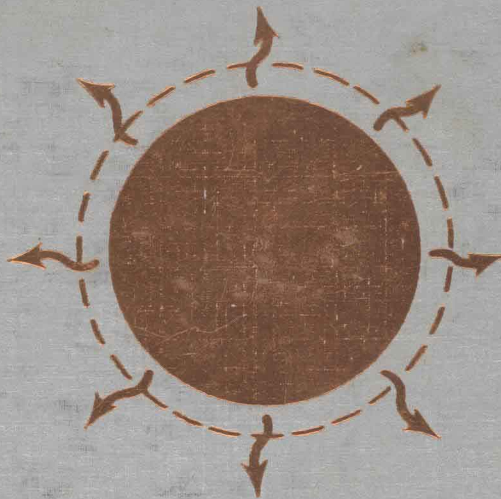

ENERGY

Conversion and Utilization

Jerrold H. Krenz

Energy
Conversion and Utilization

JERROLD H. KRENZ
University of Colorado

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Preface

Seldom do advanced engineering and physics courses attempt to develop a comprehensive overview of a segment of technology. To deal with the present energy crisis, a broad range of advanced technologies will undoubtedly be necessary.

A quantitative treatment of the technical limitations and potentials of energy-related processes requires a background in physics and calculus. The text, in note form, has been successfully used in classes of senior-level engineering, physics, architecture, and mathematics students. It is hoped that this treatment will also be of value to graduates in its coverage of the alternative energy conversion processes that are now receiving considerable attention. Estimates of the potential of various energy conversion processes are included even though vast quantitative differences often exist between various "experts." For cases in which large uncertainties exist, the different assumptions used in arriving at the estimates are pointed out.

A complete and rigorous in-depth treatment of all limitations associated with energy conversion and usage is obviously beyond the capability of a single text. Very likely it is even beyond that of a four-year curriculum, since ideally what is needed for it is not only a good background in mathematics, science, and engineering, but also economics, geology, biology, ecology, as well as climatology. However, the understanding of the fundamental limitations associated with many basic energy conversion processes requires only a minimal background in physics and mathematics. Technically educated students seldom realize the potential of their general background. One of the objectives of this text is to demonstrate that one need not be an expert in a particular field to be able to appreciate fundamental limitations. Hopefully, students will develop an interest in specialized areas and will consequently enter specialized courses, at the same time keeping in mind the broad general picture.

While the author has attempted to be thorough in his treatment of the subjects covered, completeness was obviously impossible. Many topics discussed in single sections are frequently the subject of book-length treatments. Sufficient references are included for the reader who wishes to pursue a particular topic. The aim of the text is to develop an energy overview and hence interrelate the various aspects of energy conversion and usage that are all too often regarded as unrelated concepts. For example, the treatment of thermodynamics is obviously incomplete. Overly sophisticated introductory treatments of thermodynamics, however, can leave students confused and despondent. Also, more rigorous treatments often ignore the very thermodynamic processes used for large-scale energy conversion. While attempting to be comprehensive, an encyclopedic cataloging of numerous details has been avoided. The text, an outgrowth of a one-semester energy course first offered in 1972 by the author at the University of Colorado, reflects many concerns and insights of students who are now in graduate school, industry, or government.

The order in which the material is covered is, to a degree, arbitrary. It is recommended, however, that one begin with the first chapter, which provides a quantitative perspective of energy consumption. Constant growth or percentage rates are related to exponential behavior. While this is an elementary concept, it is frequently overlooked. The chapter concludes with a brief discussion of fossil fuel reserves. Overall limitations, the thermal balance, carbon dioxide emissions, and atmospheric pollution presented in Chapter II are equally important in developing an intellectual base on which the subsequent material builds.

Chapter III is an elementary introduction to thermodynamics based on the behavior of an ideal gas. The concepts of a cyclic heat engine and the Carnot efficiency are developed. For those having had a course in thermodynamics, this chapter can be omitted (or read for review). The order in which Chapters IV through VIII are considered can be varied to suit individual interests. Occasional references, however, to the introduction of Chapter IV (data on the electrical consumption rates and generating capacities) will be found in the subsequent chapters.

Chapter V attempts to present a perspective on nuclear energy derived from the fission of uranium and plutonium. A wide diversity of views on the desirability of nuclear power may be found. As a consequence, highly committed proponents as well as opponents of fission will probably find the material lacking, each group for opposite reasons. The treatment includes a discussion of radioactivity and a quantitative calculation of reactor waste products. While the quantity of wastes produced is not debated, the safety with which they can be isolated from the environment is questioned. (It is interesting to note that a discussion of waste products is often omitted in texts on nuclear reactors.) Experts also disagree on the probability of a catastrophic failure and the effects of low-level radiation. The debate on fission power will probably ensue for many years.

Chapter VI is probably the most difficult one in the book. The problems associated with achieving a controlled plasma reaction, however, are quantitative. More than a descriptive treatment is necessary to understand the present status and the improvements necessary to achieve a net energy-producing reaction.

While energy derived from fossil fuels will undoubtedly remain important for many decades, interest in alternative energy conversion processes is presently very high. Therefore solar energy and other sources (Chapters VII and VIII) might be covered immediately following Chapter III. On the other hand, a consideration of nuclear energy (both fission and fusion) prior to solar energy does make the yet-to-be-solved problems associated with solar energy seem much less formidable. The chapters are ordered according to historical interest (and research activity) in the various subjects. Interest in solar energy is not new but it has become economically attractive only recently. The recent high interest in wind (again, an old technology), ocean temperature gradients, and geothermal energy sources covered in Chapter VIII is also evident.

The concluding chapter, dealing with energy and the economy, could be covered (or read) at any point after the third chapter. Indirect energy requirements are often neglected due to the difficulty of obtaining data. Input–output techniques provide a convenient approach and a method to obtain at least a moderately accurate estimate of total energy requirements. A sufficiently detailed treatment is offered so that a previous knowledge of economics is not required.

A multitude of units of measure exist for specifying energy and power. Even though technologists and scientists frequently express a preference for the metric system, the corresponding unit of energy, the joule, is almost totally neglected. The mks unit of power, the watt (J/s), is frequently used and a physical feel tends to exist for it. Even though energy is a topic of almost daily discussion and news, a physical feel for energy units is lacking. While one may know the quantity of gasoline required for a given automobile trip, it is unlikely that one would know the required energy expressed in joules (or, for that matter, in any other units). Energy consumption rates, that is, the quantity of energy consumed in a given interval (often for a calendar year), are important. Energy consumption rates, however, have the dimension of power. If the energy consumed is divided by the corresponding time interval, an average power is obtained. Units of power expressed in watts are therefore appropriate for specifying energy consumption rates.

Hybrid energy quantities based on nonfundamental units of time are presently used; witness the watt-hour and kilowatt-hour (a watt-second is a joule). Similarly, an average power for a year, the time interval often used to specify consumption rates, results in an energy quantity which, if expressed in watt-years, is numerically equal to the average power. While mks units are emphasized, units commonly used for particular fields are added when appropriate. A multilingual understanding of physical units will no doubt be required for many years.

Important quantities, such as the rate of energy consumed by the United States, for example, change with time. A quantitative perspective, however, necessitates the use of such quantities, even though they tend to date the material of the text. The base year for most of the data utilized was 1972, the most recent year for which reasonably complete data were available. This may have been a rather fortuitous choice, since the high growth rates (4% to 5% per year) which preceded 1972 seem unlikely to persist. The U.S. consumption rate for 1974, owing to the 1973–1974 decline, was approximately the same as that for 1972. The quantities for 1972 may, if present difficulties are indicative of future problems, not be very far in error for the next several years.

In addition to providing a needed coverage of energy, it is hoped that this text will serve as a stimulus to develop similar comprehensive courses. Hopefully these courses will not only provide a dimension needed in the technical curricula, but also can have a major effect in revitalizing the present educational process.

Special appreciation is due to my colleagues at the University of Colorado, John Cooper, Jan F. Kreider, Frank Kreith, and Jerome B. Martin, and also to Charles D. Beach, then at the solar energy laboratory at Colorado State University, for reading portions of this manuscript and providing many useful comments. The author, however, accepts full responsibility for any errors that have gone undetected.

The writer would also like to acknowledge the support of his wife, Maria, without whose patience and encouragement the manuscript would not have reached fruition. Since Maria both edited and typed the manuscript, the completed work truly reflects a joint effort.

Boulder, Colorado — JERROLD H. KRENZ

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Introduction

I

1. THE ENERGY CRISIS

As early as 1969 New York City had experienced an electrical energy shortage. On August 5, 1969, *The New York Times* carried a front page story with the following title [1]:

Con Ed Power Cut 20% by Mishaps; Long Crisis Ahead
Generator Repair May Take up to Month—Consumers Help Save Electricity

While this particular crisis was precipitated by an untimely series of breakdowns, it provided a warning signal for events to come. Since the 1969 crisis, Consolidated Edison Company has moved from a position of advocating increased use of electricity to urging customers to conserve electricity [2].

Con Ed Says it Will Confine Ads to Urging Power Conservation

> The Chairman of the Consolidated Edison Company, Charles F. Luce, said yesterday that the utility has disbanded its sales promotion department and would use advertising only to urge customers to conserve electricity. Mr. Luce said he believed it was the first such action by any utility in the nation.

Electrical energy consumption within the United States has been increasing at an average annual rate of 7% since 1900. At this rate, the consumption doubles every ten years. Therefore, generating capacity must also double every ten years.

A continuation of this growth rate implies a quadrupling in twenty years and an eight-fold increase in 30 years. Over an interval of 30 years, seven additional generating units would need to be added for each initial unit.

The energy crisis is not only associated with electrical energy. The total consumption of energy had, prior to 1974, been increasing at a 4 to 5% rate within the United States as well as the world. Approximately one-quarter of this energy is used for the generation of electricity. The other three-quarters is used for transportation (electric propulsion is negligible in the United States), industrial processes, and heating. While the known reserves of coal are sufficient for at least the next millennium at the present rate of consumption, this is not true for petroleum and natural gas. The known reserves of natural gas and petroleum reserves will last (at the 1972 world consumption rate) for many decades. Exploration costs, a measure of scarcity, however, have been steadily increasing.

While scientists have for many years been concerned with the rapid increase in energy usage, the oil embargo during the latter part of 1973 and the beginning of 1974 served to focus the public attention on energy issues. The curtailment of exports by the petroleum producing Middle Eastern countries resulted in serious economic disruptions throughout the world. Petroleum consumption during this period in the United States was reduced by 14%. This cut represented a reduction in total energy consumption of approximately 6%. While a decrease in consumption is possible through more effective energy utilization, several years would be required to effect the required changes (for example, increased building insulation and smaller automobiles).

The increasing scarcity of fuels is not the only factor contributing to the crisis. Associated with the combusion of fossil fules is the unavoidable release of pollutants. Coal and petroleum contain sulfur impurities which form sulfur oxides during combusion. At the high temperatures typical for the internal combustion engine, nitric oxides are produced. Incomplete combustion produces carbon monoxide and hydrocarbons. Even if these undesirable and biologically hazardous by-products are eliminated, the generation of carbon dioxide is unavoidable. While the atmosphere contains carbon dioxide (an essential component of the life processes), the effect of an increase in the atmospheric content is uncertain. Finally, essentially all energy generated creates heat, due both to the inefficiencies of various conversion processes and to its eventual utilization. The present rate of energy consumption in heavily populated metropolitan areas is sufficient to substantially increase the ambient temperature.

The pollution aspect of high energy consumption has emerged as a national problem. Not only do Los Angeles and New York have smog problems, but cities such as Denver, long noted for its clean air, are also troubled. Warnings of pollution alerts with a concurrent curtailment of energy consumption are forecast [3]:

Emergency Pollution Measures Would Include Local Shutdowns

Emergency air pollution alert procedures being considered for the Denver metro area would affect 'a big percentage' of industries and individuals in Boulder County, according to local health officials.

> Major sources (of pollution) include all large users of power such as cement plants and power companies.
>
> Other emergency measures being considered would involve cutting back on heating plant power use, turning off street lights to conserve power, and urging voluntary public cooperation in minimizing power use.

A sampling of article titles such as a three-article series carried by *The New York Times* reveals the severity of the crisis [4, 5, 6].

Nation's Energy Crisis: It Won't Go Away Soon

Nation's Energy Crisis: Nuclear Future Looms

Nation's Energy Crisis: Is Unbridged Growth Indispensible to the Good Life?

Only in the area of atomic energy has there been a research effort commensurate with the magnitude of the crisis. Electricity is generated by the same steam cycle as used in 1900, albeit efficiencies have been increased from less than 10% to 40%. Nuclear plants simply replace the fossil-fueled boiler with a nuclear reactor. While the internal combustion engine of the automobile has been improved and extensively modified since its introduction, it is basically the same engine. Gasoline mileage has not only decreased over the past two decades, but today's engines require a higher octane fuel and operate at higher temperatures than their 1940 predecessors. Both these characteristics increase the emission of pollutants.

Shortly after World War II, nuclear energy was hailed as the promise for the future. Electricity produced by nuclear energy was to be so cheap that metering would be unnecessary. While the first nuclear chain reaction was produced in 1942, thirty years later reactors were only beginning to emerge from the experimental stage. In 1974 only 1.4% of the energy used in the United States depended upon the splitting of the atom. Proponents of nuclear energy envision that a substantial fraction of the energy generation will be nuclear by the year 2000. Opponents seriously question both the prediction and the wisdom of nuclearly derived energy.

Sorting out the conflicting positions on nuclear energy is not easy. The effect of radiation and radionuclides on biological materials is far from well understood. Of particular importance is the disposal of long-half-life waste products that need to be isolated from the environment for thousands of years. For every book supporting nuclear development, an equally well-documented case against nuclear energy may be found; for example, Seaborg and Corliss's *Man and Atom* [7] vs. Gofman and Tamplin's *Poisoned Power* [8]. Texts on nuclear energy stress the design of reactors with only a very limited treatment of radiation and usually no discussion of waste disposal. Opponents of nuclear energy deal extensively with radiation and disposal as well as with possible cataclysmic accidents. At present, the nuclear future is far from certain.

Nuclear fusion, the process of putting light atoms together (as opposed to fission, the process of breaking apart heavy atoms), is seen by many as an ultimate energy solution. Radiation problems are minimal and nonradioactive waste products are generated. Unfortunately, a controlled fusion reaction (the hydrogen bomb is an uncontrolled fusion reaction) had eluded scientists. While very few doubt that a controlled fusion process is possible, several more years of development will be necessary. Unless an unforeseen major breakthrough occurs, even its most optimistic proponents do not expect nuclear fusion to modify this century's energy picture.

That the consumption of energy must increase is implicit in most views of the energy crisis. Growth is often accepted as the normal state, whereas nongrowth, that is, a steady-state equilibrium, is often perceived as inherently undesirable. An article on the Philadelphia meeting of the American Association for the Advancement of Science indicates that not all scientists applaud growth.

Conservationists Oppose Rise in Supply of Power

> While others reported technological advances toward new sources of energy, a panel of experts today suggested the need to relieve the nation's energy shortage by reducing the demand for power, not by increasing the supply. [9].

Reducing energy consumption does not necessarily imply reducing the quality of life. An increase in the efficiency of use can be equivalent to an increase in supply. The manner in which energy is used also determines demand. The individual atomobile, while offering convenience and privacy, is an excessively large consumer compared to mass transportation systems. Another large consumer of energy is the container industry (aluminum cans). A container does not necessarily add to the value of its contents.

The crisis is thus a conflict between supply and demand, even though some of the demand may be induced by the supplier. From a purely technical viewpoint, a minimization of energy consumption for a given quality of life is entirely reasonable. Such a change, however, would require a profound shift in social and economic values.

2. ENERGY CONSUMPTION

While world population has been increasing at a rate of approximately 2%, energy consumption has been increasing at a higher rate of 5%. High energy consumption has traditionally been associated with a high quality of life, which is often associated with the Gross National Product. Using per capita economic and energy rates of countries at various stages of development for 1965, a linear relationship between energy consumption and level of life is suggested (Figure 1.1). Included in the graph are the ten countries with the highest per capita energy consumption, as well as several other countries.*

* A more complete listing is given by Joel Darmstadter in *Energy in the World Economy* [10]. Much of the statistical data of this section was obtained from this source, as well as from more recent compilations [11–13]. Two methods are used for an energy accounting of hydropower. Darmstadter and U.N. statistical data specify hydro energy in terms of the electrical energy pro-

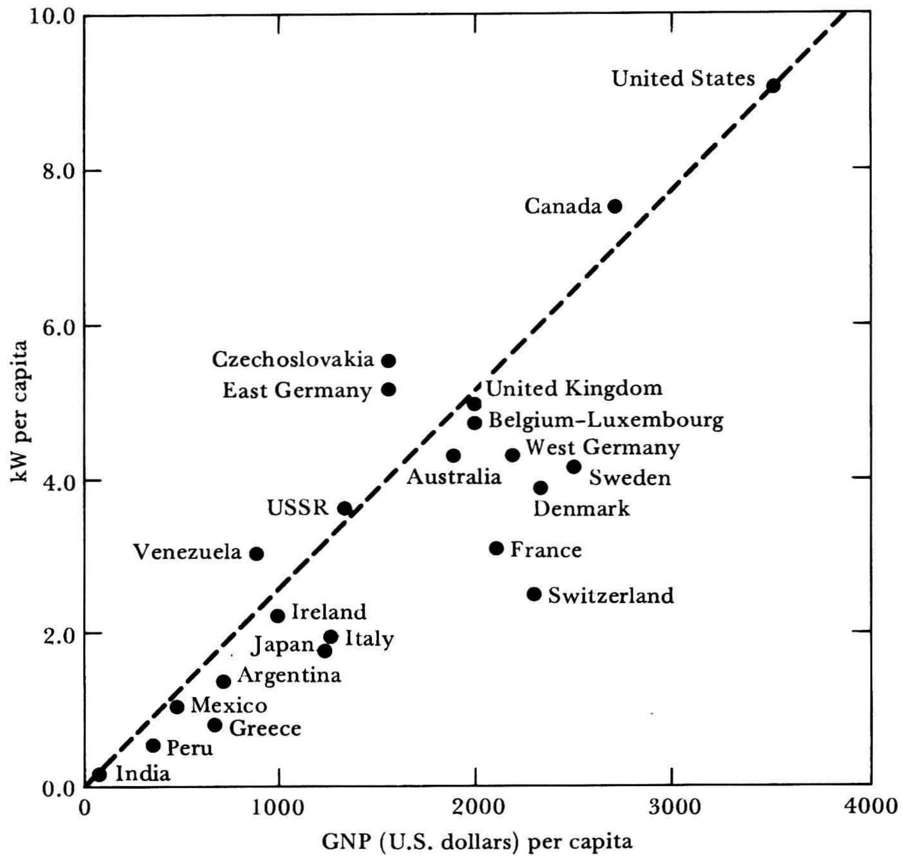

FIGURE 1.1 1965 Per Capita Energy Consumption vs. Per Capita GNP (reference 10)

While economic development (to the extent that GNP is a valid indicator) and energy consumption are closely related, extrapolation for values of per capita GNP beyond that of the United States may not necessarily be valid. The GNP itself is being increasingly questioned as a valid indicator of economic and social well-being [14].

Figure 1.2 is a plot of the world energy consumption rate for the twentieth century. To emphasize the exponential nature of the consumption curves, a semilogarithmic plot has been used. Exponential functions result from constant

duced. Often, particularly in the United States, hydro energy is specified in terms of the heat energy required to produce an equivalent quantity of electrical energy in a thermal power plant. Since approximately three units of heat energy are required to produce one unit of electrical energy (Chapters 3 and 4), hydro energy, so specified, is greater by a factor of three. The data of this chapter is based on the former accounting method utilized by Darmstadter and the United Nations. The small differences between various sources of data may often be attributable to this accounting difference.

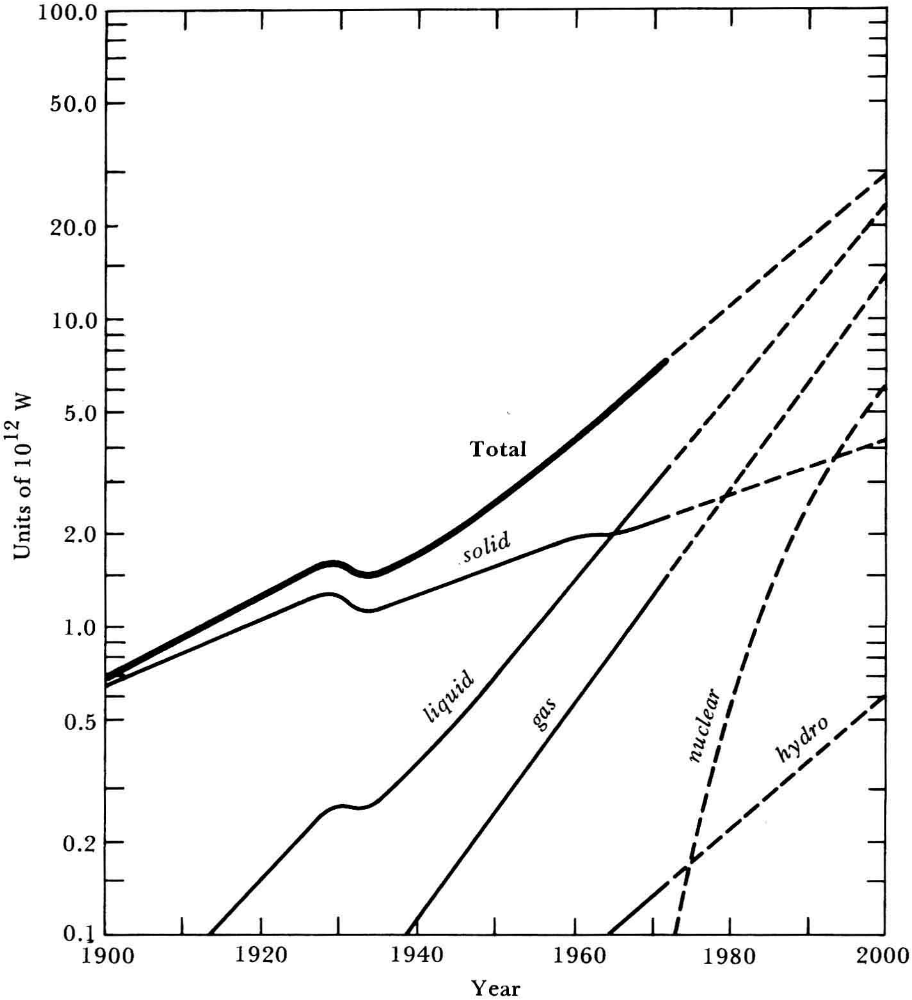

FIGURE 1.2 World Energy Consumption Rate

growth rates and appear as straight lines on such a plot.* The projections to the year 2000 are simply straight-line extrapolations based upon the average growth rate in the period from 1964 to 1972. Present trends indicate a growth rate of 5% for total energy consumed. Solids have a growth rate of approximately 1%, liquids 7.3%, natural gas 7.7%, and hydro 2%. The nuclear energy curve is an estimate rather than an extrapolation [15]. While economic planning is often based upon a continuation of present growth rates, such projections do not, however, take into account possible technical innovations that may reduce energy needs.

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* If $y = Ae^{at}$, $\log y = \log A + at \log e$. Therefore if $\log y$ is plotted as a function of t, a straight line with a slope of $a \log e$ results.

Solids include both coal and wood. Wood was important in 1900, but the quantity used now is insignificant. Liquid (petroleum) and gas consumption show the greatest growth rates. Hydropower remains an order of magnitude less than fossil fuels. All significant amounts of hydropower, however, are used to generate electricity. In this respect it is more effective than fossil fuels used for the same purpose. Thermal generation of electrical energy is presently no more than 40% efficient, whereas efficiencies for hydroelectric generation can approach 100%.

The 1972 world rate of energy consumption was approximately 7.1×10^{12} watts. Units of 10^{12} watts or 1000×10^9 watts are beyond normal everyday experience. Large scale fossil and nuclear fuel electric power plants are presently being designed and constructed for electrical outputs of 10^9 watts. For a conversion

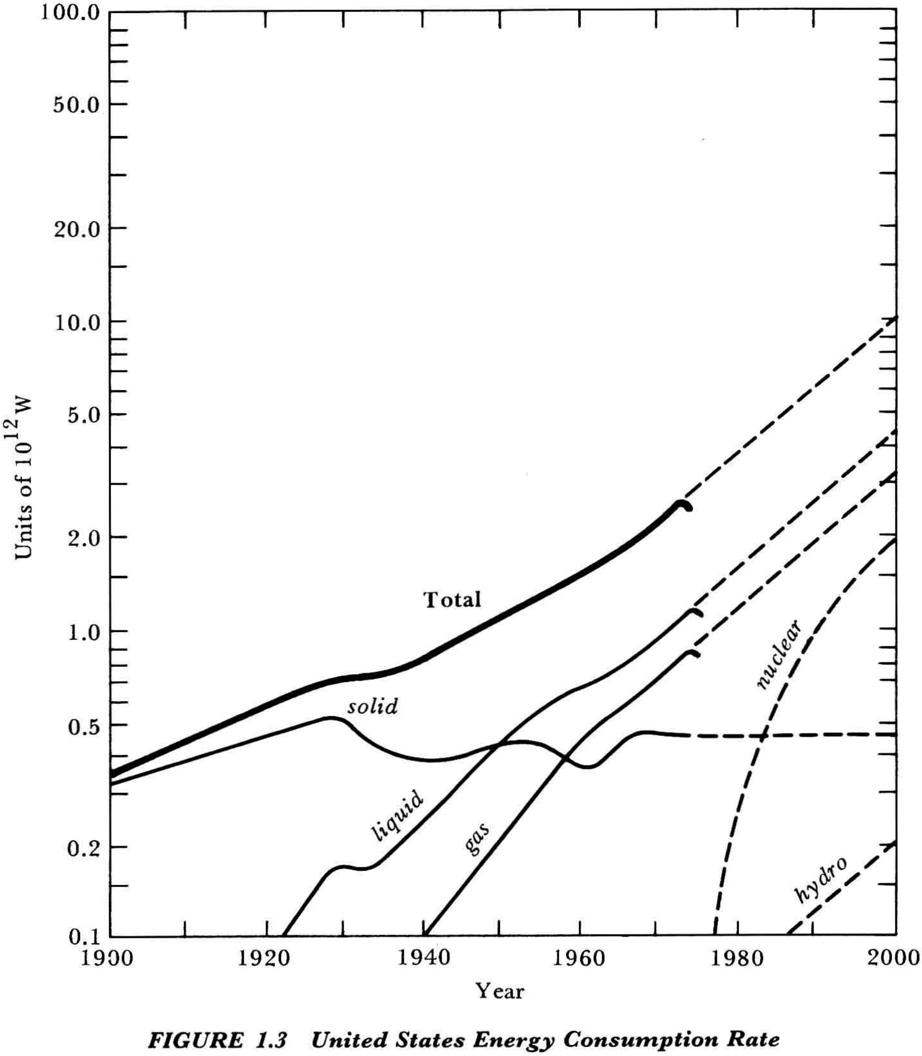

FIGURE 1.3 United States Energy Consumption Rate

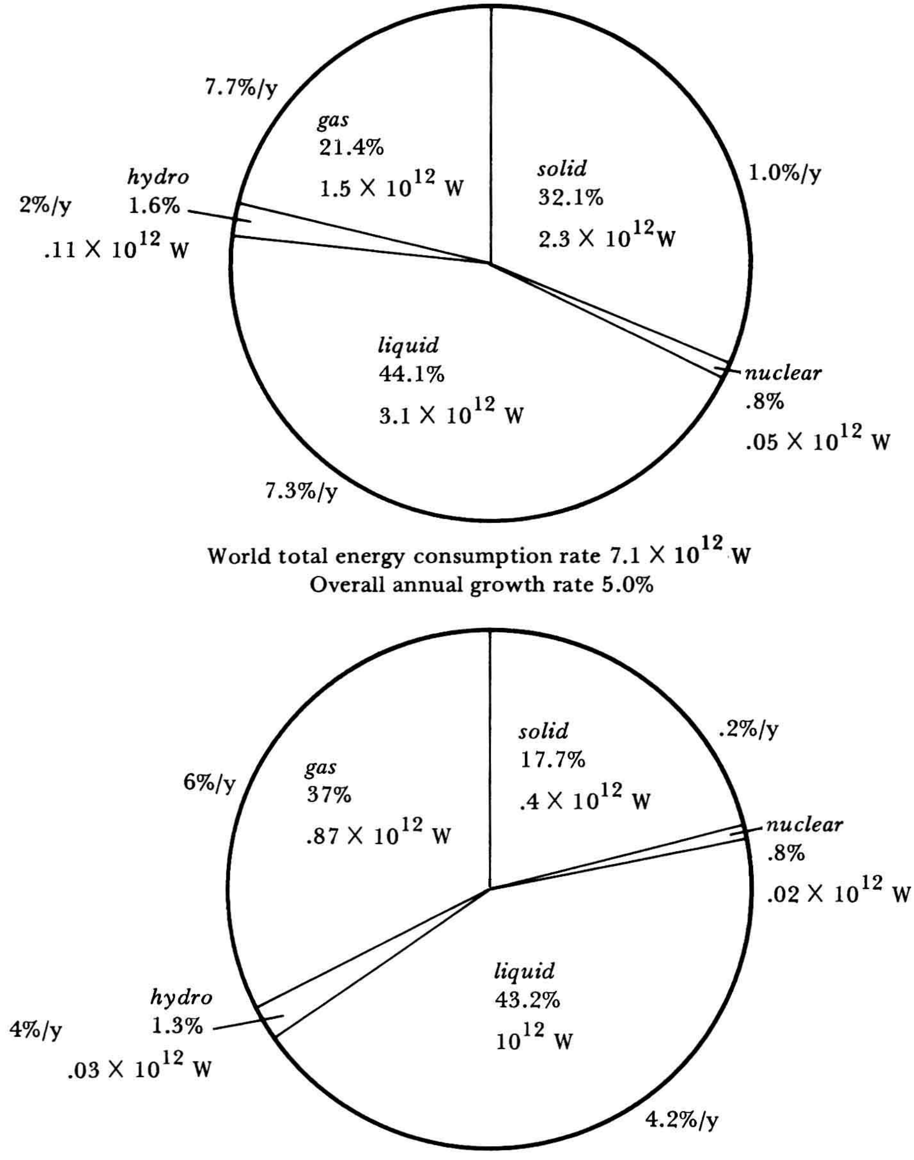

FIGURE 1.4 ***1972 Consumption by Energy Sector (Percentages outside circles are average growth rates, 1964–1972.)***