Energy

Conversion and Utilization

Second Edition

JERROLD H. KRENZ

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TO CHRISTOPHER

May the world he and others of his generation inherit be a world which bears the mark of our intelligence.

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Preface

Since the publication of the first edition of *Energy: Conversion and Utilization*, the perception of energy-related problems has changed markedly. While there has been a concerted research and development effort in the area of energy supplies based upon alternatives to fossil fuels, there also has been a greater realization that fossil fuels will continue to supply a substantial portion of the energy needs of industrial societies for the next few decades. Concurrently, it has been "discovered" that the potential for reducing energy usage is far greater than was generally accepted during the early 1970s. The new revised and greatly expanded edition addresses these important developments.

Chapter 1, in addition to providing an updated quantitative perspective on energy usage, highlights the importance of a systems perspective. It is, generally, the accomplishment of various tasks, such as keeping warm or cool, that is of importance whereas the supplying of a given quantity of energy is of secondary importance. It is shown that policies based upon constant growth rates are unrealistic since this results in unbounded exponential increases. A mathematical discussion of exponential growth is included.

An extensive treatment of fossil fuel reserves (Chapter 2) has been added. Not only are estimates of various fuel reserves included, but the methodology for dealing with a depletable resource is also developed. Although estimates of reserves are expected to change, this methodology provides a perspective by which the reasonableness of new estimates may be judged. The refining of petroleum fuels is covered as well as methods by which they may be synthesized from coal. Chapter 3, Terrestrial Limitations, has been revised to reflect an increased knowledge of the earth–atmosphere system. Growing concentrations of carbon dioxide, an unavoidable consequence of the combustion of fossil fuels, and acid rain continue to be a source of concern.

Chapter 4 has an elementary-level introduction to thermodynamics based upon the behavior of an ideal gas. The concepts of a cyclic heat engine and the Carnot efficiency are developed. A discussion of available work and second-law efficiencies has been added to this chapter. These topics are generally ignored in the popular thermodynamics texts, but they must be understood if energy is to be used in an efficient manner. The utility of these concepts is emphasized in Chapter 5, Electrical Energy from Fossil Fuels. The advantage of cogeneration, that is, supplying process steam or thermal energy for a district heating system, along with electrical energy, is stressed. Again, it is through a systems approach to supplying jointly thermal energy and electricity that primary energy needs may be reduced.

While the desirability of fission-produced energy (Nuclear Energy, Chapter 6) continues to be debated, estimates of the energy that will be supplied by this technology have been declining. In addition to a general discussion of nuclear physics and of reactors, a discussion of radioactivity and a quantitative calculation of fission waste products is presented. Although the quantity of wastes 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.) This new edition provides a detailed description of the sequence of events of the Three Mile Island-2 reactor accident. Both the likelihood of a catastrophic reactor failure and the effects of low-level ionizing radiation remain a part of the debate on fission-produced energy.

Chapter 7, Fusion, is probably the most difficult one in the book. An appreciation of the problems associated with achieving a controlled plasma reaction requires a quantitative treatment of fusion physics. This is necessary for an understanding of the experimental results obtained and the developments that are yet needed to achieve an energy-producing reaction. Developments that have occurred since the publication of the first edition are included.

The analysis of solar energy systems (Chapter 8) is based upon principles of basic physics. The chapter has been expanded to include developments that have occurred over the past several years. A cost-benefit analysis, suitable not only for solar energy systems but also for other capital-intensive, energy-related activities, has been also added to the chapter. Several examples illustrative of economic cost-benefit analysis are included. In addition, the treatments of both photovoltaics and photosynthetic reactions for producing biomass have been expanded. The data of Chapter 9 (Water, Wind, and Geothermal Power) has been updated and recent developments are included in this new edition.

Chapter 10, dealing with energy and the economy, has been expanded in an effort to make this material more accessible to technically oriented students. Input–output techniques provide a convenient approach to obtaining a moderately accurate estimate of the total energy required for producing a particular economic good or service. The interrelatedness between economic activity and energy usage is also emphasized.

A quantitative treatment of the technical limitations and potentials of energy-related processes requires a background in physics and calculus. The first edition of the text has been successfully used in classes of senior-level engineering, physics, architecture, and mathematics students. It is hoped that the new edition 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 among 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 in 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.

The author has attempted to be thorough in his treatment of the subjects covered, but 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 specific 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. (The introductory sections may be omitted if students have had an introductory thermodynamics course.) 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. The concept of available work, discussed in Chapter 4, which is the key to understanding energy conservation, is frequently ignored in thermodynamics texts. While attempting to be comprehensive, an encyclopedic cataloging of numerous details has been avoided.

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 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 1979 for the United States and 1978 for the world. In the United States, 1979 corresponded to a peak in energy usage, and consumption from 1980 to 1982 declined, with consumption in 1982 being about the same as in 1972, the base year for the first edition of the text. If consumption again increases, the data for 1979 will tend to be typical of that for future 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, Jerome B. Martin, and Ronald E. West, 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. I am especially indebted to Frank Kreith at the Solar Energy Research Institute in Golden, Colorado, for his continued assistance in completing both editions of the book. While deeply appreciative of the help provided, the author accepts full responsibility for errors that have gone undetected as well as for any misconceptions that may exist.

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

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CHAPTER 1

Introduction

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 had, prior to the 1970s, 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 20 years and an eightfold 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 increased at a 4 to 5% annual rate within the United States as well as the world. Approximately 31% of this energy is used for the generation of electricity. The other 69% is used for transportation (electric propulsion is negligible in the United States), industrial processes, and heating. Although 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 world reserves of natural gas and petroleum will last, based upon present consumption rates, many decades. If, however, consumption of these premium hydrocarbon fuels continues to increase, the world's reserves will be depleted in the early part of the twenty-first century.

While scientists have for many years been concerned with the rapid increase in energy, 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 Arab petroleum producing countries resulted in serious economic disruptions throughout the world Petroleum consumption during this period in the United States was 14% less than anticipated prior to the embargo [3]. The reporting of this and other petroleum shortfalls has tended to be misleading. The impression often conveyed is that petroleum supplies fall short of a quantity that has traditionally been used. This is not the case Petroleum usage, even following the embargo and the numerous subsequent OPEC price increases, has been increasing. The aforementioned 14% shortfall reduced consumption, temporarily, to a level corresponding to that of 1970, a year not noted for shortages.

Petroleum consumption in the United States, as indicated in Figure 1.1, had been increased rapidly [4–6]. Domestic production, even including the crude oil now obtained from Alaska (the initial pipeline capacity was 1.2×10^6 bbl/day), has been insufficient to meet the growing demand. Hence imports have steadily increased. Imported crude oil and petroleum products in 1979 supplied nearly half of the nation's demand for petroleum. Although the imports attract the most attention, because of their cost in foreign exchange and the uncertainty of supplies resulting from the political instability of many of the exporting nations, the United States is still one of the largest petroleum producers in the world. Prior to 1966, U.S. production exceeded that of the entire Middle East. It was not until 1975 that the Soviet Union's production surpassed that of the United States, moving the USSR into the lead [7, 8].

Domestic production of petroleum and natural gas, the premium hydrocarbon fuels that provide almost three-quarters of the nation's energy inputs, has been declining. If presently accepted estimates of yet-to-be discovered hydrocarbon fuels prove valid, half of the nation's original endowment has already been depleted. The remaining reserves are therefore insufficient to justify a significant increase in production.

The increasing scarcity of fuels is not the only factor contributing to the crisis. Associated with the combustion of fossil fuels is the unavoidable release of pollutants.

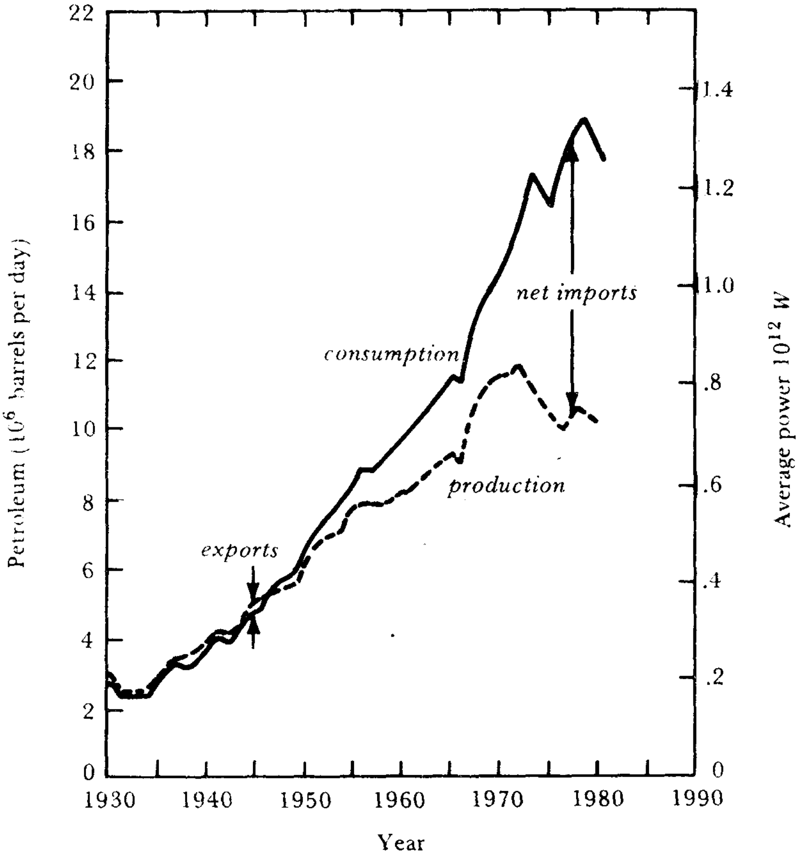

FIGURE 1.1 U.S. Petroleum Consumption and Production (References 4–6).

Coal and petroleum contain sulfur impurities which form sulfur oxides during combustion. 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. The atmosphere contains carbon dioxide (an essential component of the life processes), but 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.

Before shortages of fuels were experienced, excessive levels of atmospheric pollutants were recognized as a national problem. As a consequence, the Clean Air Act (PL 91–604) was enacted in 1970 and the Environmental Protection Agency

(EPA), also established in 1970, was given the responsibility of implementing the provisions of the act. Ambient air quality standards were established that provided a quantitative measure for assessing air quality. To reduce pollutant levels which for most urban areas were deemed excessive, a set of permissible pollutant emission levels was established that would gradually become effective. This legislative action, in effect, recognized the societal costs of air pollution and by means of emission restrictions transferred the costs directly to energy users. Automobile owners, electric power plant operators, and other energy consumers had to bear the cost of reducing pollutant emissions.

Many have recommended that alternative supplies of energy be developed. Only in the area of atomic energy, however, has there been a sustained research effort commensurate with the magnitude of the crisis. 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. Although the first nuclear chain reaction was produced in 1942, 30 years later reactors were only beginning to emerge from the experimental stage. In 1979, 3.5% 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 in the future. Opponents seriously question both the prediction and the wisdom of nuclear-derived energy.

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 less severe and nonradioactive waste products are generated. Unfortunately, a controlled fusion reaction (the hydrogen bomb is an uncontrolled fusion reaction) had eluded scientists. Very few doubt that a controlled fusion process is possible, but 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 the energy picture for several decades.

As a result of the 1973–1974 oil embargo and subsequent events, technologies that rely either directly or indirectly on solar energy received by the earth have received considerable attention. Even though these technologies are frequently viewed as new, solar collectors for producing both heat energy and mechanical work were utilized at the beginning of the century. Interest in these technologies rapidly waned since plentiful supplies of fossil fuels were discovered during the first half of the century. There was a renewed interest in solar-derived energy during the 1950s but this interest too was short-lived. Not only were petroleum supplies abundant, but gluts of petroleum in which crude oil was sold as cheap as 10¢ a barrel at the wellhead were not uncommon.

Solar-derived energy, other than that of fossil fuels which are the result of photosynthetic reactions that occurred several hundred million years ago, will undoubtedly be the future energy source for the world. But a direct replacement of the energy provided by fossil fuels may not be in order. Solar-derived energy, if present indications prove valid, will be expensive. To collect the "free" solar energy, very large capital investments are required. For example, one square foot of a flat-plate collector system which may cost $25 will yield on a daily basis the amount of thermal energy provided by a mere thimblefull (1 oz) of petroleum when used in a conventional furnace. While lower priced solar collection devices are envisioned (as a result of being mass-produced), the price of energy derived from solar technologies will probably remain considerably higher than the price of fossil fuels of the past. This implies that it will be economic to use energy more effectively and efficiently.

For the U.S. energy system, approximately half of the fossil fuels consumed (over 90% of the energy inputs) is used to power heat engines of electric power plants and internal combustion engines employed by the transportation sector. The other half is used for producing heat, very high temperatures for industrial activities such as reducing ores, moderate temperature process steam, and fairly low temperatures to supply comfort heat and hot water needs. Heat engines, owing primarily to the nineteenth-century thermodynamic developments, are considerably more efficient and reliable than their early predecessors. Their conversion efficiencies have been markedly improved by reducing avoidable irreversibilities; that is, entropy increases have been minimized. Heat engines, however, are the only portion of the nation's energy system that may be characterized as relying upon highly sophisticated thermodynamic principles. While these principles apply equally to all aspects of energy usage, they have been extensively utilized only in the design of heat engines, and they have tended to be neglected in the heat-providing portion (furnaces) of the energy system or in the usage of electrical and mechanical energy derived from heat engines. Hence the potential for using energy more effectively is very great.

As evidenced by a three-article series carried by *The New York Times*, it was recognized as early as 1971 that a national energy dilemma existed [9–11].

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

Nation's Energy Crisis: Nuclear Future Looms

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

Despite subsequent presidential calls for energy independence and a moral equivalent of war, little visible change occurred in the nation's energy policy during the decade of the 1970s. While temporary shortages of fuels and electricity occurred and energy prices increased substantially, there was little change in the manner in which energy was used. However, during this decade, not only politicians but also physical, social, and political scientists began to grapple with the problems of energy production and utilization. As a result, there is a considerably better understanding of the philosophical issues involved. An intellectual base from which rational policy decisions could be derived is beginning to emerge [12].

2. ENERGY CONSUMPTION

While world population has been increased at an annual rate of approximately 2%, energy consumption prior to the 1973–1974 embargo had been increased at a higher rate of 5%. High energy consumption has traditionally been associated with a high

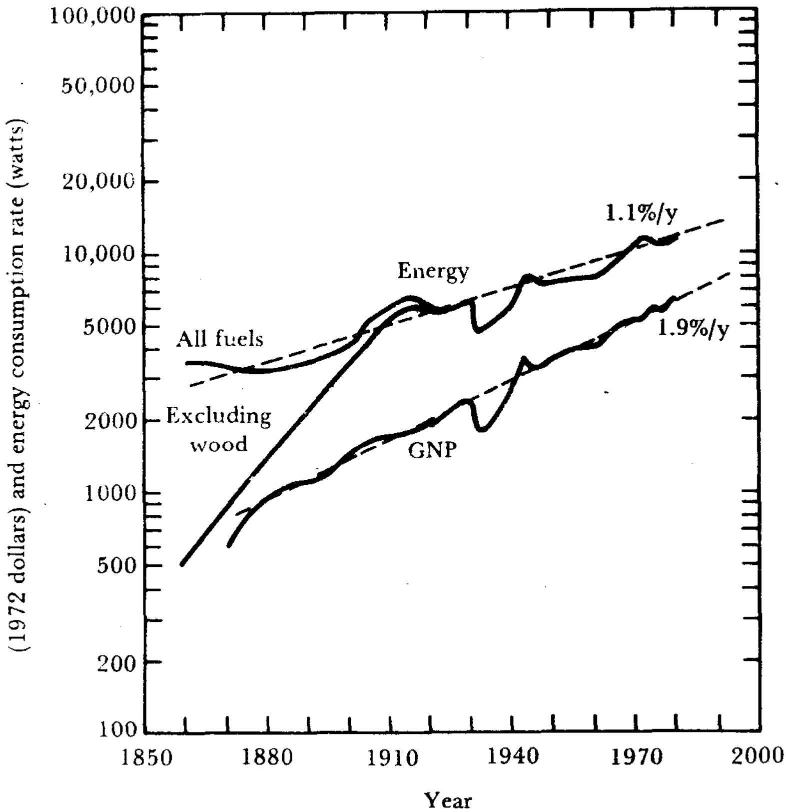

FIGURE 1.2 U.S. per Capita Energy Consumption Rate and Gross National Product (Reprinted by Permission from Energy, 2, 2 (June 1977), p. 116).

quality of life, which is often associated with a high gross national product. In the United States both the rate of which energy is utilized and economic activity have been increasing [4, 5, 6, 13] (Figure 1.2).

Although the long-term average per capita growth in energy usage has been approximately 1.1%/y, the growth over the decade preceding the 1973–1974 oil embargo was slightly greater than 3%/y. Though the large increase in both energy consumption and economic activity that occurred during this period was unusual—if not unique—projections for future demand based upon the growth rates of this period have been common. From 1973 to 1979, however, per capita energy usage changed very little.

Energy usage and economic activity tend to be similarly related for other nations [8, 14]. The data in Figure 1.3 for 1978 provides a comparison in the manner in which energy is used by developed nations. The United States and Canada, on a per capita basis, use considerably more energy than do equally affluent European nations. This comparison has received considerable attention [15–21], since it raises