1 Introduction

Introduction

The necessity for assessment

What are the prospects for energy supplies in the 21st century for this country and the world at large? Energy, after all, drives the industrialized world and is essential to the development of the Third World. At the same time, energy production is the chief pressure for the degradation of the environment in the industrial world and promises to add to the myriad problems of the developing world as well. We are prompted to ask: "Are there alternatives to the present path of the world's energy, economy and environment?".

Fossil-fueled combustion accounts in the late 1990s for 89% of the commercial energy consumption in the USA (Bodansky, 1991; Weisel & Kelly, 1991) and 80% of the total energy use worldwide (Hollander,1990). The worldwide fossil-fuel emissions of the greenhouse gas carbon dioxide have been estimated at over 20 billion metric tonnes (mt) annually. The International Energy Agency (IEA) (Ferrier, 1996, 1997; IEA, 1996) expects world primary energy demand to increase with an annual growth rate of around 2%, reaching 50% above the levels of the 1990s by the second decade of the 21st century. They also forecast that 90% of that energy will still be supplied by fossil fuels in that decade. It is to be expected that energy-driven carbon dioxide emissions will increase in about the same proportions. The IEA further expects that the largest developing countries (China and India) will have a greater increase in CO_2 emissions than the already industrialized nations of the Organization for Economic Cooperation and Development (OECD). And while control of the emissions of pollutants, such as sulfur dioxide (SO_2) and carbon fine particles, is being established in many countries, there remains a debate over further reductions. Even in the face of optimistic energy-efficiency scenarios, Anderson (1995) expects that the growth of demand from developing countries will result in a net growth of world fossil-fuel consumption into the 21st century.

These facts alone tell the tale of environmental pressures. There is an increasing consensus in scientific circles that anthropogenic sources of the "greenhouse gases" (carbon dioxide, methane, chlorofluorocarbons (CFCs), nitrous oxide, etc.) are contributing to climate change worldwide (NAS, 1991; Rosen & Glasser, 1992; Steen, 1994). (Of these, CO_2 and nitrous oxide are emissions from fuel combustion.) The documented rise in global average temperatures is now undisputed. The steady annual increases in atmospheric concentrations of CO_2 and the other gases have been recorded and have long been unquestioned. The theoretical understanding of the mechanism of interaction with thermal radiation, whereby heat is held by these gases in the upper atmosphere, is unchallenged. Whereas the atmospheric physics issues of counterbalancing effects (e.g., cloud cover) and the dynamics of atmospheric and oceanic circulations have not been fully resolved, there has been increasing scientific agreement that the prospect of global warming resulting from human activities is real, with fossil-fuel combustion a major contributor. But in the face of these findings, there is still not a concerted effort by the industrial nations to take strong measures to reduce greenhouse gas emissions worldwide (*New York Times*, 1997). Nonetheless, in view of these prospects, there has been a call to "decarbonize the world economy" (Goldemberg, 1996).

In addition, however, are the prospects of long-term exhaustibility of the fossil resources and their present uneven geographical distribution. The industrial world has already experienced the implications of the latter in the second half of the 20th century. The "energy crises" of the 1970s were simply disruptions in the supplies of oil for the industrial nations who were, and still are, heavily dependent on oil imports. The question of *security* of supplies for oil-importing nations could be revisited by the turn of the century, according to some analysts (Amirahmadi, 1995; Ferrier, 1996, 1997; Salameh, 1996; Goldstein, 1997). It is expected that the USA, which has a major share of the world market, will have to import over two thirds of its oil in the first decade after the turn of the century, as its domestic production continues to decline. Other oil-importing industrial countries, such as in Western Europe, are apt to fall into greater dependence on imports, with North Sea production declining into the second decade of the 21st century and limited prospects in the future for imports from Eastern Europe. Japan will have to compete with a growing demand by China for oil supplies, which may still be dependent on imports from the Persian Gulf, even with increased exploration and production in the Far East (IEA, 1995).

By the second decade of the 21st century, it is expected that the Organization of Petroleum Exporting Countries (OPEC) could be supplying 50% or more of the world oil market, at a rate of 50 million barrels per day or greater (IEA, 1996). But this will be technically feasible only if they have made the investments necessary for that production capacity. In addition, the political situation in the Persian Gulf shows no signs of stabilization within the foreseeable future (Salameh, 1996). This will make prospects precarious for uninterrupted exports for the major fraction of OPEC production and require extensive diplomatic and military efforts by the industrial powers to prevent further disruptions.

There is even a running debate about the exhaustability of world oil and natural gas resources. Industry spokesmen continue to assert that technology gains in exploration will tend to increase world reserves (*Oil & Gas Journal*, 1996); this has the support of some analysts (Cleveland & Kaufman, 1997) who claim that the historic decline in exploration yield per unit of drilling is beginning to slow. Other analysts, however, challenge the optimistic view that innovations in exploration are delaying the exhaustion of these resources (Laherrere & Perrodon, 1997). They believe that peaks of world production of oil will be not far off the peak predicted in the historic logistics curves of Hubbert, produced as long ago as the beginning of the 20th century, resulting in an increase in prices thereafter. They also predict that world gas production will peak in the second decade of the 21st century, thus flying in the face of current optimism about the future of natural gas, as promoted by the gas interests.

The present commitment to fossil-fuel energy is best exemplified by the massive use of oil: the world consumption is over 25 billion barrels annually and the USA uses close to 6 billion barrels. Two thirds of this demand is for transportation, which is over 95% petroleum based in the US. Similarly for coal, the US consumption is currently approaching 1 billion metric tonnes annually, about 85% of which supplies nearly 55% of the nation's electricity. World coal consumption is expected to increase to about 3 billion tons annually by the year 2010, up from 2.3 billion in 1990 (IEA, 1996). Annual wholesale expenditures for all fossil fuels (including natural gas) in the USA exceed $250 billion ($250B). The aggregate value of capital assets in fossil-fueled technology, including power plants, petroleum-fueled vehicles, industrial plants and residential/commercial space heating, exceeds two trillion dollars in the USA. Similar consumption and investments for fossil-fired technologies occur in other industrialized countries (Ager-Hanssen, 1993).

If we examine the energy prospects for the less-developed countries (LDCs), we find a potential demand several times that of the industrialized world, since the LDCs total population is over three times as great. Already, the demand for energy is growing in the Third World at about 7% per annum, compared with around 3% for the developed world (Hollander, 1990), and much of this demand is being met with imported oil. This continues despite the constraints imposed on the oil-importing LDCs by the debts of the oil-crisis period of the 1970–80s (Cassedy & Grossman, 1990).

With the further thrusts toward development, large demands for fossil fuels can be expected unless alternative energy technologies become available. These demands will be for oil in those LDCs having resources or able to afford imports. Other LDCs can, and have started to, develop other fossil fuels, such as coal and natural gas, wherever these are indigenous resources (Cassedy & Meier, 1988). This will accelerate the trends in global pollution and climate change. However, those LDCs without access to energy resources will be crippled in their attempts to start industrial development. Technological developments in alternative energy sources will help to alleviate these pressures on the LDCs but cannot be assumed, for the most part, to originate within those countries. Technological innovations will most likely emanate from the research and development (R&D) establishments of the industrial countries, and our focus for assessing the prospects for these developments will accordingly be there, in the USA, Europe, and Japan.

In recent years, advocates from the industrialized world have promoted the use of renewable resources (such as biomass or hydropower) or inexhaustible resources (such as solar energy or wind power) as the solution to the development dilemmas of the Third World. Some have even proposed that such resources be the chief means of powering the developing world, in order that it does not repeat the despoilation that has accompanied industrialization of the Northern nations. As we shall see in later chapters, the technical, financial, and institutional barriers to alternative technologies make widespread non-fossil development quite uncertain in the near future, in the developed world as well as in the LDCs. The developing nations have already indicated their impatience with unproven solutions and have escalated their use of fossil fuels as their financing and development programs have permitted.

Overall, it is becoming apparent that the demands for energy, both for the continued prosperity of the industrial nations and for the development of the non-industrial nations, are coming more and more into conflict with the world environment. Such conclusions are not confined to environmental activists; the differences expressed in public debate seem only to be about the degree and urgency of this conflict. Indeed, the questions posed for public policy seem, to a large degree, to be about priorities: the economy or the environment? And this, like most questions of public policy, has come down to a matter of values and perceived worth.

Some industrial countries have made major commitments to slowing the growth of the greenhouse gases, as part of the world agreements for *sustainable development* (Brundtland, 1987). Several countries in the European Community (EC) have put emphasis on developing alternative source technologies, such as the "renewables" (solar, wind, and biomass) (Chartier *et al.*, 1996). Denmark, Holland, and Germany have declared policies for development of these new technologies and have active research programs working toward their goals. However, the policies of most governments in the industrialized world, including the USA, have emphasized merely the promotion of energy efficiency in the various sectors of the economy, attempting only to slow the increase of fossil-fuel combustion rather than embarking on major programs to develop alternatives for the *supply* of energy.

Such policies do not look beyond the short/medium term when the limits of energy-efficiency savings will be overtaken by the increased demands for energy. This will come with economic growth and development, especially when the expected swelling in demand in the developing world is taken into account (Anderson, 1995). It is with this *longer-term* perspective that this book is concerned: assessing the prospects for *mass* substitutions of fossil fuels by energy sources that do not threaten our environment and climate: sources that are inexhaustible and that provide secure access for the critical requirements for an energy input to the economy. Such sources will here be termed *sustainable* energy sources, including the solar, wind, and biomass technologies that have the potential to displace fossil fuels on a mass scale in the long term.

If there are alternative technologies for the supply of energy and there are ways of using energy more efficiently, it may be asked why these alternatives are not used if they can eliminate some or all of the problems created by fossil fuels. The answers, to date, are technological, economic, and otherwise behavioral and have been dealt with in many different treatises in recent years. This book deals with the prospects for the technological change in the energy industry that is needed for alternative sources of energy to substitute for the fossil fuels on a mass scale.

The purpose here is not to dwell on the market failures, failures of political leadership, or lack of industrial innovations for alternative energy technologies. These failures have made up the history of the period, starting with the energy crisis of the 1970s. Concerns during this period were focused, on and off, on the supplies of fossil fuel, principally oil. The level of anxiety rose and fell with world oil prices, and technological innovation was cut off when the price of oil fell. This, of course, was not a new pattern in American history and had been occurring since petroleum came on the scene a century ago (Cassedy & Grossman, 1990, 1998).

While not reviewing the history of the failures of alternative energy technologies, we will nonetheless be interested in the causes of failures in the past, insofar as they related to the innovation process itself. In the process of innovation, leading from invention to market adoption of new technologies, there are critical points where progress can stop. These failures in the process are rarely a consequence of the technology alone and frequently are entirely apart from the technical promise of the invention or new process itself. The most common obstacle, as mentioned above, has been the market, where a drop in competitive prices undercuts the anticipated profitability of the new innovation before it can be brought to the commercial stage.

There are other factors for the success (or failure) for the process; in some cases economics is the explanation, while some are explained by other theories of human behavior, such as sociology (Rogers & Shoemaker, 1971). The economic theories of innovations deal with factors of industrial firms, such as size, that are thought to influence the success of the processes of R&D (Mansfield, 1968). The sociological theories of innovations, by comparison, deal more broadly with the adoption of new technologies as they are involved in cultural change. We will explore both perspectives as we consider the various options that appear open to society.

The heightened concern over the environment during the 1990s has transformed our perspectives of technologies in general, with energy production, in particular, coming under intense scrutiny (Hollander, 1990). The possibility of global climate change has become a public issue for the longer term, while acute pollution conditions, as in the Los Angeles air basin, have galvanized urgent efforts for the near term. The emergence of the electric vehicle (EV), not considered a serious automotive competitor since the advent of the petroleum-fueled, internal combustion engine (ICE), is attributable almost entirely to the awakening to environmental realities for the people of California. As we shall see in this text, if the EV had continued to be judged on the basis of its present technical performance and costs, it still would not compete nor would it have had any likely prospects for the near future.

This approach to assessment

A major purpose for this book is to reassess the prospects for these alternative energy technologies in light of the growing public sentiment for an environmental approach and out of older concerns, such as energy security, which could return at any time. For the most part, the assessment will be of the renewable energy *sources*, such as those using solar, biomass, or wind resources. However, technologies that deal with energy end use, for instance those that store energy, such as batteries, will also be assessed. In some cases, these seemingly auxiliary technologies are crucial to the ultimate success of a source technology, with solar power plants or wind generators as prime examples of technologies that are reliant on auxillary support to be really effective. The EV is another example where storage not the primary creation of energy is crucial to success. However, we will not generally deal with entire energy systems, such as the entire energy conversion process in solar–thermal electric generation or the complete automotive-drive functions of an EV. Rather we will examine the attributes of these prospective technologies as basic sources of the energy required to perform their functions in the economy.

The prime criterion for selection of each prospective alternative for assessment will be that it could fit into an overall scheme leading toward sustainability overall for the supply of energy and the preservation of the environment. *Sustainability* is a term, or even a concept, that has been widely used in recent years, especially regarding international development. Brundtland (1987), for the World Commission on Environment & Development, has defined *sustainable development* as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This definition is the outcome of decades of debate worldwide over economic growth and the environment (Beder, 1993). It attempts to create an approach to the economic development demanded so vigorously, especially in the Third World, ". . . in which the material needs of all the world's people are met in ways that preserve the biosphere" (Brundtland, 1987).

In its broadest interpretation, it is taken to mean not only sustainability of resources and the environment but also social sustainability, including all aspects of economics, community, and social fabric (Brown, *et al.*, 1991; NRC, 1992; Daly & Townsend, 1993). It seeks ". . . an economy that exists in equilibrium with the earth's resources and its natural ecosystem . . ." (Allenby & Richards, 1994). Here, we will not be so ambitious as to encompass the broad definition but will only comment on salient cases of social sustainability, such as comparing centralized energy facilities with decentralized energy production. We will, however, be guided by criteria for energy technologies that are supportive of the broad concepts of sustainability (Steen, 1994).

In our assessment of energy technologies, that are in harmony with sustainability, we will be looking for one or more features of (i) inexhaustibility, (ii) renewability, or (iii) recyclability. By inexhaustibility, we mean superabundance, such as found with the solar technologies. Renewability is the familiar concept associated with hydropower but also is exemplified by biomass technologies. In the industrialized world (OECD) today, renewables (hydro, geothermal, and wood) account for only about 8% of primary energy consumption. Finally, recyclability can imply not only a renewing of the source of energy but also a recycling of undesirable products of energy conversion, such as the greenhouse gas carbon dioxide. Examples of this dual recycling concept would be managed energy crops or forests, where not only is the biomass fuel renewed but also the combustion product carbon dioxide is recombined in photosynthesis. Consequently, throughout our assessments of the various prospects, we will be looking for the presence or promise of these features of sustainability for an energy economy in the longer term.

The ideal of a near perfectly cyclable energy system, however, may not be technologically achievable, even in the long term. An example of such a system might be one of the "solar–hydrogen" proposals where solar energy is the primary source to separate hydrogen from water and the hydrogen is then used as an energy transmission medium. Ideally, of course, combustion or fuel-cell conversion of the hydrogen is pollutant free, having only water as the product of combustion or conversion. But such an ideal is achieved only with combustion using pure oxygen or conversion in some of the advanced fuel cells. The more practical and less costly use of air for combustion of hydrogen inevitably results in nitrogen oxide emissions, just as any of the fossil fuels do. The same is true of the much advocated use of natural gas as a means to reduce CO_2 emissions per unit of energy delivered and eliminate most sulfur dioxide emissions. Even though it is a less polluting fuel, natural gas combustion with air still results in nitrogen oxides emissions, in addition to CO_2.

Emissions are not, of course, the only possible impacts of candidate technologies to be considered for sustainability. Waste products and residues of the energy-conversion process should be scrutinized also, particularly with regard for any long-term implications. The most salient example of such is high-level nuclear waste, which presents health and security dangers extending into the future far beyond our society's control. It is for this reason, principally, that nuclear fission technologies (using uranium isotopes) have been excluded from consideration here. Nuclear fusion (using isotopes of hydrogen), where the nuclear wastes are not as long lived and do not pose long-term security, has been discussed but is questionable with regard to these sustainability criteria even if it were found to be technically feasible. The residue products of mining for alternative fossil fuels, such as oil shales and tar sands, also can have long-lasting environmental impact on more localized scales and, therefore, is questionable for fitting our criteria here.

In this book, we attempt a comprehensive assessment of the technological options open to society to supply its energy, looking forward to a goal of sustainability in the *long term*. The assessments will represent the author's best independent judgments of the realistic prospects, technically, economically, and environmentally. The emphasis will be on those technologies that, in the author's view, have the prospects for making major impacts on society's energy supplies well into the 21st century. In each case, the factors favoring sustainability will be evaluated in light of the current stage of development of the candidate technology. We will not give assessments to any extent on approaches, such as energy efficiency, demand-side management, or emissions reduction, that have been advocated to serve the transition in the medium term to a totally changed energy economy in which these sustainable technologies would be used widely.

Projections of the expanded use of renewable energy sources into the next century vary wildly. Starting from a base of total US use in 1990 of 6.8 QUAD (1 QUAD = 10^{15} BTU = 7.2 EJ), supplying about 8% of the nation's energy, these extrapolations range from 15 to almost 60 QUAD (16 to 63 EJ) by the year 2030 (Rosen & Glasser, 1992). (The 1990 base of use comprises mostly hydro and geothermal electricity plus wood burning.) The high estimates tend to come from organizations that advocate the use of renewable technologies, such as the Solar Energy Research Institute (now named the National Renewable Energy Laboratory) or the Union of Concerned Scientists and Public Citizens, whereas the more modest estimates originate from the US Department of Energy (DOE) and the Gas Research Institute, neither of which had dominant interests in renewables when these projections were made. A major objective of this book is to give insight into such forecasts, attempting to do this without underlying biases.

Critical assessment

These assessments will be of a critical nature, avoiding the promotional projections so common in reporting R&D progress. The prospects for gains or breakthroughs in technical performance or cost reductions will be cited wherever appropriate, but the optimistic projections of promoters will not be quoted. The uncertainty of the outcomes of R&D will be evident throughout all of our reviews of these new alternative technologies, especially with regard to the timescale for successes. The reader should not use the critical nature of the reviews to draw general conclusions that R&D projects on these ideas are unworthy of support – most of them are worth supporting. The author's intention here is merely to inject a note of skepticism on projections of R&D achievements by those having a stake in their future, no matter how carefully they may be constructed. The underlying motivation for this approach is to help to instill more realism into analysis and debate regarding future prospects. More discussion of such behavioral aspects will be made in the section on the R&D establishment and for specific examples in the assessments themselves.

This book is not written exclusively for the technologist, rather it should be understandable and useful to readers having a modicum of technological literacy on energy matters. Tutorial treatments for the non-specialist may be found in the science, technology, and society literature (cf. Cassedy & Grossman, 1990, 1998). The assessments are directed to business people and economists, as well as technical people, who are making business decisions or are formulating government energy policies. Students in graduate programs in business or public policy are also a prime readership for this book. In every assessment, an attempt has been made to bring out those technical features that are key to the success of the technology, without going into excessive detail. Any reader interested in further technical details will find them in the references, which have been cited at every point relevant to the assessments throughout the text.

The major objective here is to stimulate a critical appraisal by the reader of what the prospects are for each of these candidate technologies for a sustainable energy future, without the biases of promoters, and to be able to formulate a more realistic picture of where these technologies might fit into systems and schemes to meet the needs and contingencies of the future.

The presentation here will be discursive, avoiding the use of equations on technical issues, but at the same time being quantitative wherever essential for critical assessment. Figures are used mainly to convey a sense of working reality or to illustrate simple concepts, not to delve into technical detail. Economic competitiveness will always be quantified in terms of unit costs of energy that are readily compared with the market and competing technologies. This perspective is a market view, directed at broad business or public policy decision making rather than the financial analysis of individual investments in these new technologies.

Unit costs refer to the cost of energy produced per unit of energy supplied. For thermal energy we will use \$/MBTU (US dollars per million BTU) or the nearly equivalent \$/GJ (US dollars per gigajoule). For electric energy we will use \$/kW-hr or cent(¢)/kW-hr. These unit costs will always be given on a basis adjusted for the depreciation lifetime of the equipment, following the "cost of energy" definition that is commonly used in the energy industries (see Appendix A). Unit-cost comparisons will generally be made with current market prices for conventional fuels and electricity, which appears justified in most cases during the present era of relatively stable energy prices. However, the prospects for changing energy market prices, both up and down, are discussed in several cases. Finally, in a few cases where it is appropriate for investment decisions, we will cite life-cycle cost comparisons.

The organization of this book

The book is organized into three parts: following Part I, the *Introduction*, Part II covers the *Candidate technology assessment* and Part III covers the *Prospects for technological change toward sustainability*. Part II includes nine chapters assessing the technological, economic, and environmental status of prospective, sustainable technologies. At the end of the book, the appendices cover *Energy cost analysis*., a *Glossary* of terms and units used in the book, and *The conduct and management of research and development.* Major attention is given to solar energy sources, biomass energy, wind