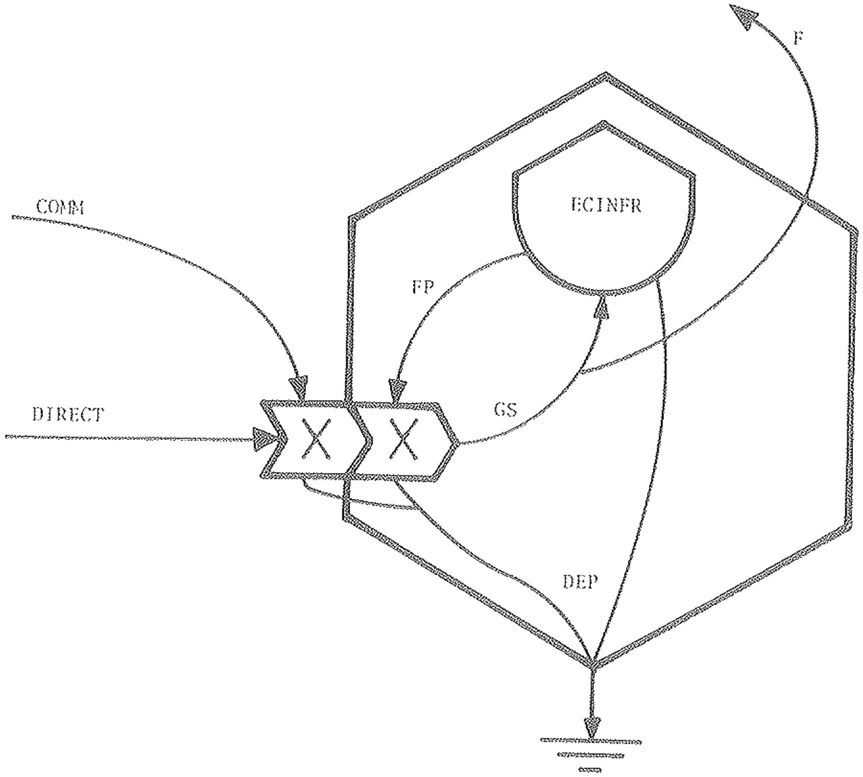


Figure 5. Producer-consumer sectors of society.

model the energy-economic system of an industrialized society that has been subjected to a multiplicity of types of energy stock resources. For the initial model, the environmental stock reserve form was subdivided into three types representing coal, oil, and gas. A single environmental flow source was used to cover all forms of renewable fuels derived from incipient solar radiation, such as wood and biomass.

Although the various energy forms can be represented by single algebraic parameters in the dynamic modeling exercise, this does not imply that they are of a constant and uniform quality, temporally or spatially. The model accounts for changing availability and accessibility as they would be experienced from within the process. The feedbacks from the producer-consumer sectors are distributed to each of the energy-refining industries. The division is on a prorated basis according to relative accessibility, the most accessible energy resource at the time attracting the greatest share of economic investment.

Treatment of Time

The dynamic changes that occur within any system as a result of the passage of time are integrally incorporated into a system's dynamics simulation model. Because the intention in this simulation exercise has been to investigate long-term trends in system behavior, it

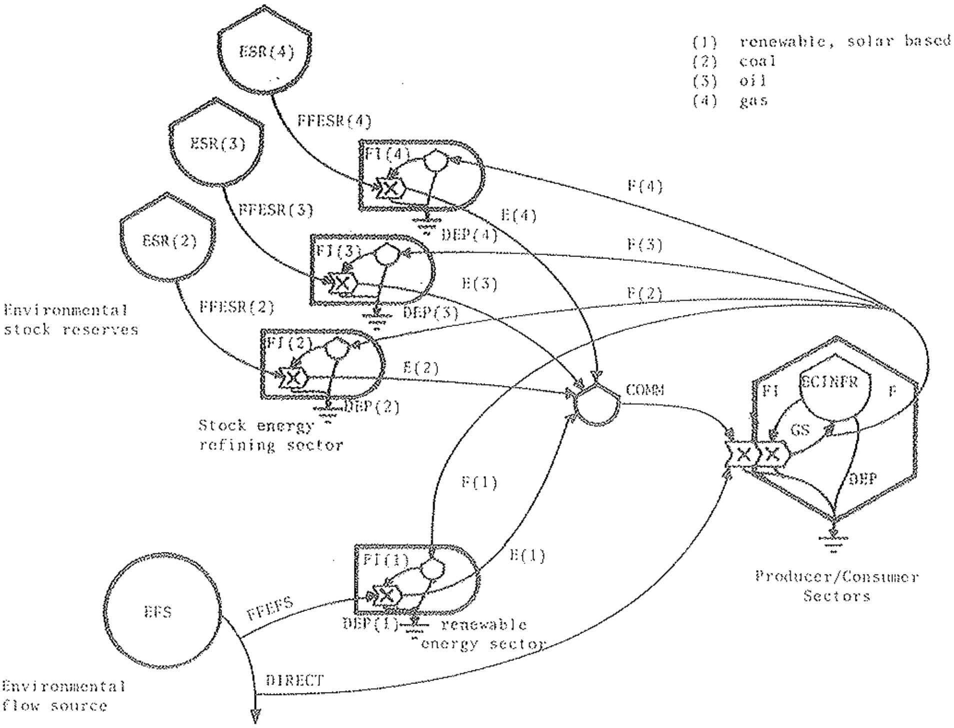


Figure 6. Model representation of the energy-economic interactions of industrialized society subjected to a multiplicity of types of stock energy resources. Numbers: (1) renewable and solar-based energy, (2) coal, (3) oil, (4) gas.

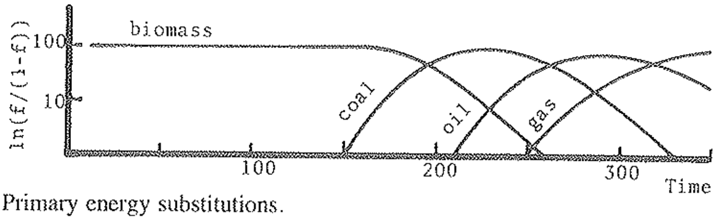


Figure 7. Primary energy substitutions.

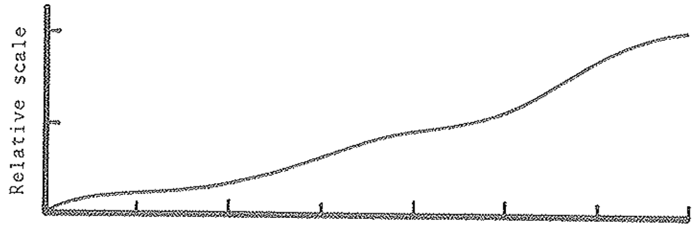


Figure 8. Total nonsolar energy supply to producer-consumer sector.

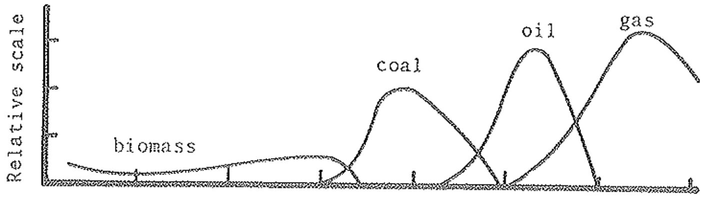


Figure 9. New capital equipment in all energy sectors.

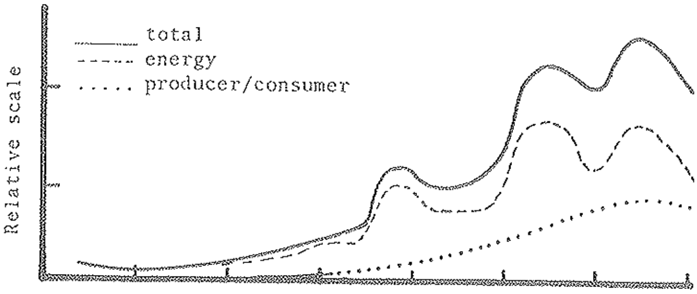


Figure 10. New investment in all energy and producer-consumer sectors.

was not considered necessary to replicate, in a precise quantitative manner, actual historical values of the various parameters. It was sufficient that the model should indicate trends for the various parameters and show how their interrelationships change with the passage of time. Once the dynamic simulation is set in motion, these changes are determined by the mutual interactions of the various parameters that are interconnected by the feedback loops of the system (or model) structure.

Model Behavior

In the simulation runs made with the model of Figure 6, the parameters were set with initial conditions representing an energy-economic system before the beginning of expansions due to fossil fuels. The environmental energy sources from the outset were flow based, representing renewable resources, with a limit on the available flow, and the first stock-based (nonrenewable) fuel was in the form of coal. The amount of this stock resource was set to a high value to represent an initial vast abundance, as were the as yet untapped oil and gas stock resources. The remaining model parameters in the form of multiplier coefficients, feedback coefficients, and so forth were set by the operator because no a priori measurements of these parameters were available. Values selected were such that final dynamic outputs illustrated recognizable and definitive patterns (if not exact historical replicas) from which meaningful discussion could result. Energy yield ratios for renewables, coal, oil, and gas were set at 10, 20, 30, and 40, respectively, to reflect energy sources of increasing accessibility.

With initial conditions set and coefficients selected, the model was allowed to run. The results obtained are presented in Figures 7 through 10. The initial penetration of coal was arbitrarily set at the 150th time step. This places the initial condition time point well before the inception of fossil fuels. Thus the model is seen to represent time before this period, and the only perturbations made after this time have been the penetrations of coal and other stock resources.

In Figure 7 the market fractions of each energy form are presented. Each new energy form, with its inherently higher energy yield ratio or accessibility, penetrates the market once its inception has been triggered. (In the real world, such triggering probably results from a combination of resource discovery and technological innovation that leads to exploitation of a resource. How automatic triggering of inception can be modeled has yet to be determined; at present a 1% inception is allowed to occur. Correspondingly, the resources with lower energy yield ratios give way and decline in market fraction, those with the lowest ratios going first. Thus coal, oil, and gas, successively, take on more share of the market while wood, coal, and oil peak and start to decline. Most important, the form of the curves is logistic, as observed by Marchetti (1980) for actual primary energy substitution trends.

Figure 8 shows the total nonsolar energy supply to the producer-consumer sector of the economy. There is a monotonically increasing trend despite the logistic penetration and decline of the individual stock resource types. This is due to the improving energy yield ratios or accessibilities of each new fossil fuel and indicates the adaptability of society to use a new energy source without apparent major interruption in the overall use of energy.

Nevertheless, this adaption from one energy source to another has major effects in economic society. In Figure 9 the amount of capital invested in each of the energy-refining industries is shown. Here it is apparent that the switch from one energy source to the next requires major development in equipment to extract, refine, and use that energy. The peaks of this investment occur well before the peaks of fractional penetration of the energy sources (Figure 7), indicating that investment and hence development of equipment must take place before the resource can be fully utilized. Furthermore, each successive peak is higher than its predecessor, indicating the growth dynamics associated with increasing accessibility. It is inevitable that the development of a new energy resource will be based on activity supported by consuming the previously dominant energy form. For example, oil capital investment peaks well ahead of its market fraction peak but follows the market fraction peak of coal, on which its development was initiated. In a similar manner, gas capital investment peaks well ahead of its market fraction peak but follows the market fraction peak of oil.

The total new capital equipment investment over all the energy-refining industries (Figure 10) shows oscillations in step with the original penetrations of various energy forms. All this investment in the energy-refining industries competes with investment in the goods and services production economy itself. The new investment in the producer-consumer sector shows an increasing trend without short-term perturbation, much like a logistic growth curve. Consequently, the total investment, combining both the energy-refining industries and the producer-consumer sectors, is a long-term logistic trend on which cyclic fluctuations are superimposed.

A further observation of note concerns the apparent depletion of each type of fossil fuel. At the end of the simulation time period, the stock reserves remaining (as a percentage of the initial values) were 49, 62, and 70 for coal, oil, and gas, respectively. That is, there is a significant amount of actual stock resources remaining, and it has not been the lack of availability that has prompted society to move from one fossil fuel form to the next.

Discussion

The results presented here show that the major dynamic patterns of individual society (energy usage and industrial production) can be generated by a systems dynamics model that uses only energy concepts and parameters. They should not be interpreted as an attempt to replicate exactly the observed patterns. Some qualitative discussion can be made with regard to the results obtained so far, however.

The use of coal, oil, and gas penetrations as the only established fossil fuels gave rise to three cyclic fluctuations in the new investment in all energy and producer-consumer sectors of Figure 10. This is not enough to explain the four long-wave cycles historically observed. Marchetti (1980) proposes a period of hay dominance between wood and coal, but no data are presented for this. Inclusion of hay in the model with appropriate availability and accessibility factors would add another perturbation to the curve of Figure 10 to give four cyclic fluctuations. This may be an explanation for the earlier long-wave apparent in the late eighteenth century.

The consequence of gas domination in the near future is incorporated into the patterns of Figures 7 through 10 in the absence of any new primary energy penetrating the market (nuclear energy has not been considered). Oil (and to lesser extents coal and wood) continues to lose its market share to gas despite a remaining abundance of the resource, as discussed above, and perhaps despite its declining real price, as purveyed by Marchetti (1980). As gas grows in significance, a new high in the total new investment in all energy and producer-consumer sectors is reached. The gas peak of Figure 9, the largest yet, indicates society reaching an economic level beyond that which it reached before (historically the 1960s). Achieving this, however, requires further development of the production, transmission, and distribution infrastructures for gas so that it can be used as the dominant energy source in industry. Its high accessibility (i.e., greater return on invested input) implies a more efficient fuel to its users than other fuels. Because such capture of a new resource is based on the existing dominant resource (oil), and because it is currently economical to do so, higher accessibility implies lower cost of supply in real terms. Thus price, which is a factor absent in the model, appears as a derived quantity and not as the determining factor of energy substitution.

Conclusions

This study puts forward a new perception of the essence of industrial society, its structure, and its iterations. That economics-derived factors are not used in the modeling is deliberate. The hypothesis is that society can be modeled as an energy system and that major societal patterns are an ultimate result of energy usage. This is in contrast to more established approaches, in which energy is considered a derived demand of or a factor input to an economic system. Although the various trends and patterns described above have been individually reported, the present work provides a common base from which they all are generated. This is the product of an energy-based system only that has its foundations in physics and thermodynamics. It portrays industrial human society in the global sense as primarily an energy-consuming organism, the development and survival of which has been achieved through the use of fossil fuels.

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