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In Xanadu did Kubla Khan
A stately pleasure-dome decree:
Where Alph, the sacred river, ran
Through caverns measureless to man
Down to a sunless sea.
So twice five miles of fertile ground
With walls and towers were girdled round:
And there were gardens bright with sinuous rills,
Where blossomed many an incense-bearing tree;
And here were forests ancient as the hills,
Enfolding sunny spots of greenery.

—Samuel Taylor Coleridge, *Kubla Khan*

1.1 Sustainable Energy: The Engine of Sustainable Development

Energy is one of the essential needs of a functioning society. The scale of its use is closely associated with its capabilities and the quality of life that its members experience. Worldwide, great disparities are evident among nations in their levels of energy use, prosperity, health, political power, and demands upon the world's resources. During recent decades, concern has grown that it is unwise for the poorest nations to be relegated to miserable poverty and for the richest ones to be able to command such large shares of the resource pie. The latter concern has been especially acute in regard to the United States, which has the world's largest economy (with about 5% of the world's population consuming approximately 25% of the world's energy production), supporting its preeminence culturally, politically, and militarily since the end of the Cold War.

Of the six-plus billion inhabitants on earth today, more than two billion are living below the poverty line as defined by the United Nations—equivalent to about 2US$ per day PPE (purchasing power equivalent). For these very poor, the basic needs of food and shelter are a daily challenge. Most scavenge biomass for any energy needs, leading to depletion of what little vegetation is locally available. Access to water is another challenge, and men, women, and children spend long hours hauling water, food, and fuel. For these people, health problems abound, and mortality rates are high.

To move out of abject poverty, access to some sort of income is necessary. This need is closely tied to the availability of energy—which makes local businesses and the transportation of commercial goods to markets possible. Energy development provides as well for health clinics, for lighting, and for basic services. The UN and the World Bank have launched initiatives to reduce world poverty. Energy development is a major aspect of their development plans.

Even developing countries that have populations well above the poverty line are seeking to improve living standards through more industrialization. Looking at per capita energy consumption is a good way to understand the disparities between the richest and poorest nations. Figure 1.1 shows the variation for typical countries.

Figure 1.1. 1999 per capita average commercial energy use for selected countries.

The average US citizen uses 100 times more commercial energy than the average person in Bangladesh. If today's energy use were distributed equally over the world population, each person would use about 1.4 tons of oil equivalent (TOE)/year.[1]

World population is still increasing; it has tripled since the late 1930s. In 1700, world population was 600 million. More people and more development suggest even higher future needs for energy. The most available and affordable sources of energy in today's economic structure are fossil fuels (about 85% of all commercial energy is derived from them). Efficiency improvements and new technologies are part of the solution. Still, society may have to make some major changes if we wish to address the challenges of eradicating abject poverty and stabilizing greenhouse gas (GHG) emissions.

Such concerns have led to the creation of political movements pressing for changes in our demands upon the environment. These pressures have ranged from criticism of individual practices (e.g., growth in the heavy vehicle portion of the passenger automobile economy) to demands that the overall structure and economic basis of societies be changed (e.g., criticism of global trade markets, with the attendant suffering of those who lose within them). Many pressures are focused on energy, in terms of its uses, supply technologies, and efficiencies. These concerns have often been expressed in demands for less use, greater end-use efficiencies, and more reliance on solar and geothermally powered technologies, rather than fossil and nuclear energy, which extract their fuels from finite earth resources.

In its most extreme guise, sustainable energy is that which can be provided without change to the earth's biosphere. However, no such form of energy supply exists. All require some form of land use, with attendant disruption of the associated ecosystems,

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1 One ton of oil equivalent (TOE) contains about 40 million Btus or 43 trillion joules of energy (see Table 2.1).

extraction, which can be disruptive for fossil fuels, and less so for nuclear ones. Ultimately, all of these extracted materials reenter the biosphere as wastes, where their sequestration practices are at least as important as their masses in determining the accompanying ecological disruption.

In this book, we treat energy technologies as being sustainable if their net effects upon the biosphere do not significantly degrade its capabilities for supporting existing species in their current abundance and diversity. This definition is inherently conservative and favorable to the status quo. It reflects our ignorance in assessing the quality of alternative ecosystems (some of which might be preferable to what exists now) and in understanding our effects upon them. However, as a response to human practices, which in many instances appear to be harmful, it is an improvement. We hope that, in time, our ecological knowledge will improve to the point that such conservatism will not be the best that we can do.

The objectives in the previous discussion demand definition (perhaps quantitatively) before a useful system for decision-making will exist. Such definitions are made via our political systems—which is another way of saying that they will be the outcomes of struggles among interest groups. This recognition is important, because, while the alternatives in achieving sustainability are technological, the social directions served by their use, and the criteria for what is acceptable, will always remain social. Thus, sustainable energy must be concerned not only with energy and environmental technologies, but also with the social and political factors that impact human lifestyles.

The patterns of energy use worldwide reflect the distribution of wealth among nations. Of the earth's approximately six billion people:

- Roughly 20% live in the wealthy, industrialized countries of western Europe, North America, and Japan. For example, the specific energy consumption rate in the US is 350 million Btu/capita annually; in western Europe and Japan, it is about half of that amount.
- An approximately equally sized group lives within rapidly industrializing South Korea, Taiwan, Malaysia, Thailand, South Africa, and China; these account for much of the growth in energy consumption. The specific energy consumption rate for China is 30 million Btu/capita with a wide variation among the population on an individual basis. More affluent urban populations are approaching energy consumption levels of Europe and Japan, while many rural populations remain at energy consumption levels typical of undeveloped countries. This group also includes countries such as Chile, Mexico, and Brazil, which are in a middle state of development but have only slowly growing economies.
- The rest of the world is largely primitive economically and is developing slowly, although many countries in this group have wealthy elite, small regions of prosperity, and more rapid development (e.g., Karala and the

region near Bangalore in India, which has specific energy consumption of 15 million Btu/capita annually).

Growth of energy demand reflects the pace of economic development. The first group accounts for most of the consumption of energy (and other resources) worldwide, and also, because of its wealth, is the group most able to protect the environment from disruption that occurs as a consequence of its consumption.

The second group is making the transition to wealth, has great disparities of individual and national abundance, and largely does not invest in environmental protection (e.g., because of regional air pollution, when flying over China it is common to be unable to see features on the ground distinctly).

The third group consists of a population subsisting largely outside the cash economy. These countries meet most of their energy needs via biomass, using their own muscles and those of their animals, and burning foraged vegetable matter. Energy-use data for these countries reflect primarily consumption within the cash economy, which is atypical of the situation of most of its members.

Overall, the available data indicate the great majority of energy consumption (80%) occurring in the first group of countries but with slow growth, most of the remainder occurring in the second group of countries (15%), and the remainder occurring in the last group. Investments in the energy supply infrastructure also reflect these trends.

In a typical developed country, such as the US, electricity production accounts for about 25% of total energy consumption (note that electricity is an intermediate energy product that is made from primary energy sources), with the remainder of energy needs met by direct fossil fuel consumption. Use of geothermal energy and the renewable technologies are negligible. Coal is used almost exclusively for electricity production (accounting for about half of the fuels used to make electricity). Remaining needs, especially in transportation, are met mainly via petroleum consumption, with natural gas being about as important as petroleum in the industrial, residential, and commercial sectors. Specific data for the US, France, and Japan are given in Table 1.1. In some special cases, national policies have affected the energy technology mix. For example, most French and Belgian electricity is from nuclear energy, and in Denmark about 20% of electricity is obtained from wind.

In partially developed countries (second group), reliance on petroleum for all needs is typically greater and fractional use of electricity is less than with the fully developed nations (reflecting the strong correlation between gross per capita domestic product and per capita electricity consumption). The partially developed countries include many that have some of the characteristics of industrialized countries (e.g., growing motorization and electrification) but retain substantial peasant populations. Those that are growing rapidly are also in the process of integrating this group increasingly into the cash economy.

Table 1.1. 2001 Primary Energy Consumption by Fuel for Selected Countries and Secondary Electricity Generation (million TOE*)

Country	Oil	Gas	Coal	Nuclear	Hydro	Total
USA	896	578	546	183	48	**2251**
Japan	248	71	103	73	20	**515**
France	96	38	12	96	18	**258**
Germany	132	75	85	39	6	**336**
UK	77	87	40	20	2	**226**
Belg/Lux	32	13	8	11	1	**64**
Netherlands	44	35	9	1	—	**89**
China	232	25	519	4	54	**834**
India	97	25	173	4	16	**314**
WORLD	**3517**	**2220**	**2243**	**601**	**585**	**9165**

Source: BP, 2001.

*Electricity is converted to TOE based on fossil fuel primary energy and 38% conversion efficiency. Since nuclear and hydro energy generate electricity at much higher efficiencies than 38%, the fractions of primary energy contribution are skewed when everything is put on a TOE basis.

The third group of countries is neither wealthy nor growing rapidly economically. These countries demand relatively few of the earth's resources. However, locally, their pressure on the environment can be heavy, due to their intense use of scavenged and harvested biomass. In these societies, the economic surplus needed to protect the environment in association with human activities is least, as is the protection. A major question for wealthy nations concerns how to persuade and help these nations protect their own environments, and, thereby, the global environment. The main feasible means for accomplishing this appear to be various forms of financial and social aid (i.e., education and health programs), and the creation of attractive technologies for their use. Past experience indicates that both of these avenues are difficult to implement successfully and may be inadequate.

Within the third group of countries, energy needs are met using indigenous sources to the extent feasible (e.g., coal in India and China, geothermal in El Salvador); most other needs within the cash economy are satisfied using petroleum. Data concerning consumption outside the cash economy are questionable, but it is evident that biomass that can be harvested by the affected individuals is the predominant energy source.

All three groups of countries aspire to more prosperity and an improved quality of life for their citizens. Such development will require expansion of energy services and infrastructure world wide. Can this be achieved in a sustainable manner so that our environment, social structures, and economy remain a viable legacy for future generations?

Energy production or utilization is often intertwined with consumption of other precious natural resources, such as minerals, forests, water, food, and land. Further, the everyday use of energy can damage human health and the earth's ecosystems over wide length and time scales (1 m to 10,000 km; 10 s to 100 yr). Yet in the developed countries, the availability of stable supplies of energy at manageable prices has propelled economic development and enfranchised most of the populace with mobility and a host of lifestyle benefits that were unimaginable a century ago. Developing countries are now dramatically expanding their energy use to extend economic prosperity within their borders. Because of growing populations and expanded development, world energy use over the next century may grow four-fold even with substantial improvements in conservation and end-use efficiency. At the same time, continued dominance of the world's energy by fossil fuels (about 85% of global consumption in 1998) is expected to be challenged, not by the red herring of scarcity, but by concern that emissions of fossil-derived CO_2 and fugitive CH_4 to the atmosphere will cause serious global climate modification.

In the energy sector, sustainability ideas confront a phalanx of trans-global forces—pervasive human impacts, current and aspirant economic well-being, ecological degradation, geopolitical equity—that are conspiring to create an energy-prosperity-environmental dilemma of epic proportions. That dilemma is how to maintain and extend energy-derived benefits for present and future generations while shepherding the planet's natural resources. Scholars differ on how to resolve this dilemma, but many support the precepts that there are multiple answers, that solutions change with time and circumstances, and that virtually every technology and policy option entails tradeoffs that must be carefully valued.

For a more sustainable energy future we need to develop a rich set of energy technology and technology-intensive policy options. These options include increased efficiency of energy production and use, reduced consumption, a new generation of renewable energy technologies, nuclear options that can win and retain public acceptance, and means to use fossil fuels in a climate-friendly way. If fossil fuel prices rise to include costs of carbon management, consumers may also modify their consumption patterns. Environmental and ethical concerns may also contribute to new attitudes about unconstrained economic growth patterns. Sustainability concepts provide a framework to focus the evaluation of energy technology and policy options and their tradeoffs and to guide decision-making on energy futures. The key to getting these concepts right is to develop a solid understanding of the multi-faceted technological, geopolitical, sociological, and economic impacts of energy use and abuse.

Sustainability is necessarily subjective because it reflects human value—the relative importance stakeholders assign to the activity to be sustained, to the perceived benefits of that activity, and to other values "traded off" to sustain the activity in question. Many sustainability tradeoffs are an inevitable result of tension between the benefits derived and the adverse consequences of the activity that provides those benefits. Examples of these tensions include: time horizons for reform, i.e., taking the "best" now versus preserving it for future generations; individual versus national versus global interests; and expansion of economic opportunity versus stewardship of resources.

Energy affects all people, is technologically intensive, and evokes diverse, value-laden, and controversial perspectives on what technologies and policies are appropriate in various contexts. Diverse views on what *sustainable energy* really means are thus inevitable. To catalyze meaningful discussion, we propose the following definition:

> **sustainable energy**: a dynamic harmony between the equitable availability of energy-intensive goods and services to all people and the preservation of the earth for future generations.

This definition is similar to the well-known one developed by Bruntland (1987)—"development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Given the past trajectory and current status of planet Earth, sustainable energy so defined is a *state of global being yet to be realized*. Some would proclaim this condition too optimistic to be possible, or, if attainable at all, inevitably unstable. We reject the idea that a condition of sustainable energy as here defined is impossible, but we recognize that to remain effective this condition is unstable in one particular sense. The specific attributes of a state of sustainability will inevitably change with time, owing to technologic and sociopolitical forces. To survive, sustainable energy must eventuate a state of *dynamic immutability*, in which desired energy-derived benefits are available without term, owing to technologic and policy measures that evolve, both rapidly and substantially, in response to evolving human and environmental needs. Engines of production transformation are technological innovation, reliable scientific understanding of how technology affects the earth and its occupants, and effective communication of technology risks and opportunities with and among stakeholders.

If sustainable energy is yet to be realized, we must consider how to get there. We see no easy or unique roadmaps, but rather a series of pathways that will be dominated by gradual transformations of institutions and individuals. This transition toward more sustainable energy use can be likened to a mission-oriented expedition, initially deliberate but sooner or later fragmented by various excursions, some rewarding, others frustrating. Because energy impacts virtually every aspect of human endeavor, this journey will attract or indenture a wide range of participants. These travelers, be their purpose "business" or "tourism," will reap more from this journey if they regularly update their understanding of mapped and unexplored territories.

This text is a travel guide for sustainable energy pilgrims. Our goal is to provide information and analysis tools for a more productive and pleasant passage. It is assumed that each traveler will wish to select his or her own major routes and side-trips and to make his or her own decisions on what to explore.

The supply and use of energy to improve human well-being has many attributes and consequences, some transparent, others opaque, some beneficial, others hostile. Thus energy exemplifies the types of tradeoffs that are the foundation of the sustainability approach. Throughout this text, we seek to identify and understand these energy tradeoffs (i.e., the human and ecological costs, benefits, and limitations in using energy to propel economic prosperity while preserving the environment and other irreplaceable resources). We will explore such questions as: How much energy is there? Is energy a thing? Is "work" the only type of energy, or are there many different forms? If so, are all of these forms equally useful to people? Can most or all energy, regardless of its form, be employed for productive purposes or must some energy always be wasted? If waste of energy is inevitable, how great are the losses and do they depend upon what energy processes or equipment are utilized? How do energy-related actions harm the ecological well-being of present and future generations? Are there countermeasures to prevent or remediate energy-related environmental degradation? How can we measure and fairly value the beneficial and detrimental effects of energy? Subsequent chapters will respond to these questions with credible technical information and with discussion of technological uncertainties, information voids, and alternative solution pathways when well-established information bases or broadly-based sociopolitical consensus are elusive.

1.2 Defining Energy—Scientific and Engineering Foundations

We need an understanding of energy suitable for quantitative study of sustainability. We must comprehend what energy *does* and what energy *is*. Webster's Dictionary (1986) defines "energy" as:

> **1:** vigorous exertion of power **2a:**. the capacity of acting or being active <intellectual ~> **b:** dynamic quality <narrative ~>; **3:** the capacity for doing work
> **4:** usable power (as heat or electricity); *also*: the resources for producing such power.

The implications are that "energy" embodies animated and possibly productive physical or mental activity—presumably by humans, animals, machines, nature, "electricity," etc. Definition (3) reprises what apparently was the first use of the term "energy" as "ability to do work," by Thomas Young in his 1805 Bakerian lecture to the Royal Society (Levenspiel, 1996).

Experientially, we think of "work" as arduous physical or mental exertion. To comprehend sustainable energy, we need to refine our understanding of four key concepts: "energy," "work," "heat," and "power."

Centuries of observations show that a certain quantity remains constant during physical, chemical, and biological changes. This conserved or "immutable" quantity is energy. First, consider some of the consequences if energy is conserved. One is that we cannot get rid of it. Let us divide up the entire universe into specific regions with well-defined boundaries and other particular characteristics. We define each such region as a *system*. Often we divide the universe into just two systems: the region we wish to analyze in some detail (System 1, e.g., the combustion chamber of an automobile engine), and all the rest of the universe (System 2), which we define as the *surroundings*. What is important with a system is not the absolute energy content of the universe, a system or even a set of systems, but rather the *change* in the energy content of particular systems within the universe and their interactions with their surroundings during the course of that change. In energy analysis, it is important to know, for particular circumstances, the total amount of energy a system can give to or take from its surroundings *and* what fraction of that exchanged energy can be converted to useful purposes such as the motion of an automobile or the generation of electricity.

The First and Second Laws of Thermodynamics (see Chapter 3) provide us with the theory to answer these questions quantitatively, assuming that we have the necessary data to implement the tools of thermodynamics for practical calculations. It is often important to know how rapidly energy can be generated within, assimilated by, or released from one or more systems (e.g., how fast can the chemical energy of a fuel be converted to the kinetic (motive) energy of an automobile or the thrust that propels a rocket). To address these questions, we need to draw on thermodynamics and on the disciplines of chemical kinetics, physical transport, and fluid dynamics to describe the rates of chemical reactions and of the exchange of heat, material, and momentum within and between single and multiphase media. Sections 3.4 and 3.5 introduce chemical kinetics and heat transmission in the context of sustainable energy.

The position or motion of matter causes energy to exhibit diverse forms. Many are readily observed (e.g., as changes in pressure [stress fields], volume, temperature, surface area, and electromagnetic properties) (Table 1.2).[2] Heat is a familiar form of energy, defined formally below. Thermodynamics shows that heat and all forms of energy are related to mechanical work, such as the raising or lowering of a weight in a gravitational field (Tester and Modell, 1997).[3]

A *closed* thermodynamic system is completely surrounded by movable boundaries (walls) permeable to heat but not matter (e.g., a vertical cylinder filled with a gas and covered with a piston that can be moved up and down). By adding weights to the piston, we can compress the gas and store energy in analogy to pushing on a coiled spring. This addition of weights is an example of *work performed by the surroundings* on our system. The resulting downward movement of the piston is *work obtained by the system* from its surroundings. Regardless of how meticulously we add the weights, the amount of work taken up by the system is always less than the work done on the system by its

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2 These effects are practical scale manifestations of microscopic changes in matter, e.g., molecular vibrations and rotations, motion of electrons, spinning of nuclei, formation and scission of chemical and nuclear bonds. Thus, fundamental studies of molecular and nuclear phenomena provide crucial insights on how to make energy more sustainable.

3 Establishing the mechanical equivalence of heat is a seminal triumph of early thermodynamics scholars, i.e., Rumford, Mayer, Joule, and Carnot (Carnot, 1824).

surroundings by an amount of energy exactly equal to the heat gained by the system. This is a rudimentary expression of the Second Law of Thermodynamics. Thus *heat* is a form of energy. In the piston example, it arises from wasted or lost work. Rigorously, heat is defined as a mode of energy transfer to or from a system by virtue of contact with another system at higher or lower temperature (Levenspiel, 1996; Denbigh, 1981).[4] *Work* is defined as any mode of energy transfer, other than heat, that changes the energy of a system (e.g., by a chemical reaction, raising or lowering a weight, turning an electrical generator). *Power* is the rate of energy exchange between two systems. It has units of energy per time and may represent a flow of work, heat, or both.

Table 1.2. Changes in System Properties That Produce or Consume Work[a]

Category of Work	**Responsible Physical Process**	**Energy-Related Example**
"Generalized Work"	(A Force) *timesüR RÇ* (A Spatial Displacement)	NA[b]
Pressure-volume[c]	Volume change caused by force per unit area (pressure).	Movement of piston in internal combustion engine.
Surface deformation	Surface area change caused by surface tension.	Small (stationary) droplet of liquid fuel suspended in a quiescent fluid (assumes a spherical shape).
Transport of ionized (electrically charged) material	Movement of charged matter caused by an electric field.	"Electrostatic" precipitation of particulate pollutants in stack gas.
Frictional	Movement of solids in surface contact.	Generation of waste heat by unlubricated moving parts in machinery.
Stress-strain	Deformation (strain) of a material caused by a force per unit area (stress).	Pumping of a viscous (highly frictional) liquid through a pipe.

[a]Mathematical treatments are given by Tester and Modell (1997).

[b]Not applicable.

[c]Often called "*PdV*" work.

The formal thermodynamic statement of the law of conservation of energy is the First Law of Thermodynamics. To apply this law, we first state it mathematically. For a closed system, we have:

$$\Delta E = Q + W \quad \text{[closed system]} \tag{1-1}$$

4 In Section 3.5, we will consider the main mechanisms by which heat can be exchanged between two systems at different temperatures.

where ΔE is the change in the energy content of the system, Q is the amount of heat transferred *to* the system *from* its surroundings, and W is the amount of work done *on* the system *by* its surroundings. (Many textbooks write Equation (1-1) as $\Delta E = Q - W$ because they define W as the amount of work done by the system on its surroundings. Both expressions are correct provided work is defined consistently throughout.) In many practical energy problems, the system is not closed but "open," i.e., matter can flow inward, outward, or in both directions, across the system boundaries. Equation (1-1) must then be modified to account for this transport of matter and for any other processes that change the system energy content (see specialized thermodynamics texts such as Tester and Modell, 1997, Levenspiel, 1996, Smith and Van Ness, 1949, Weber and Meissner, 1939).

For practical calculations, we can rewrite Equation (1-1) as:

$$\Delta E = \Delta U + \Delta E_p + \Delta E_k = Q + W_{sh} - W_{PV} \quad \text{[closed system]} \tag{1-2}$$

This expression tells us that a change in the energy content, E, of a closed system can be divided into changes in the internal energy, U, potential energy, E_p, and kinetic energy, E_k, of the system. The internal energy can be changed by modifying the system temperature, changing its phase (e.g., solid to liquid), by chemical reaction (i.e., changing its molecular architecture), or by changing its atomic structure (e.g., by fragmenting [fission] or coalescing [fusion] nuclear particles; Chapter 8). The potential energy is changed by shifting the system location in a force field (e.g., gravitational, electrical, magnetic). The kinetic energy is varied by increasing or decreasing the system velocity (Levenspiel, 1996, and Feynman et al., 1963). Equation (1-2) disaggregates work into W_{PV}, which we call "PV" work, and W_{sh}, i.e., "shaft work." We define shaft work as any work other than PV work—it may involve rotation of a shaft, but it may also include electrical work and other forms. PV work arises from the fact that every system, however small, has some volume. Recalling our *gedanken* (thought experiment) of compressing a confined gas by adding weights to a movable piston, we conclude that a change in system volume changes the system's potential energy. Any system at equilibrium (i.e., at a fixed temperature, pressure, and composition) has a constant volume. To attain that volume, the system had to push its surroundings out of the way to make room for itself. The work done by the system to reach a volume, V', by shoving back a pressure p, is PV work and is given by:

$$W_{PV} = \int_o^{V'} PdV \tag{1-3}$$

It is often convenient to combine a system's internal energy, U, with the energy it has by virtue of its volume, V, at a pressure, P. The resulting thermodynamic quantity is the *enthalpy*, H, defined mathematically as:

$$H = U + PV \tag{1-4}$$

Note that P is the pressure *in* the system. In some situations, it may also be the pressure of the surroundings (e.g., the pressure of the atmosphere) but not always. As with other forms of energy, we are interested in the change in enthalpy when a system changes from a state 1 to a state 2:

$$\Delta H = H_2 - H_1 = \Delta U + \Delta(PV) \quad (1\text{-}5)$$

$$= (U_2 + P_2V_2) - (U_1 + P_1V_1) \quad (1\text{-}6)$$

Equations (1-4) through (1-6) apply to closed and open systems. If a closed system undergoes a change in energy but remains at constant volume, there is no PV work, and Equation (1-2) reduces to:

$$\Delta U + \Delta E_p + \Delta E_k = Q + W_{sh} \quad \text{[closed system, constant volume]} \quad (1\text{-}7)$$

A second case is when pressure remains constant so that from Equation (1-2):

$$\Delta U + \Delta E_p + \Delta E_k = Q + W_{sh} - (P_2V_2 - P_1V_1) \quad (1\text{-}8)$$

i.e.,

$$(U_2 + P_2V_2) - (U_1 + P_1V_1) + \Delta E_p + \Delta E_k = Q + W_{sh} \quad (1\text{-}9)$$

or from Equation (1-6):

$$\Delta H + \Delta E_p + \Delta E_k = Q + W_{sh} \quad \text{[closed system, constant pressure]} \quad (1\text{-}10)$$

For a change in the energy content of a closed system at constant pressure, we can write the law of energy conservation directly in terms of a change in the system's enthalpy, potential energy, and kinetic energy (Levenspiel, 1996). Further, if a closed system is at rest or moves at a constant velocity, and any motion in a force field does not modify the potential energy (e.g., the system remains at the same height in a gravitational field), then the enthalpy change accounts for all the change in energy brought about by addition or removal of heat and shaft work.

Now, can we know the *absolute* energy content of a substance? The answer, provided by Einstein's theory of special relativity (1905), is of great scientific and practical importance. Einstein discovered that the total energy content, E_{tot}, of a quantity of matter of mass, m, equals the product of m with the square of the speed of light, c, i.e.:

$$E_{tot} = mc^2 \quad (1\text{-}11)$$

Special relativity also teaches the speed of light in a given medium remains constant, and an object's mass increases with its velocity according to:

$$m(v) = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (1\text{-}12)$$

In Equation (1-12), m_o is the "rest mass," or the mass of the object standing still ($v = 0$).[5] By expanding the square root term in Equation (1-12) in a Taylor series in (v^2/c^2), we see that m doesn't change very much from m_o unless the velocity approaches the speed of light:

$$m(v) = m_o\left[1 + \frac{1}{2}\frac{v^2}{c^2} + \frac{3}{8}\frac{v^4}{c^4} + \frac{5}{16}\frac{v^6}{c^6} + \ldots\right] \tag{1-13}$$

We can combine Equations (1-2), (1-11), and (1-12) to write:

$$E_{tot} = U + E_p + E_k = \mathrm{m}c^2 = \frac{m_o c^2}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1-14}$$

The deltas of Equation (1-2) have disappeared because now we are dealing with absolute amounts of energy, not differences in the energy content of two systems. From Equation (1-14), we find the expression for the absolute energy content of a body at rest, i.e., where $v = 0$ and thus $E_k = 0$:

$$E_{tot,\ rest} = U + E_p = m_o c^2 \quad \text{[body at rest]} \tag{1-15}$$

Thus, for the more general case of a body in motion from Equations (1-14) and (1-15):

$$E_{tot} = U + E_p + E_k = \frac{E_{tot,\ rest}}{\sqrt{1 - \frac{v^2}{c^2}}} \quad \text{[body in motion]} \tag{1-16}$$

We now use Equation (1-13) to eliminate m from Equation (1-14):

$$E_{tot} = m_o c^2\left[1 + \frac{1}{2}\frac{v^2}{c^2} + \frac{3}{8}\frac{v^4}{c^4} + \frac{5}{16}\frac{v^6}{c^6} + \ldots\right] \tag{1-17}$$

$$= m_o c^2 + \frac{m_o v^2}{2}\left[1 + \frac{3}{4}\frac{v^2}{c^2} + \frac{5}{8}\frac{v^4}{c^4} + \ldots\right] \tag{1-18}$$

Using Equation (1-15) to replace $m_o c^2$, Equation (1-18) becomes:

$$E_{tot} = U + E_p + \frac{m_o v^2}{2}\left[1 + \frac{3}{4}\frac{v^2}{c^2} + \frac{5}{8}\frac{v^4}{c^4} + \ldots\right] \tag{1-19}$$

From Equation (1-14) or (1-16) this requires that:

$$E_k = \frac{m_o v^2}{2}\left[1 + \frac{3}{4}\frac{v^2}{c^2} + \frac{5}{8}\frac{v^4}{c^4} + \ldots\right] \tag{1-20}$$

5 Equation (1-12) is derived in physics textbooks, e.g., Feynman et al. (1963).

Equation (1-20) tells us that, except at system velocities approaching the speed of light, the kinetic energy of the system is almost the same as that computed from the non-relativistic formula of classical mechanics using the rest mass m_o, i.e.,

$$E_k = \frac{1}{2} m_o v^2 \tag{1-21}$$

Changes in system energy content are virtually always the crucial issue in sustainable energy calculations. Nevertheless, the theory of special relativity (Equations (1-11) through (1-20)) elucidates foundational concepts that are essential to a thorough understanding of energy engineering. In particular, relativity theory teaches us how to calculate the *absolute* energy content of a quantity of matter at rest (Equation (1-15)) and in motion (Equation (1-16)), and that the results differ. More important, the theory provides us with quantitative rules to tell us when these differences are consequential for practical applications (i.e., for objects moving at high velocity). Thus, relativity reveals that the mass of a substance increases as the velocity of that substance gets larger (Equation (1-12)). A practical consequence is that above a certain velocity, the classical formula for the kinetic energy of an object in motion (Equation (1-21)) will need to be replaced by Equation (1-20). When this becomes important depends upon the degree of accuracy required, but from Equation (1-20) it is clear that the non-relativistic approach (Equation (1-21)) increasingly underestimates the true kinetic energy as the velocity more and more closely approaches the speed of light.

An important result of special relativity is that energy and matter are different manifestations of the same thing (Pitzer, 1923), or *energy and matter are interchangeable* (Equation (1-11)). In writing Equation (1-14), we modified our earlier statement of the "law" of energy conservation (Equation (1-2)) to account for this fact. Equation (1-14) tells us that for a specified quantity of matter the sum of its internal, potential, and kinetic energy is constant and equal to mc^2. A practical consequence is that destruction of a small amount of matter can produce enormous amounts of energy (note the huge magnitude of c^2 in Equation (1-14)). Thus, if we could convert just 1 gram of matter to energy, we would produce 9×10^{13} joules, i.e., 8.5×10^{10} Btu or roughly the energy equivalent of 15,000 barrels of oil!

In practice, it is difficult to produce useful energy in this way, especially under controllable conditions. This is because fundamental building blocks of the atomic nucleus must be ripped apart (fission) or coalesced (fusion). Strong nuclear forces (for fission roughly 10,000 times those of chemical bonds, even larger for fusion) must be overcome. This is why nuclear fission or fusion can produce so much more energy from the same amount of material than can a chemical reaction. Today, controlled nuclear fission generates over 20% of the electricity consumed in the US and over 75% of that produced in France (Chapter 8). Nuclear fusion could become a commercial source of electricity, but this may require several more decades of research and development (Chapter 8).

For non-nuclear energy processes, the gain or loss of matter is far too small to be consequential. For example, burning 1 US gallon (3.78 liters) of gasoline in a typical spark ignition automobile piston engine releases about 140,000 Btu (1.48×10^8 joules) of energy, which, depending on the vehicle and driving conditions, provides 10-30 miles of travel. From Equation (1-11), the change in mass associated with release of this much energy is 1.64 μ*g*, versus the 3,175 g in one gallon of gasoline (i.e., the relative mass decrease is $< 6 \times 10^{-10}$ g/g). This is negligible for practical purposes and would be difficult to detect.

In light of Equation (1-14), we can think of all our practical energy "sources" (Figure 1.2) as reservoirs "pre-stocked" with energy from elsewhere. In the language of thermodynamics, these reservoirs are "systems." Humans obtain useful energy by changing the relative stability of these systems. For example, we could open the sluice gate on a dam to release water that would gain kinetic energy by converting potential energy owing to a drop in the height of the water (Chapter 12). We could expose a fuel like natural gas to a high temperature and enough oxygen that chemical equilibrium demands a new state in which the carbon and hydrogen atoms of the gas respectively become CO_2 and H_2O, in the process releasing about 1,000 Btu for each standard cubic foot of gas reacted/burned (Chapter 7).

Figure 1.2 shows the origin of our familiar energy sources in a range of biochemical, geological, cosmic, and nuclear processes of diverse time scales. For example, only a single growing season of a few weeks is long enough for photosynthesis to convert solar energy plus CO_2 and H_2O to biomass, whereas millions of years are required for the bio-geochemical production of coal from plant and animal debris. Within the sun, continuous fusion of hydrogen nuclei consumes matter to produce energy, a minute fraction of which (about 5×10^{-10}, Feynman et al., 1963) is transmitted to the earth by thermal and other forms of electromagnetic radiation, such as solar energy. Interestingly, the earth's primary source of renewable energy is nuclear energy! In fact, Figure 1.2 shows that all the common forms of energy utilized on earth can be traced to ongoing or defunct cosmic processes (tides from lunar cycles, geothermal magma from the survival of deep subterranean molten material owing to the slow cooling and resolidification of the earth's inner core), or to nuclear phenomena in the heavens (the sun) or within the earth (geothermal heat created by subterranean nuclear decay).

As we quantify amounts and rates of transfer of various types of energy, it becomes immediately apparent that there are many different systems of units in common use. The metric system provides a good scientific set of units, but many still use British units. Further, each industry has developed convenient units to describe stocks and flows of energy—barrels of oil, standard cubic feet of natural gas, tons of coal, megawatts of electricity, etc. Energy practitioners need to become proficient in converting from one set of units to another. Conversion factors are provided in the Appendix to aid our readers.

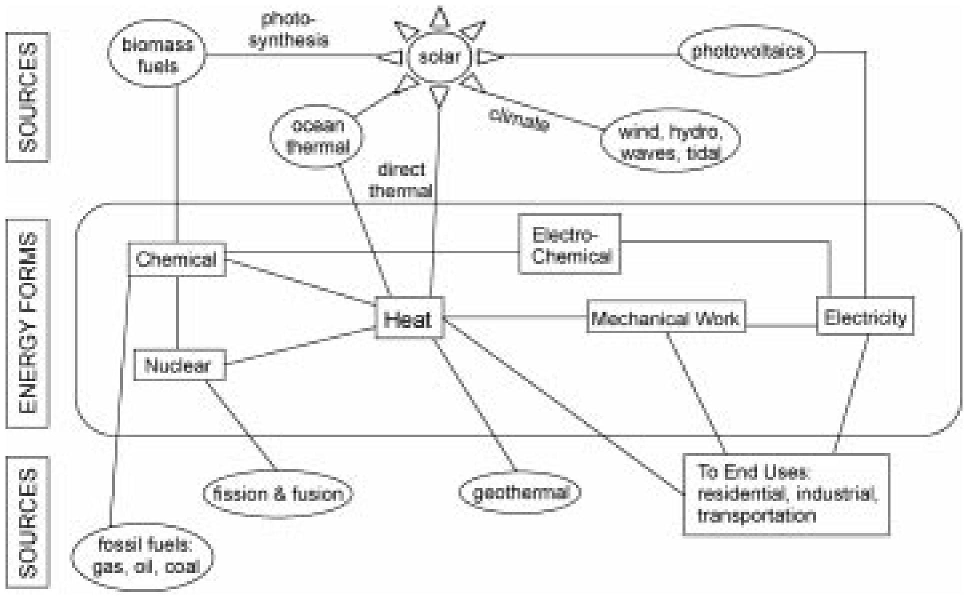


Figure 1.2. Energy sources and conversion processes.

A final caution is that electricity and hydrogen are energy "carriers" that are made from primary energy sources like fossil fuel or renewable energy. To calculate the primary energy consumption associated with producing a unit of electricity, for example, one must also divide the amount of electricity by the efficiency of the actual primary energy conversion process. To differentiate the different forms of energy, sometimes *e* (electrical) and *t* or *th* (thermal) are used, often subscripted.

1.3 Aspects of Energy Production and Consumption

In understanding energy needs and the technologies for supplying them, it is important to have an idea of the energy requirements of specific activities. Until the start of the Industrial Revolution in the 18th century, almost all energy needs were met by renewable sources (i.e., using biomass for heat and muscular energy; wind). Then, machines of increasing power and efficiency were devised to permit much greater power to be generated from the burning of fossil fuels. In the second half of the 20th century, these power sources were complemented by devices using much more energetic nuclear reactions.

In considering energy evolution since the Industrial Revolution, Table 1.3 (Levenspiel, 1996) compares the power dissipated by living creatures in various activities with the power consumed in some modern energy conversion machines. Note that even arduous human labor musters only as much power as that expended in a single 100W incandescent light bulb. Even the 10-fold higher power of a draft horse is barely 1% of the power needed to operate a compact car (25 miles per gallon of gasoline). Thus, driving a compact car is like having 1,000 people working hard to propel the vehicle and driver. If these workers were paid \$8.00 per hour (somewhat above the US federal minimum wage in 1999), it would cost \$8,000 an hour to operate this car. Some employers reimburse business use of private automobiles at 30-40 cents per mile to offset fuel and other operating costs, plus vehicle depreciation. If the car were driven at 60 mph, the highest reimbursement for an hour's travel would be 60 miles x \$0.40/mile = \$24.00 or only 0.3% of the \$8,000 cost of human propulsion. If gasoline costs \$1.30 per gallon, the corresponding fuel cost for gasoline power is [60 miles/hr] × [1 gal/25 miles] x [\$1.30/gal] = \$3.12 or about 5.2 cents per mile. Clearly, it would be economically (and mechanically) impossible to achieve the speed, service, and convenience of a modern gasoline-powered car by using human or animal power. This example shows the tremendous amplification of human labor made possible by the availability of high-quality energy at tractable costs.

Moreover, for many applications, human or animal labor cannot match the efficiencies and power densities of modern energy conversion technologies. Table 1.4 (Levenspiel, 1996) shows that an "average" human needs about 4,000 kJ/day of energy just to survive and about five times that (i.e., 20,000 kJ/day) to sustain intense exercise or hard labor. Let's estimate an efficiency for human conversion of energy by assuming that all the food intake above the subsistence level is consumed to produce work in an 8-hour shift:

Human Output (Hard Work) = 0.1 kW (Table 1.3) × 8 hr x 3,600 s/hr × 1 (kJ/s)/kW
= 2,880 kJ vs (20,000 - 4,000) kJ input

Percent Efficiency = [2,880 kJ/16,000 kJ] × 100 = 18%

This seems like a good efficiency for a person because many modern coal-to-electricity plants with SO_2 scrubbers have an efficiency of 37%, and many spark-ignition automobiles, at best, convert about 18% of the energy of their gasoline to useful power at the vehicle wheels (Chapters 7, 18). But the "fuel" to provide this energy is food, and the human body is only about 10% efficient in converting food to fat and muscle tissue that can in turn be converted to useful work (Levenspiel, 1996). Thus, the efficiency in using the human "engine" in going from food like grain to useful work is not 18% but 0.1 × 18, or 1.8%. Moreover, if the human eats lots of beef rather than cereal, the net efficiency from grain to human work drops 10-fold to 0.18% because the animal first converts grain or grass to animal fat and muscle at 10% efficiency. Using a bicycle, however, maximizes the efficiency of the human "engine." Bicycles use human power to transport people and light goods relatively efficiently and have added sustainability appeal in dense population areas where motor vehicles contribute to traffic, parking congestion, and air pollution.

Table 1.3. Power Expended in a Sampling of Activities

Power Producers and Users	Power Involved
Lifting a mosquito at 1 cm/s A fly doing one pushup	1 erg/s = 10^{-7} W = 10^{-10} kW
Cricket chirps	10^{-3} W = 10^{-6} kW
Pumping human heart	1.5 W = 1.5×10^{-3} kW
Burning match	10 W = 10^{-2} kW
Electrical output of a 1 m^2 solar cell 10% efficiency	100 W = 0.1 kW
Bright lightbulb	100 W = 0.1 kW
Human hard at work	0.1 kW
Draft horse	1 kW
Portable floor heater	1.5 kW
Compact automobile	100 kW
Queen Elizabeth (giant ocean liner)	200,000 kW
Boeing 747 passenger jet, cruising	250,000 kW
One large coal-fired power plant	1×10^6 kW = 1 GW of electricity
Niagara Falls, hydroelectric plant	2×10^6 kW = 2 GW of electricity
Space Shuttle Orbiter (3 engines) Plus its 2 solid booster rockets at take off	14×10^6 kW = 14 GW
All electric power plants worldwide	2×10^9 kW = 2,000 GW
U.S. automobiles, if all used at the same time (150 million)	15×10^9 kW = 15,000 GW
Humankind's total use in 2005	1.1×10^{10} kW = 1.1×10^4 GW = 400 Q/yr
SUV[a], 15 mpg at 60 mph	160 kW

Sources: Levenspiel (1996) and EIA (1998).
[a]Sport utility vehicle.

Table 1.4. Energy Requirements for Various Human Activities

Activity	Energy Needed Per Day	
	kJ	kcal[a]
Minimum to "survive," i.e., to just maintain vital cellular activity	4,000	1,000
"White collar" work, full-time/steady	8,000[b]	2,000
Bicycle riding, jogging, construction work	20,000	5,000

Adapted from Levenspiel (1996).

[a]Approximately. Note that here 1 kcal = 1 Calorie, as seen in US food labels, also called a "large" calorie or a kilogram calorie.

[b]This assumes 24 hours of work at this rate.

The limited productivity of human and animal labor has serious geopolitical ramifications. Nations lacking modern infrastructures for energy conversion and utilization face competitive disadvantages, not only in the manufacture of energy-intensive goods but in all commerce dependent upon reliable supplies of high-quality energy (e.g., transport, safe habitat, information technologies). Nations that possess up-to-date energy infrastructures need access to assured supplies of energy at manageable costs to sustain and grow their economies. Continuous technological improvements in efficiency and demand-side management will temper but not eliminate growth in energy consumption. Developed nations without indigenous energy resources can trade products of their economies for energy, at least in peace time. Developing nations lacking indigenous energy face a Catch-22 situation because energy drives the economic productivity that creates value tradeable for importable energy.

The most important fuel worldwide is petroleum. It is extracted in many countries and consumed primarily in the industrialized countries. An international trade exists from several unindustrialized producing countries, especially those of the Middle East (Figure 1.3). Because this commerce is essential for international economic vigor, the wealthy nations have demonstrated a willingness to use strong measures (including the Gulf War of 1991) to keep it stable. Since many of the producer countries have experienced political instability, or are in politically unstable regions, accomplishing this can be difficult.

Currently, international trade in energy (largely fossil mineral fuels) is colossal. Figures 1.3 and 1.4, respectively, show the magnitude and direction of international petroleum and natural gas trades in 2002. Also shown are the regional divisions of fossil energy exporters and importers, the former dominated by countries in the Middle East, Africa, Central and South America, Indonesia, and the former Soviet Union, the latter by Japan, the US, and western Europe. (The large transfers of petroleum from the Middle East to the general area of Malaysia reflect petroleum transport to Singapore for refining.)

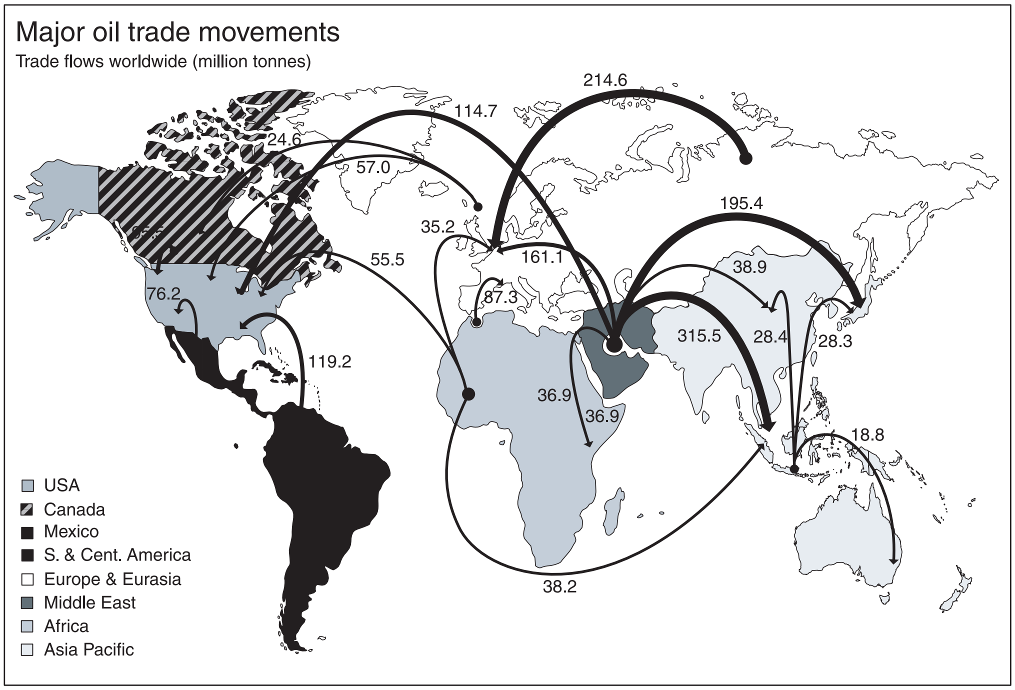


Figure 1.3. Major global trade movements of crude oil in 2002. Source: British Petroleum, (2003): www.bp.com. Reprinted with permission of British Petroleum.

Another important disruption of the petroleum market occurred with the 1973 Organization of Petroleum Exporting Countries (OPEC) shutoff of oil shipments to the US and western Europe in reaction to perceived favoritism of Israeli over Arab interests in the Middle East.

Many of the same countries that are rich in petroleum also have abundant natural gas supplies. However, a corresponding international commerce in natural gas has not emerged due to the greater difficulty and expense of transporting natural gas. Thus, natural gas found at sites far from population centers, especially if they are separated by water, has gone largely unexploited.

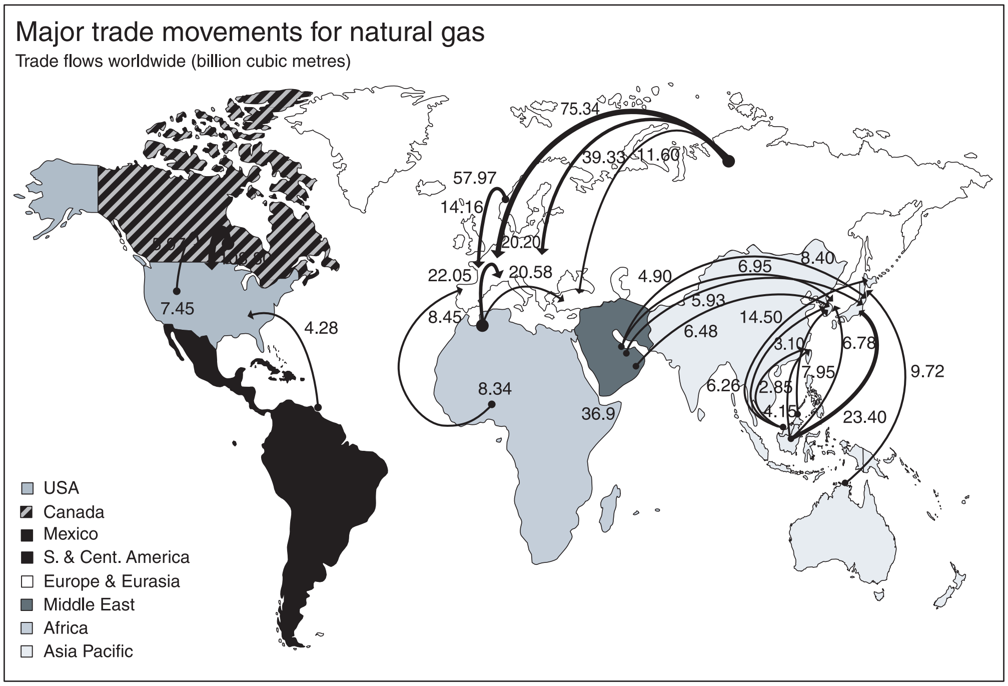


Figure 1.4. Major global trade movements of natural gas in 2002. Source: British Petroleum, (2003): www.bp.com. Reprinted with permission of British Petroleum.

The principal means of transporting natural gas is via pipeline. Important systems for this link are the fields of the western US, serving eastern and western population centers, and the gas fields of Russia and the North Sea, which supply users in western Europe. Liquefied natural gas is transported in ships more expensively (by about an order of magnitude) and less abundantly, thereby permitting some remote sources (e.g., Indonesia, Venezuela, and Algeria) to supply industrialized markets. Both modes of transport are likely to become more important, reflecting the convenience of natural gas for consumers and the relatively low environmental effects of its production.

Similarly, an international trade exists in coal. However, it is less important than those of oil and natural gas. This reflects the environmentally detrimental nature of its production and use, which effectively restricts its consumption primarily to production of electricity and, to a lesser degree, metallurgical coke manufacture, at least in the industrialized countries.

Figure 1.5 shows historical data and growth projections for world population from 1900 to 2100, while Figure 1.6 depicts the contributions of major sources to world energy consumption from1850 to 1995. The dramatic increases in world energy use since World War II reflect the revival of war-torn economies, expansion of the middle class, and exponential growth in world population. The intense coupling of population and energy use is further illustrated by the correlations between per capita gross domestic product (GDP) or gross national product (GNP) and per capita energy use shown for various countries in Figure 1.7. At least for the US, per capita GDP is even more strongly correlated with per capita electricity use, showing the importance of electricity over other forms of energy in driving wealth creation in the US. Figure 1.7 also reveals another important geopolitical issue in sustainability, namely the broad range in aggregate energy efficiency of different countries. Note that the slope of a line connecting the origin with the data point for any country has units [(GJ/person)/(gross national product (GNP)/person)], i.e., GJ/GNP, and is thus an aggregate measure of the amount of energy consumed in each country to produce a unit of GNP.

Composite efficiency metrics are useful, but policy and technology decisions are better informed by dissecting these indices to determine how energy is used in various sectors and then adjusting for patterns of industrial activity, mobility infrastructure, lifestyle, geography, and climate. For example, the lower aggregate energy efficiency of the US as compared to Japan might be explained by the lower population density of the US leading to larger living spaces and longer travel distances per journey. Figure 1.8 shows energy consumption, energy consumption per capita, and energy per unit of GDP for the US from 1949 to 2001. Note that energy/GDP has declined significantly over this period. The causes include sectoral shifts to less energy-intensive industries, as well as improved energy efficiency in manufacturing and the piston engine automobile. The ratio [energy per capita/energy per GDP], i.e., [GDP/capita] is a plausible aggregate measure of economic well-being or quality of life. Estimating this quantity as the ratio of Curve II to Curve III in Figure 1.8 shows that, by this metric, the US average standard of living has increased substantially from 1950.

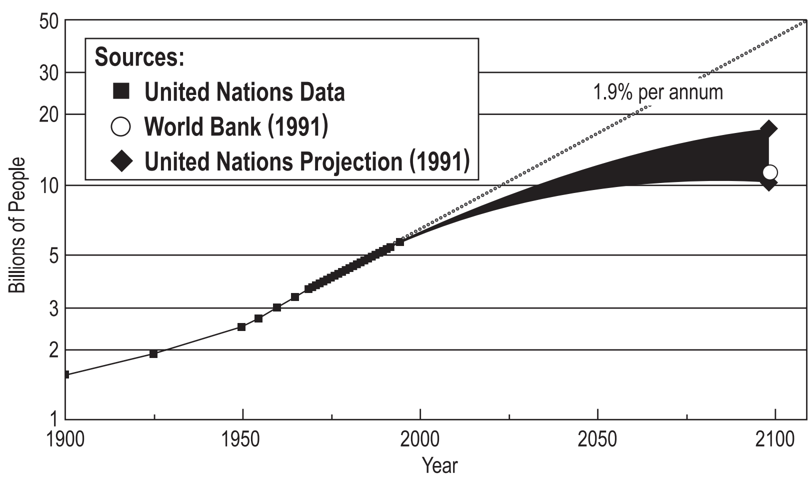


Figure 1.5. Historical data and projected growth in worldwide population (1900 to 2100).

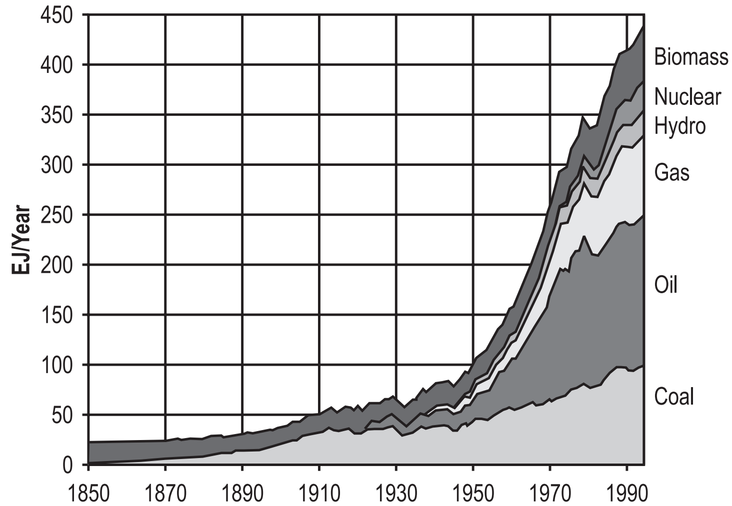


Figure 1.6. Sources of the world's primary energy supply from 1850 to 1995. Source: WEC (1995).

The message of this section is that energy is intimately commingled with the economic vitality and social progress of individual nations and of the world. Since the Industrial Revolution, energy has been a "critical enabler" of economic productivity. The availability of energy at tractable (although not necessarily competition-driven) prices has extended economic and social benefits to countless humans in the democratic countries of the world, which in pre-18th century, non-mechanized societies were reserved for a privileged few. Further, since the 1860s, sales of energy itself have been a "great provider" of economic opportunity. Global daily trade in crude oil is on the order of $1 billion (Moore, 1999). The addition of natural gas and coal probably triples this cash flow. The market value of electricity produced in the US is some $0.5 billion per day (Moore, 1999). The major geopolitical impact is the transfer of huge amounts of wealth to individuals, industrial companies, geographic regions, whole nations, and governments, which has created new global financial powers. Further, governments harvest astonishing revenues by taxing wholesale and retail transactions in energy (Chapter 7).

1.4 National and Global Patterns of Energy Supply and Utilization

In 1997, the world used almost 450 quads of energy. The sheer magnitude of this amount of energy is astonishing. If it were entirely petroleum, it would be enough material to cover an area of about 15,600 square miles (i.e., about the same area as the Netherlands and almost twice the area of Massachusetts) with a 1-foot deep layer of oil. Of course the amount of energy consumed and how that energy is used varies by country and region. Figures 1.7 and 1.9 respectively show the per capita and total energy consumption for various countries in 1992. Clearly, there are wide differences among nations, with developed countries accounting for large portions of the world's total annual consumption. However, these countries also account for much of the world's economy (Table 1.5). The correlation between economic prowess and energy consumption further illustrates the daunting challenges of how to make sustainability practical, how to equitably redress apparent imbalances in economic prosperity enabled by energy, and how to extend energy and energy-derived services to constituencies previously under-represented in the energy marketplace while continuing to meet the energy needs of established energy consumers.

Figures 1.10 and 1.11 respectively show historical records of energy production by source for the world (1970-2000) and for the US (1949-2002). The figures also show how both regions have been dominated by fossil fuels. Figure 1.12 shows detailed patterns of energy supply and consumption for the US for 1997 (EIA, 2002). Based on this figure, end-use consumption can be divided into four major sectors—transportation, residential, commercial, and industrial—that, respectively, consume about 28%, 21%, 18%, and 33% of total US energy. Total consumption in 2001 was about 97 quads, which was about 1/5 the world's total energy use. Fossil fuels accounted for about 85% of this amount.

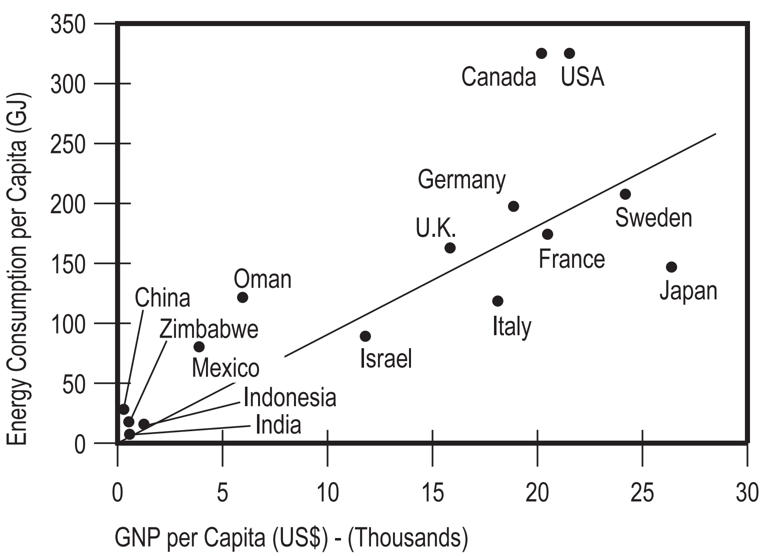


Figure 1.7. Comparison of energy use per capita per year versus GNP per capita for various countries. The line is only to show a general trend. 1 GJ = 10^9 Joules. Source: The World Bank (1992).

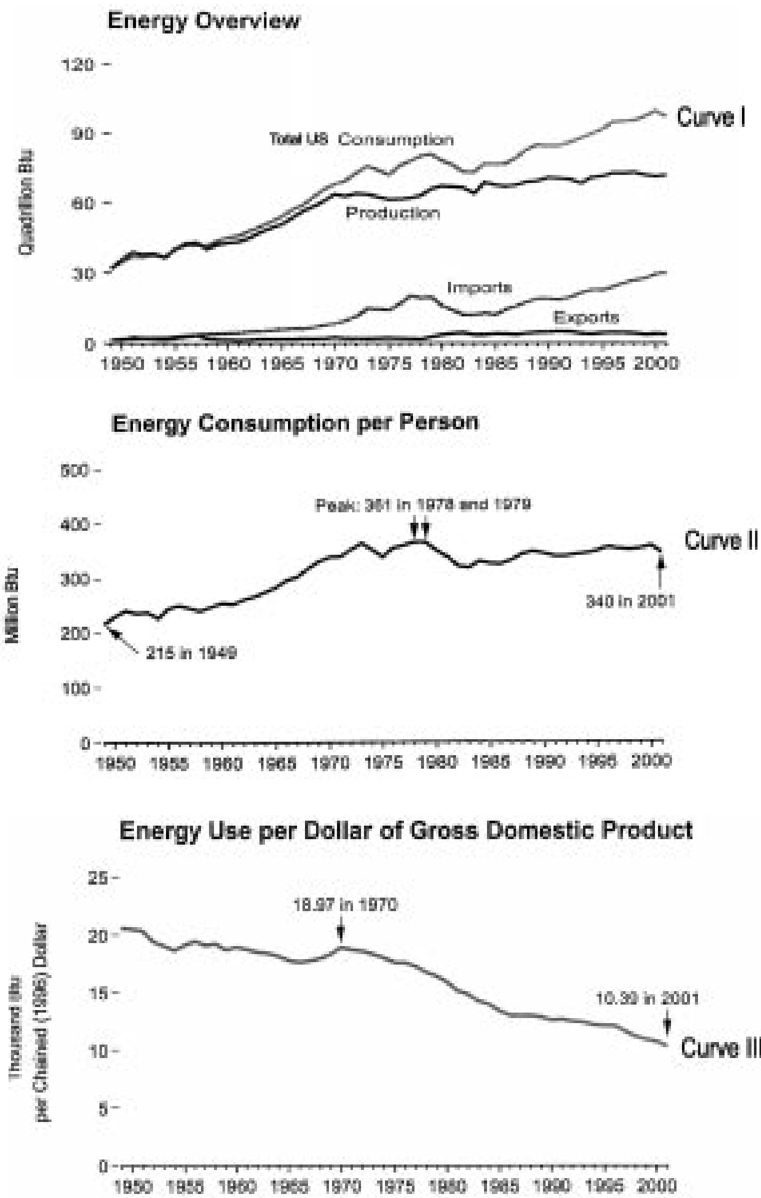


Figure 1.8. US Energy consumption (Curve I), energy consumption per capita (Curve II), and US energy consumption per dollar of Gross Domestic Product (Curve III), for the period 1949 to 2001. Note that some analysts take the ratio of Curve II to Curve III, i.e., $ of GDP/capita, as an index of aggregate economic well-being. Source: EIA (1998).

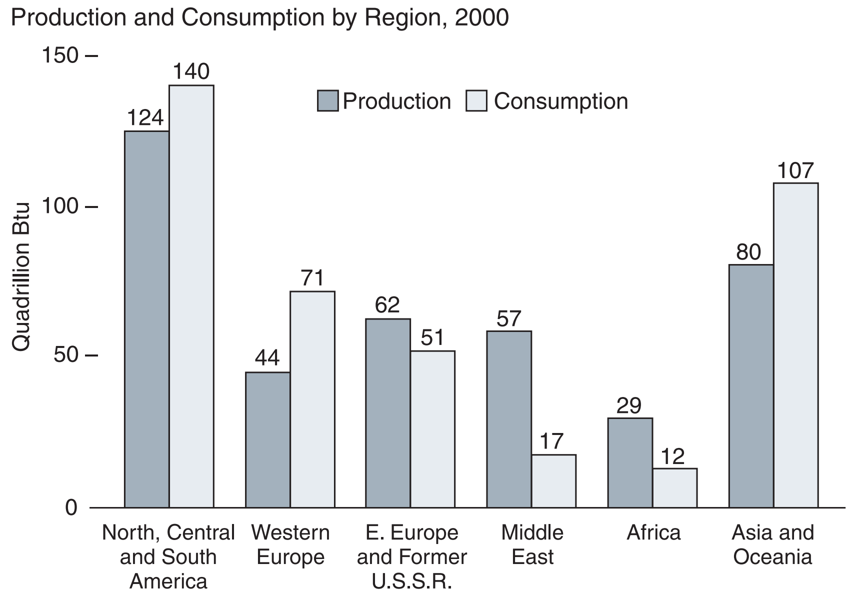


Figure 1.9. Total energy production and consumption in 2000 by region. Source: BP (2001).

Table 1.5. Percentage shares of world population, world GDP, and world commercial energy consumption for selected countries

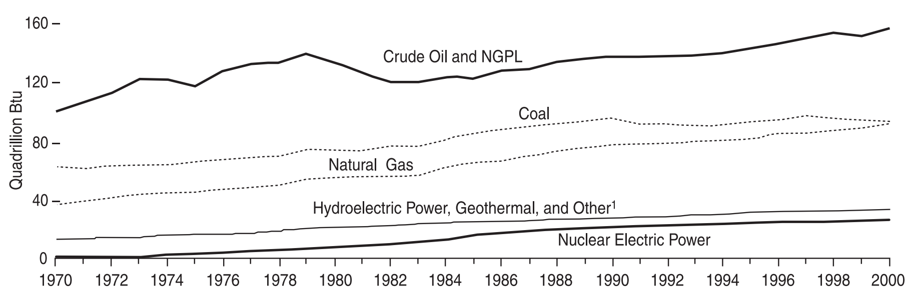
Country	% of World Population 2001[a]	% of World GDP 2002[b]	% of World Energy Consumption 2002[c]
United States	4.6%	32%	24%
Japan	2.0%	12%	5%
France	0.9%	4%	3%
Germany	1.4%	6%	4%
United Kingdom	1.0%	5%	2%
China	20%	4%	11%
India	17%	2%	4%

[a]World Population 2001 was 6.2 billion. Country data from The Institute of Memetic Research. www.futuresedge.org/World_Population_Issues/
[b]World GDP 2002 was $32 trillion dollars. Country data from World Development Indicators database, World Bank, July 2003. www.worldbank.org/data/
[c]World primary energy consumption 2002 was 9.4 billion tonnes of oil equivalent. Country data from BP. Statistical Review of World Energy 2003. www.bp.com/centres/energy/index.asp

Interestingly, the US exports almost 5 quads of energy. About half of this energy is coal. The balance is a mix of electricity, metallurgical coke, and other fossil fuels and their derivatives. However, US energy imports of over 21 quads of petroleum and petroleum products, plus about 3.7 quads of natural gas, coal, electricity, and metallurgical coke more than offset these outflows. Renewable and nuclear energy, respectively, account for about 7.6% and 7.1% of US energy consumption.

Figure 1.13 shows that hydro (55%) and biofuels (38%) accounted for most of the renewable energy contributions in 1997. Most of the hydro and some of the biomass was used for electric power generation. Some biofuel was also employed for blending of ethanol into gasoline for motor transport. The hydro and geothermal figures include some imports from Canada and Mexico respectively. The role of wood in residential heating is not known, so the biofuels contribution may be underestimated.

Use of renewable technologies may expand in the US with time, although growth in market share may be slow owing to environmental resistance to new large hydropower dams, limited availability of major high grade wind resources in acceptable locations, and appreciable cost disadvantages for several other forms of renewables except in some niche markets. This prognosis could change if there are technological breakthroughs, or if concerns over global climate change result in mandatory reductions in fossil CO_2 emissions.



[1]Net electricity generation from wood, waste, solar, and wind. Data for the United States also include other renewable energy.
Note: NGPL is natural gas plant liquids.

Figure 1.10. World primary energy production by source for the period (1970-2000). Source: EIA (1998).

The outlook for nuclear energy is also uncertain. Economic factors and the desires for energy supply security and diversification of energy supplies may propel continued expansion of nuclear electric power production in Asian rim countries like China, Taiwan, and South Korea. Concerns over fossil carbon emissions may improve the acceptability of nuclear energy in other countries, but, barring a dramatic shift in US policy, it seems unlikely that new nuclear plants will be constructed in the US for several decades. However, it is difficult to envision how, over the longer term, the US can adopt a low-carbon energy society without a substantial contribution from nuclear energy.

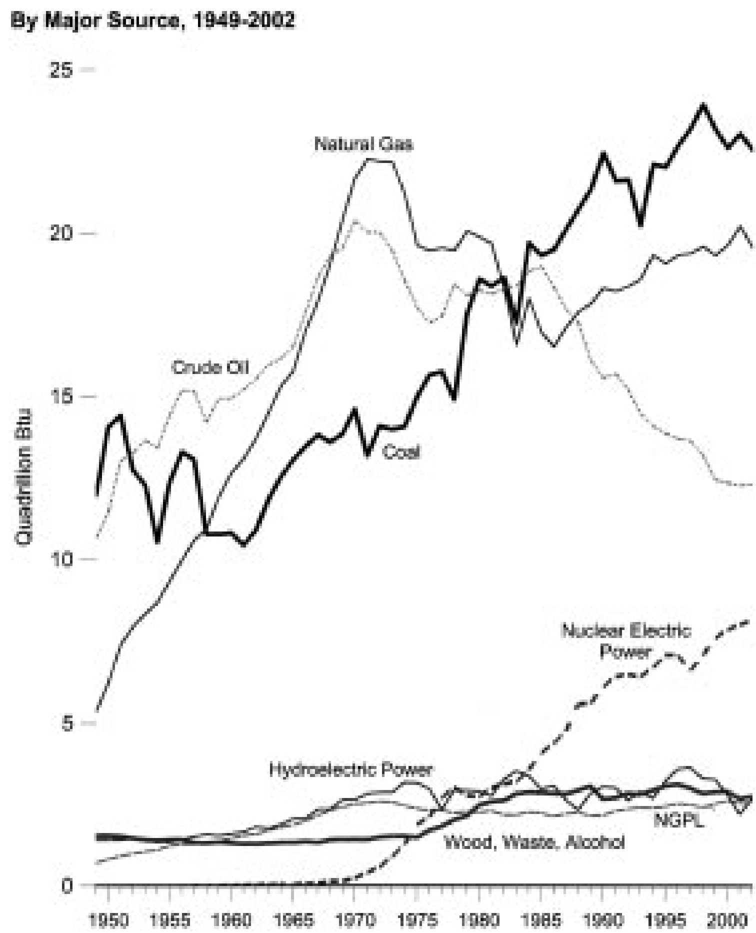
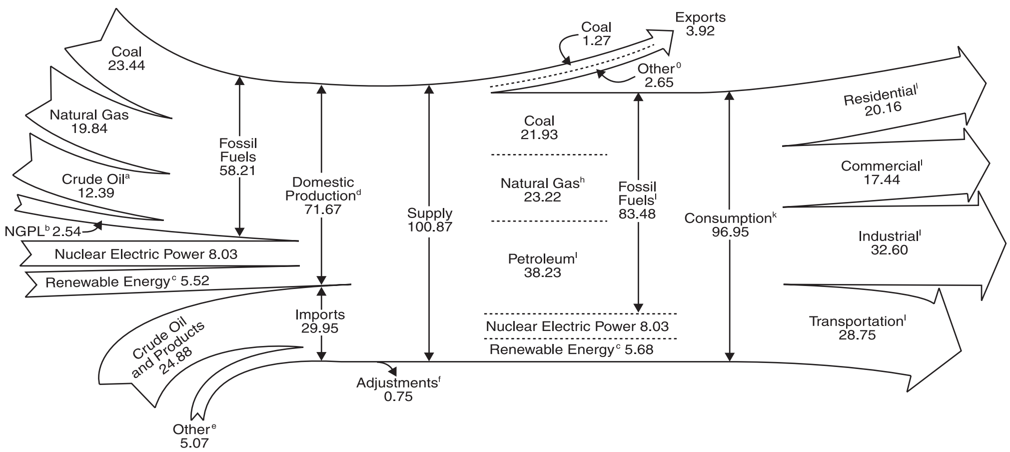


Figure 1.11. US energy production by major source, 1949–2002. Source EIA (2003).

Figure 1.14 provides historical data for and US Department of Energy (DOE) projections of US nuclear generating capacity from 1960 to 2055. This figure shows that without a major re-licensing program, US nuclear capacity will fall to about 1/4 of year 2000 levels by 2025. Even with 20-year re-licensing of 3/4 of the current plants, US nuclear capacity falls to about 1/5 that of year 2000 by 2045. Given that construction of a 1,000 MW nuclear power plant in the US can take 7-10 years, versus less than 5 years elsewhere, the real message of Figure 1.14 is that if the US contemplates, even as a backstop or insurance measure, a useful contribution from nuclear-generated electricity to reduce fossil-derived CO_2 emissions, serious planning for new capacity should begin within the next decade.



[a]Includes lease condensate.

[b]Natural gas plants liquid.

[c]Conventional hydroelectric power, wood, waste, ethanol blended into motor gasoline, geothermal, solar, and wind.

[d]Includes -0.09 quadrillion Btu hydroelectric pumped storage.

[e]Natural gas, coal, coal coke, and electricity.

[f]Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.

[g]Crude oil, petroleum products, natural gas, electricity, and coal coke.

[h]Includes supplemental gaseous fluids.

[i]Petroleum products, including natural gas plant liquids.

[j]Includes, in quadrillion Btu, 0.04 coal coke, net imports and 0.05 electricity net imports from fossil fuels.

[k]Includes, in quadrillion Btu, 0.09 hydroelectric pumped storage and -0.15 ethanol blended into motor gasoline, which is accounted for in both fossil fuels and renewable energy but counted only once in total consumption.

[l]Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales.

Notes: Data are preliminary. Totals may not equal sum of components due to independent rounding.

Figure 1.12. Pattern of energy supply and utilization in the US for calendar year 2001. Units are quadrillion (i.e., 10^{15}) Btus. Source: EIA (2002).

Figure 1.13. Contributions of various renewables and other major sources to US energy consumption in 1997. Source: EIA (1998).

Figure 1.15 provides a detailed breakdown of US production and utilization of electricity in 2001. The dominance of electric utility generation by fossil fuels (71%) is clearly shown in the upper part of the figure, especially coal (51%), although nuclear (21%) and hydro (9%) also make significant contributions. Biomass, wind, solar, geothermal, and other renewables have little US impact (0.4%), but their contributions are more significant in other countries (Chapters 9 through 15). "Conversion losses" in Figure 1.15 are largely energy lost as waste heat during the conversion of heat to mechanical work that rotates the shafts of electrical generators (Chapter 3). At present, these losses are about 67% for generating equipment installed in the US. Modern gas-fired, gas turbine-steam turbine combined-cycle (GTSTCC) generators (Chapter 7) reduce this loss to about 40% by using waste heat from the gas turbine to raise steam that generates additional electricity. Figure 1.15 also shows that the non-utility power producers contributed about 8.4% of the retail sales of electricity to end users. Data are not available to gauge the amount of heat wasted during electricity generation by these producers. Because many use efficient natural gas-fired GTSTCC generation equipment, we can assume that their waste heat losses are closer to the 40% noted above for these power cycles.

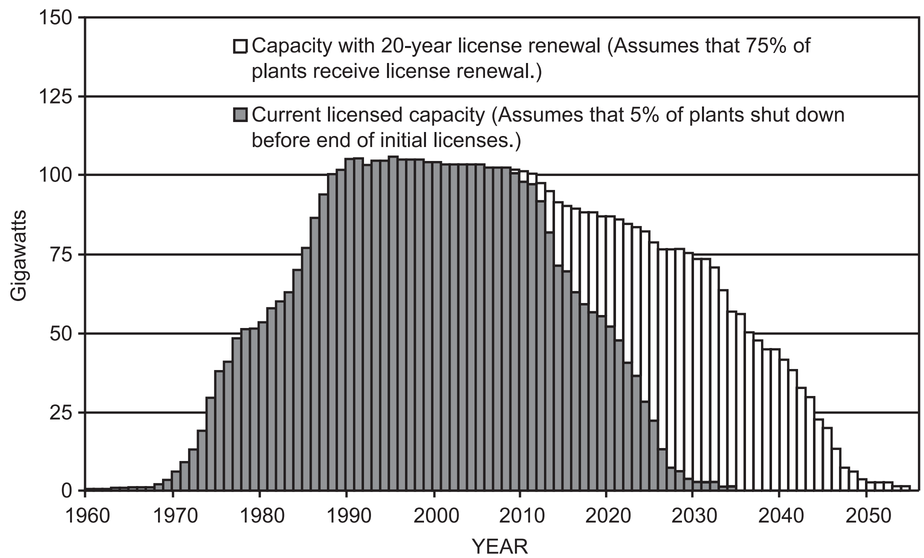
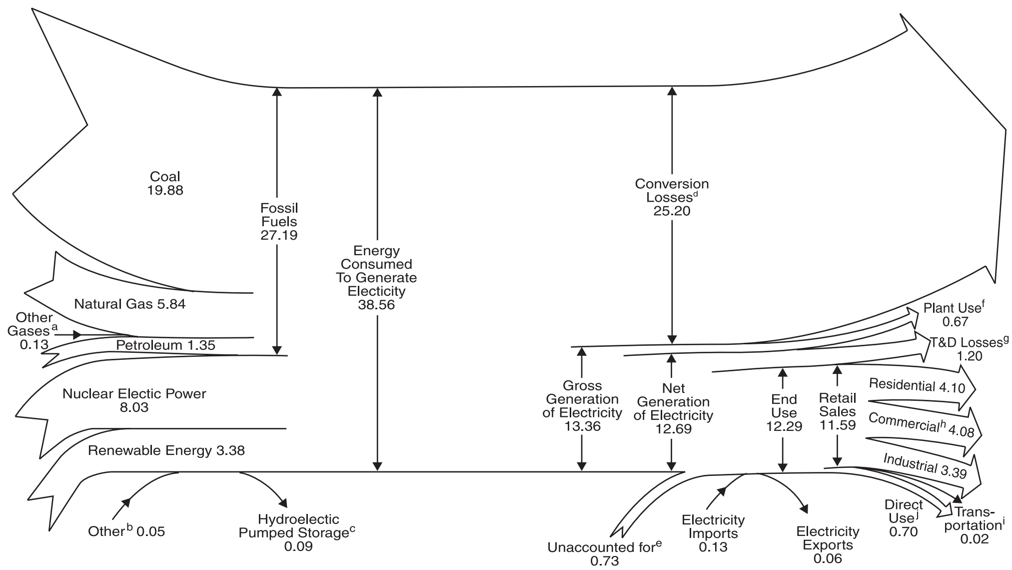


Figure 1.14. Historical and projected US nuclear electric generating capacity 1960-2055. Source: PCAST (1997).

1.5 Environmental Effects of Energy—Gaining Understanding

In Chapter 4, we consider environmental impacts of energy supply and utilization. We begin our study of these matters here because perseverant environmental stewardship must be a cornerstone of any scenario for sustainable energy. In fact, environmental considerations affect virtually all aspects of energy decision-making by government, the private sector, and increasingly, by consumers. Sustainability advocates and architects must resolve a vexing question: how can humankind equitably provide energy-derived benefits to a growing world population without degrading the environment or exhausting resources for which there are no apparent substitutes?



[a]Blast furnace gas, propane gas, and other manufactured waste gases derived from fossil fuels.

[b]Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, and miscellaneous technologies.

[c]Pumped storage facility production minus energy used for pumping.

[d]Approximately two-thirds of all energy used to generate electricity.

[e]Data collection frame differences and non-sampling error.

[f]Electric energy used in the operation of power plants, estimated as 5 percent of gross generation.

[g]Transmission and distribution losses, estimated as 9 percent of gross generation.

[h]Commercial retail sales plus approximately 95 percent of "Other" retail sales.

[i]Approximately 5 percent of "Other" retail sales.

[j]Commercial and industrial facility use of onsite net electricity generation.

Note: Totals may not equal sum of components due to independent rounding.

Figure 1.15. Sources and end use of electricity in the US for 2001. Units are quadrillion (i.e., 10^{15}) Btu. Source: EIA (2002).

Figure 1.16 displays some attributes of this *energy-prosperity-environmental dilemma*. Note that adverse impacts from energy include a vast legacy of prior damage, current pollution, and the real prospect of continued ecosystem degradation for decades or more to come. Table 1.6 lists some of the environmental and other hazards from a selection of renewable and non-renewable energy supply technologies.[6] Note that energy-derived pollutants include gases, liquids, solids, or mixed phases, and that they may adversely impact a host of environmental media and ecosystems. Further,

6 Links between energy and the environment are not new. In 1776, British physician Percival Pott attributed the high incidence of scrotal cancer among London chimney sweeps to their regular exposure to combustion-derived soot (NRC, 1972). Supposedly when the King of Denmark learned of Pott's findings, he ordered all Danish chimney sweeps to take daily baths, thereby promulgating one of the earliest energy-related environmental regulations.

energy-derived pollutants may act over a wide range of length and time scales (Table 1.7). On the other hand, as Figure 1.16 shows, energy-driven economic progress benefits humankind by preserving and extending prosperity *and* improving the environment through redress of past damage and prevention of future pollution.

Human activities have economic consequences that are not always reflected in the prices of related goods and services. Sometimes these "hidden costs" or *externalities* are so minute as to be inconsequential and not to justify their internalization or inclusion in the costs of an activity. Contrastingly, many scholars believe that the supply and use of energy is accompanied by significant expenses that are not captured in present-day energy prices. Many of these externalities are associated with adverse environmental impacts of energy, including the costs for health care, lost productivity, air and water pollution, aesthetic damage, destruction of open space, remediation of wastes, etc. (Table 1.7). Chapters 5 and 8 describe modern efforts to quantify the hidden costs of energy, with particular attention to the supply of energy from nuclear fission. What is interesting about attempts at internalizing external environmental costs is not that it is difficult to do, but that reasonable people make the attempt. This is because the basic knowledge needed to quantify such effects at a useful level of precision are often absent, and a reliable calculus for homogenizing a set of disparate external costs into a common basis (e.g., money) does not yet exist. Thus, the qualitative concept of internalization is appealing but difficult to implement in the absence of complementary mechanisms to induce the affected parties to compromise their differences in determining acceptable practices.

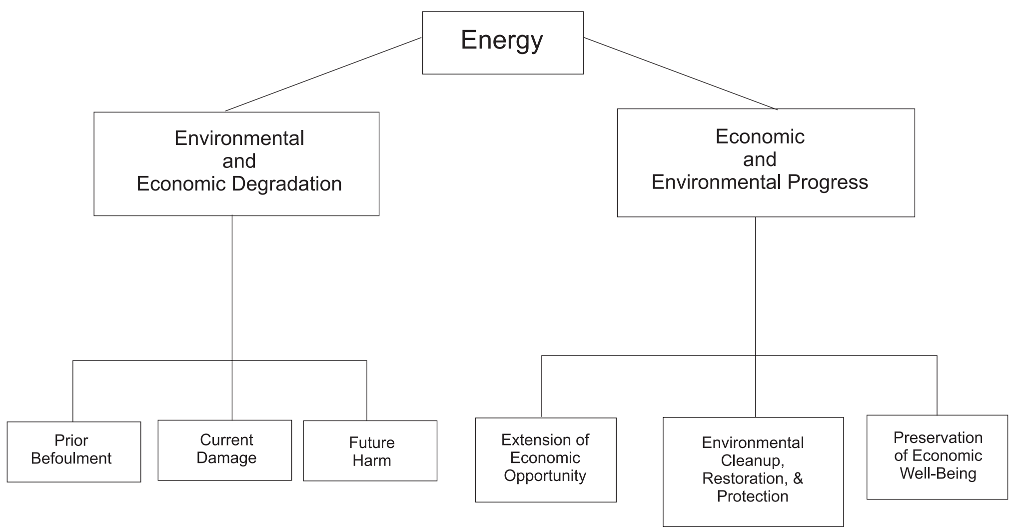


Figure 1.16. Schematic illustration of the energy-prosperity-environmental dilemma.

For example, any attempt to assign monetary value to loss of human health or life necessitates highly subjective judgments and risks alienating stakeholders. Actuarial data on life expectancies, insurance policy values, and lost productivity costs would seem to be a logical source of information for costing externalities. However, the appeal of this method quickly fades when faced with the need to apply its statistically based conclusions to a particular individual. Another vexing problem is the lack of unambiguous data relating environmental risk to specific causes. For example, in the case of human health effects of energy-derived pollutants, there are few cases where human morbidity or mortality can be unequivocally linked to specific toxic substances. To reliably "close the loop" between an adverse impact in a human and an energy-related cause of that impact, we need to know a variety of things: what agent caused the human impact; whether that agent was formed within the human body by transformation of some exogenous substance; whether multiple agents were involved within the body; if undesired transformations of exogenous substances occurred because the body's natural defense mechanisms were disrupted; whether the human was exposed to environmental agents that themselves, or via their transformation products (metabolites) within the body, caused adverse health consequences; whether such agents were produced directly as emissions, effluents, or by-products of some energy technology (e.g., air emissions from an automobile); what the identities and amounts of such agents emitted were; whether harmful agents generated from energy-derived effluents were attributable to chemical or physical changes in ambient air or water. These are just some of the questions that toxicologists ask as they seek to determine whether environmental agents contribute to adverse health effects in humans, and as they work with experts from other disciplines to learn whether energy or other technologies are responsible for the generation of such agents or their progenitors (W.G. Thilly, personal communication).

Another complication is that energy-related environmental effects can occur over diverse length and time scales—from millimeters to 10,000 kilometers—and from seconds to more than 100 years (Table 1.7). Thus, an environmental insult that leads to cancer or an inheritable birth defect might go undetected for several decades. Similarly, CO_2 emissions in one location may ultimately upset the climate halfway around the world 40 years later. The presence of diverse length and time scales also makes it difficult to develop an integrated mathematical simulation of all the suspected environmental agents and their unwanted impacts on humans and the planet. This is because any such model must accommodate wide variations in spatial and time coordinates, an historically difficult problem in systems evaluation (Chapter 6).

Table 1.6. Examples of Environmental and Other Hazards of Various Energy Supply Technologies (None is free of adverse effects)

Fuel/ Phase	**Coal**	**Petroleum**	**Natural Gas**	**Nuclear**	**Hydro**
Extraction	Mining Accidents Lung Damage	Drilling Spills (off-shore)	Drilling	Mining Accidents Lung Damage	Construction
Refining	Refuse Piles	Water Pollution	—	Milling Tails	—
Transportation	Collision	Spills	Pipeline Explosion	—	—
On-Site:					
Thermal	High Efficiency	High Efficiency	High Efficiency	Low Efficiency	—
Air	Particulates SO_2, NO_x	SO_2, NO_x	NO_x	Low Radiation	—
Water	Water Treatment Chemicals	Water Treatment Chemicals	Water Treatment Chemicals	Water Treatment Chemicals	Destroys Prior Ecosystems
Aesthetic	Large Plant Transmission Lines	Large Plant Transmission Lines	Large Plant Transmission Lines	Small Plant Transmission Lines	Small Plant Transmission Lines
Wastes	Ash, Slag	Ash	—	Spent Fuel Transportation Reprocessing Waste Storage	Fish Killed
Special Problems	—	—	—	—	Population, Agricultural Displacement
Major Accident	Mining	Oil Spill	Pipeline Explosion	Reactor Cooling Failure Nuclear Weapons Proliferation	Dam Failure

Table 1.6. Examples of Environmental and Other Hazards of Various Energy Supply Technologies (None is free of adverse effects) (continued)

Solar Terrestrial Photovoltaic	Solar Power Tower	Solar Satellite Photovoltaic	Nuclear Fusion	Geothermal	Wind
Mining Accidents	—	Mining Accidents	H^2, Li Production	—	—
—	—	—	—	—	—
—	—	—	—	—	—
				—	—
Low Efficiency Ecosystem Change	Ecosystem Change	Genetic Change	—		
—	—	—	—	H_2S	
Water Treatment Chemicals	Water Treatment Chemicals	Water Treatment Chemicals	Tritium in Cooling Water	Brine in Streams	
Poor Large Area	Poor Large Area	? Large Area (Antenna)	Large Area Plant	Large Area	Locally visible
Spent Cells	—	—	Irradiated Structural Material	Cool Brine	—
Construction Accidents	—	Vulnerability in Wartime	Occupa-tional Radiation Doses	—	Siting Structural Failure
Fire	—	Intense Microwave Beam	Tritium Release	—	—

Table 1.7. Approximate Length and Time Scales for Selected Known and Potential Environmental Effects of Energy Production and Utilization

Local	0.001-10 km e.g., Air Pollutants – Acute Respiratory Episodes: < 1 day – Lung Cancer: 10-50 years – Mutagenicity: 1 – 5 generations
Regional	100-500 km e.g., Acid Rain – Forest and Aquifer Damage: 1 – 20 years e.g., Particulate Pollution
Global	5,000-25,000 km e.g., Climate Modification – Sea–level Rise } 30 – 100 years – Desertification } or more

A further challenge is that pollutant inventories are often the result of a complex interplay of multiple physical and/or chemical factors, so that seemingly intuitive pollution control measures can be horribly flawed. The point is illustrated by ozone (O_3), a human respiratory irritant and smog precursor in the troposphere (0–10 km above the earth's surface).[7] Tropospheric O_3 is formed by sunlight-induced chemical reactions of two combustion-derived pollutants, nitrogen oxides, NO_x, and volatile organic compounds, VOCs. It is intuitive to reason that tropospheric O_3 pollution can be reduced by lowering emissions of NO_x or of hydrocarbons. Figure 1.17 shows that matters are not so simple. It plots, as a series of contours, atmospheric O_3 concentrations for an ambient air-shed as affected by corresponding ambient air concentrations of NO_x and VOCs. The figure is based on simulations of chemistry along moving parcels of air in Atlanta, and is a simulated version of one shown by Seinfeld and Pandis (1998) from Jeffries and Crouse (1990). The figure shows that reduction of NO_x emissions does not guarantee lower tropospheric ozone and may even be counterproductive. Depending on the prevailing VOC inventories, lowering NO_x may have no effect or even increase ambient O_3 concentrations! The reason is that the mechanisms for O_3 formation and survival are complex and, in general, are not linearly proportional to ambient concentrations of NO_x. The key message from Figure 1.17 is that effective regulation of energy-derived pollutants must be based on reliable quantitative understanding not only of pollutant origins, but also of their transport and transformation in air, water, and other media. Similar complexities and needs for care in formulating policies are encountered all over the energy-environment landscape as further explored by Kammen and Hassenzahl (1999).

In summary, every important energy-environment question is uncertain to a substantial degree because the models and data for comprehensive understanding are usually unavailable and will remain so. Coupling such uncertainties to the differing interests and values that affect the parties involved, it is almost unavoidable that serious disagreements will arise among them. In other words, treating such questions as purely technical ones, for which true answers can be found, is usually unrealistic. Rather, it makes greater sense to use analyses, including treatments of uncertainty, to characterize the plausible range of potential energy-environmental outcomes. To date, this last step

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7 In the stratosphere, 10-50 km above the earth, ozone becomes a strong friend to humans by filtering out harmful UV radiation from the sun. Depletion of stratospheric O_3 by anthropogenic chlorofluorocarbons (CFCs) exemplifies an adverse environmental impact of human technology that could have culminated in a human catastrophe (Chapter 4). However, good science discovered the problem and led to an exemplary model of science-intensive public policy, namely the international decision to phase out use of CFCs in what has become known as the Montreal Protocol. Professors Mario Molina and Sherwood Rowland earned the 1995 Nobel Prize in Chemistry for their discovery that reactions with CFCs threatened to deplete stratospheric O_3.

of policy formulation has been largely ignored in the US and elsewhere. Not surprisingly, such ignorance has resulted in impasses and waste in the resolution of energy-environment questions.

The energy-prosperity-environmental dilemma is intensely intertwined with issues of fairness and equitable treatment of all stakeholders. These matters command high visibility with voters and consumers, as well as with politicians, advocacy groups, and commercial enterprises. Part of the dilemma is that there are diverse and seriously held convictions as to what energy technologies and policies constitute fair treatment of affected constituencies. Consensus becomes especially elusive when there are issues of risk to ecosystems and/or humans. Limitations in risk assessment, risk analysis, or risk communication (Chapter 6) can damage public confidence so badly that it may be virtually impossible to win acceptance for sustainable energy reforms.

Such impasses may be aggravated when the parties involved exaggerate the merits of their case and the weaknesses of those of their opponents. Such distortions are common in political power struggles. It should not be a surprise that they occur when such struggles occur under an energy-environment guise.

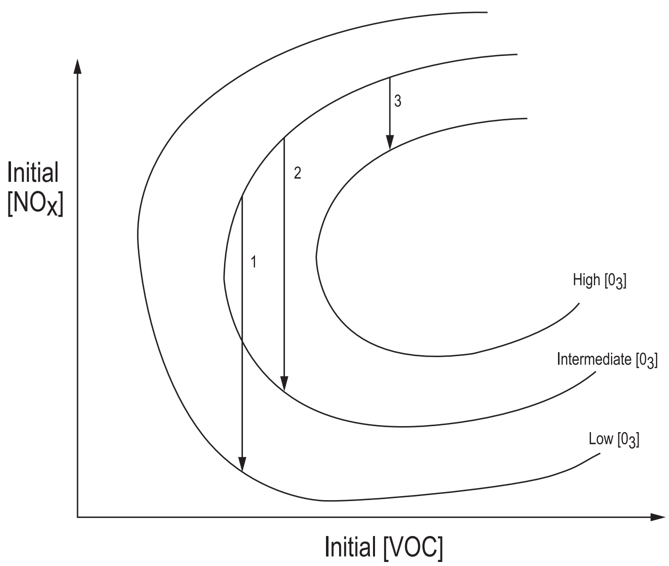

Figure 1.17. Schematic illustration of how changes in ambient concentrations of nitrogen oxides [NO_x] may impact levels of ozone [O_3] pollution in an urban airshed with high photochemical activity. Note that reducing NO_x inventories, depending on the ambient concentrations of volatile organic compounds [VOC], may decrease (Case 1), have no effect (Case 2), or increase ozone pollution (Case 3). Source: Seinfeld and Pandis (1998) citing Jeffries and Crouse (1990).

There are various motivations for public sector involvement in these issues. In developed countries, governments seek to protect people seen as especially vulnerable (e.g., lower-income people, children, the elderly, the homeless) from impacts of energy development, energy pollution, or loss of essential energy services. Objectives are to prevent regions occupied by these stakeholders from being unfairly selected as sites for energy or environmental cleanup facilities and to guard the financially destitute against termination of energy services. Developing countries may wish to use the benefits of energy to accelerate economic progress and improve the social well-being of their citizenry. Thus they may, in the near term, assign lower priority to environmental concerns in order to accelerate industrialization and infrastructure expansion by means of lower cost but potentially higher polluting energy resources. In many cases (e.g., until relatively recently in the Asian rim nations), this need has been driven by a combination of growing populations and dramatic annual increases in economic output. Poorer countries understandably ask why they should temper what they perceive to be essential growth in their own economies in the name of environmental protection, while already developed nations with dramatically higher standards of living do little to abate their own consumption of energy. Many lesser developed countries (LDC) and non-LDC experts believe developed nations that already enjoy the economic benefits of high per capita energy use should shoulder a "proportionate" share of the financial costs of providing for global environmental stewardship. To some, this means devising programs that curtail energy-related environmental damage in the developed world and assist LDCs in developing their own clean energy resources. Technology transfer, educational programs, and financial assistance are proposed as means to the latter end. One prominent global environmental thinker, Dr. Maurice Strong,[8] has suggested that developed countries formalize these goals by committing to spend a fixed percentage of their GDPs to improve environmental quality in developing nations.

Energy and environmental concerns ultimately boil down to two basic questions: who pays for pollution and when? Sustainable energy advocates respond that *everyone* pays for pollution *all the time*, whether or not the consequences of that pollution are immediately visible. For them, sustainable development seeks to confederate all stakeholders. Their mission is to devise technological and policy options to preserve and improve the earth's environment while protecting and extending socioeconomic progress throughout the planet.

A "confederation" does not mean that sustainability approaches will eliminate controversy or perfectly satisfy all expectations of every stakeholder. To the contrary, tradeoffs in the world's energy future are inevitable. The goal of sustainable energy is

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8 Dr. Maurice Strong served as the Under Secretary General of the United Nations and Special Advisor to the President of the World Bank. Formerly Chairman of Ontario Hydro and senior executive in several other Canadian companies, he now sits on many advisory boards. He served as Secretary-General of the 1992 UN Earth Summit.

to understand these tradeoffs and then elucidate workable technological and policy responses that will create more environmentally sound *and* consumer-friendly energy futures. Part of the sustainability process must be science-intensive, inclusionary discourse to unite potentially adversarial stakeholders and build lasting covenants for environmental and economic survival. As illustrated above for tropospheric ozone pollution, such engagements will only succeed if they are based on solid scientific and engineering foundations. Furthermore, sustainability goals will evolve as more is learned about tradeoffs and as new policy and technology innovations are discovered. Thus, research on scientific, engineering, and policy issues is essential to assuring the timely availability of information that can overcome the energy-prosperity-environmental dilemma.

1.6 Confronting the Energy-Prosperity-Environmental Dilemma

Sustainability and Alternative Proposals

The magnitudes of world daily energy consumption, financial expenditures for energy, and international trade in energy are colossal. This textbook introduces sustainable energy as a plausible response to a technology-intensive problem that is expected to vex humankind for decades to come. We can headline that problem as *the energy-prosperity-environmental dilemma*. Figure 1.16 captures the essence of this dilemma in schematic form. The thesis of this book is that persistent application of sustainable development concepts to energy and its environmental impacts is a viable solution to this dilemma. Realization of this solution will be challenging because current and future stakeholders embrace diverse and frequently contradictory sociological, geopolitical, technological, and environmental objectives. Subsequent chapters examine tradeoffs created by these diverse requirements, together with technology and technology-intensive policy options, that can bring about sufficient consensus to create a more sustainable energy future. However, there are alternative proposals for managing or combating adverse environmental and resource consumption impacts of energy utilization. Chapters 2 through 6 provide background information and methodologies to assess the claims and prospective performance of sustainable energy and other approaches to the world's energy future.

Table 1.8 (Allenby, 1999) summarizes four approaches to societal governance of technology and their probable implications for population growth and economic expansion. Each approach provides a significantly different philosophy for addressing the energy-prosperity-environmental dilemma. Whether any of these philosophies can be translated into an efficacious operating strategy remains to be seen. Nevertheless, there is merit in examining the tenets of all four approaches in Table 1.9, noting that they differ substantially from each other. At one end of the spectrum, we have *continuation of the status quo*, a largely *laissez faire* methodology punctuated occasionally by high visibility interventions, such as the chlorofluorocarbon (CFC) ban. At the other extreme stands *radical ecology*, a deeply penetrating technological revisionism in which most of society would return to low-technology methods for providing goods and services. Since the 1960s, mini-movements to this end have surfaced from time to time in the US (e.g., in the form of individuals and families seeking solace from urban pressures by taking up residence and vocations in rural areas). Less extreme is so-called *deep ecology* based on use of "appropriate technology," including low-technology approaches where possible.

Table 1.8. Proposed Responses to Societal Concerns Over Adverse Impacts of Industrial Activity[a]

Response Strategy	Effect on Technology	Implications
Radical Ecology	Return to low technology	Unmanaged population crash: economic, technological, and cultural disruption
Deep Ecology	Appropriate technology, "low tech" where possible	Lower population, substantial adjustments to economic, technological, and cultural status quo
Industrial Ecology	Reliance upon technological evolution within environmental constraints: no basis for "low tech" unless environmentally preferable[b]	Moderately higher population, substantial adjustments to economic, technological, and cultural status quo
Continuation of Status Quo (*Laissez Faire*)	Ad hoc adoption of specific mandates (e.g., CFC ban): little effect upon overall trends	Unmanaged population crash: economic, technological, and cultural disruption

Source: Allenby (1999).
[a]These strategies and consequences are also plausible outcomes of societal reactions to the energy-prosperity-environmental dilemma (see text and Figure 1.16).
[b]Or as a better match to ambient socio-economics.

Table 1.8 projects painful consequences from both the *status quo* and *radical ecology* approaches (i.e., economic and social calamities including population explosions or collapses) and associates *deep ecology* with some decline in population as well as appreciable mutations in current economic, technological, and cultural norms. As presented in Table 1.8, *industrial ecology* shares appreciable common ground with the concepts of sustainable energy as presented in this book. However, sustainability leaves open the depth, direction, and time scales of "substantial adjustments to economic, technological, and cultural status quo," preferring instead to emphasize judicious use of technology and technology-intensive policy measures to both preserve and extend the economic opportunities enabled by energy.

Industrial ecology forecasts substantial technological and economic changes. Historically, technology has advanced by continuous evolutionary improvements, interdicted at certain defining moments by revolutionary changes (e.g., steam engines replacing human and animal power, semiconductors replacing vacuum tubes, information technology). Thus, given sufficient time, the technology prognoses of *industrial ecology* seem likely to prove correct. Less certain however, is whether over one or two inter-generational time scales (e.g., in the next two to five decades) the pace of technological change in the energy, environmental, and closely related sectors (e.g., automotive and electric power) will become more revolutionary than evolutionary, thereby unleashing dramatic transformations in industrial practice and consumer behavior.

The prospect of "substantial adjustments" to the economic status quo (Table 1.8) would be welcomed by some but certainly not all sustainable energy proponents. Serious adherents range from advocates of appreciable governmental intervention to die-hard free marketeers. Appropriate missions for government and for non-governmental institutions in stimulating economic growth and protecting the environment will continue to be debated in democratic societies. The existence of different perspectives on the depth and means of economic adjustment needed to achieve meaningful progress on sustainability should be recognized as a positive force that can enrich, strengthen, and diversify the pathways to effective reforms. Diversity is a strength—not a weakness—of the sustainable energy credo.

The extent to which sustainability ideals will penetrate industry and society more broadly is not known, but there are several encouraging signs. Many global industrial companies, without governmental regulations, have adopted industrial ecology and sustainability thinking as part of their business practices (Allenby, 1999, Graedel and Allenby, 1995, Schmidheiny and Zorraquin, 1996, Schulze, 1996, Socolow et al., 1999). In a 1997 address that attracted major attention from environmental groups, Sir John Browne, the chairman of British Petroleum, committed his company, now one of the world's three largest producers and marketers of fossil energy products, to major development of non-fossil renewable energy sources over the next several decades. Sustainable development is gaining industrial favor as a means not only to improve corporate images but also to retain and expand market share and to increase economic profitability.

Academic institutions and governmental laboratories in the US and abroad are mounting serious educational, research, and development programs to infuse sustainability concepts into the formal classroom training of new generations of scientists and engineers and into the design and implementation of emerging technologies and policy measures for supply and utilization of energy. Many of these initiatives have attracted financial support from industry. Some programs (e.g., the U.S. Program for a New Generation of Vehicles [PNGV]) feature industrial cost-sharing and hands-on partnering with industrial companies. These and many other examples suggest that there is reason for optimism that the benefits of sustainability approaches to the world's energy future will find increasing acceptance as the rational norm among industrial and governmental decision makers.

Each reader of this book must draw his or her own conclusions regarding whether the sustainability approach offers the best prospect for obtaining and maintaining global environmental stewardship and energy-enabled social progress. In reaching that decision, all of us are advised to consider possible obstacles to constructive change and ponder what unexpected events might modify the outlook for sustainability and alternative approaches. Thus, we posit that most sustainability advocates have embraced certain tacit assumptions about the world's future:

- that the apparent international trend toward increased democratization will continue
- that the globalization of commerce will not be seriously attenuated
- that protracted (exceeding one year), large scale, and, in particular, transcontinental military conflicts are unlikely, but local and regional conflicts will continue to plague the planet and will include flareups in areas containing or proximate to major deposits of fossil and other energy resources
- that cataclysmic economic disruptions among major economic giants such as Germany, Japan, and the US will not occur
- that within three decades certain developing nations such as China will hold economic power comparable to or eclipsing that of at least some, and possibly most, current economic superpowers

If reality proves to be substantially different from any of these assumptions, the cultural, social, technological, or economic incentives for timely adoption of sustainability concepts could change dramatically. If sustainability is to succeed, it must have broad-based public acceptance.

In particular, sustainability proponents must consider:

- **Practical political reality:** How to economically preserve the services and lifestyles in developed nations that historically have been enabled by high per capita fossil energy consumption.
- **Globalization of commerce and more democratic ideals:** How to equitably extend to developing nations and nations in transition energy-related goods and services, especially in light of elevated rates of economic and population growth.
- **Environmental stewardship:** How to prevent and/or redress environmental damage, known and potential, from the supply and utilization of energy.
- **Constructive engagement:** How to earn and maintain a consensus for sustainable energy throughout the global community, in light of diverse and potentially conflicting individual, local, national, and regional priorities for environmental responsibility, economic progress, and stewardship of natural resources.

A major pitfall in responding to these challenges is failure to impose a systems view (see Chapters 6 and 21). The beneficial and adverse consequences of energy utilization arise from many interacting processes that change with time and location. The energy-prosperity-environmental dilemma is a prototypical large complex system. It exhibits diverse length and time scales for the supply of energy (Figure 1.2), and for ecosystem damage (Table 1.7), sociopolitical transformations, and technological innovation. Further, this system is inextricably connected to related complex systems, such as resource management (e.g., water, minerals, fertile land), micro- and macro-economic growth, and geopolitical stability. These realities complicate analysis and decision-making on energy and its impacts, but they must be accounted for in devising and implementing sustainable energy strategies.

1.7 Mathematical Representations of Sustainability

If sustainability could be objectively measured and described quantitatively, analysts would have a powerful tool for prioritizing and defending sustainable energy strategies. However, sustainability is a cloth woven of objective and subjective fibers. Potent "hot button" issues in the subjectivity category are how to value human health and human life, open space, and species diversity. Methodologies to assign economic costs to these values have been proposed (Chapters 5 and 6). Many object to such metrics on moral grounds or seriously question the underlying assumptions for value assignments, especially in light of appreciable uncertainties or gaps in crucial data. Even putatively objective measures, like the mass of pollutant a technology emits per unit of useful energy provided (e.g., lbs of SO_2 per kWh of electricity), are vulnerable to subjectivity in that different evaluators will give more or less weight to a given attribute. Further, the weighting factors may well change with time as more is learned about human health and the adverse impacts of energy-related pollutants. Thus "metricators" face a complex stew of parametric uncertainty, imperfect miscibility of objectivity and subjectivity, and transient weighting factors. Consequently, a meaningful mathematical representation of sustainability will presumably need to be more robust than a single number or even a list of numbers. Such a representation should nevertheless be subject to well-established rules for mathematical manipulation so that metrics for various options can be easily compared, contrasted, and, where appropriate, reduced or combined. Given these requirements, we propose that tensors, which disaggregate and openly reveal anisotropy in real quantities (Jeffreys, 1961, and Margenau and Murphy, 1956), may provide a powerful mathematical apparatus for quantitatively describing and comparing the sustainability potency of diverse options. To the best of our knowledge, the mathematical analysis and data fitting to test this hypothesis have never been performed.

Some measurement approaches assume that the sustainability of a technologically intensive activity reflects:

(a) how many people use the technology,

(b) the role of the technology in the economy, and

(c) some measure of the resource consumption or environmental degradation caused by the technology.

Translating this hypothesis into useful formulas for comparing sustainability impacts is more challenging. One algorithm assumes that population (*P*) is a good surrogate for (a), but that the metrics implied by (b) and (c) should be expressed mathematically, not as absolute quantities, but rather as relative impacts on the population and economic activity respectively. Thus, useful simulants for (b) and (c) are per capita gross domestic product (*GDP/P*), and energy consumption per GDP (*E/GDP*), giving the following equation for the sustainability impact, S_I:

$$S_I = (P) \times (GDP/P) \times (E/GDP) \qquad (1\text{-}22)$$

Some analysts interpret (*GDP/P*) and (*E/GDP*) as aggregate measures of standard of living and energy intensity (i.e., reciprocal energy efficiency). Multiplication of the three factors on the right hand side (RHS) of Equation (1-22) suggests the seemingly trivial result that $S_I = E$ or that total world energy consumption is a measure of sustainability, suggesting that energy use only benefits sustainability. This result alone might satisfy some sustainability "metricators," but Equation (1-22) offers much more. It can reveal the potency of specific adverse impacts simply by appending its RHS with one further multiplicative factor depicting the intensity of that impact per unit of energy used, e.g., the amount of carbon dioxide CO_2 emitted per Btu (CO_2/E):

$$S_I = (P) \times (GDP/P) \times (E/GDP) \times (CO_2/E) \qquad (1\text{-}23)$$

Multiplying the RHS terms of Equation (1-23) equates S_I with total CO_2 emissions.[9]

Equation (1-23) can be modified in several ways (e.g., to allow for human actions that mitigate undesired impacts of energy). For example, CO_2 emissions can be combated by intentionally removing CO_2 from the atmosphere (e.g., by planting more trees; Chapter 10) or by capture and sequestration of anthropogenic CO_2 emissions (Chapter 7). Then, Equation (1-23) would become:

$$S_I = (P) \times (GDP/P) \times (E/GDP) \times (CO_2/E) - (CO_2)_{sq} \qquad (1\text{-}24)$$

where $(CO_2)_{sq}$ is the amount of CO_2 sequestered. Another CO_2 mitigation approach would be to use some form of solar energy (e.g., tides, wind, photovoltaic electricity) to displace energy that was previously supplied from fossil fuels. This would reduce the

9 When used to quantify release rates of CO_2 to the atmosphere, Equation (1-23) is commonly referred to as the Kaya Equation, in recognition of Professor Yoichi Kaya.

carbon intensity (i.e., the last term on the right hand side of Equation (1-23)). Equation (1-23) could be further modified to account for the association of energy with a diverse array of impacts known or suspected to be harmful (e.g., air pollution, water consumption, degradation of wildlife habitat, global climate modification) and for the distinct probability that different stakeholders will weight the sustainability importance of each impact differently. Then, for a set of independent impacts, Equation (1-23) would become:

$$S_I = [(P) \times (GDP/P) \times (E/GDP)] \sum_{i=1}^{n} W_i(t)\left[A_i(E)/E\right] \qquad (1\text{-}25)$$

where $A_i\,(E)$ is the i_{th} particular impact related to energy, $W_i(t)$ is the weighting factor assigned to the i_{th} impact at a particular time, t, and n is the total number of impacts to be considered. The limitations of Equations (1-22) through (1-25) are that they assume the various terms are independent of one another, which is often incorrect. For example, living standards can cause birth rates to decline, in some cases below the 2.2 children per couple needed to sustain zero population growth. Similarly, advances in living standard may give rise to great ability to purchase or develop more efficient and less polluting energy generation/utilization technologies, or substitutes like effective transportation infrastructure, that will decrease the adverse impacts of energy. We will revisit these factors when we examine sustainable energy from a systems perspective in Chapters 6 and 21.

1.8 The Rest of This Book

This book was written for diverse audiences. It is a textbook for graduate or senior undergraduate courses in engineering, public policy, or environmental science, that are concerned with energy *and* its technological, socioeconomic, and geopolitical ramifications. Thus, the sections and chapters are crafted to provide an orderly study of sustainable energy. However, this book is also a sustainable energy reference work, designed to serve the needs of inquisitive non-specialists for a useful introduction, as well as to augment the understanding of serious cognoscenti.

To serve these different audiences, this book looks at the topic of sustainable energy in two ways. First, we consider sustainable energy as a complex system that, in the broader context, is subservient to the "supersystem" of sustainable development. Then, we candidly discuss the prospects for sustainable energy to have practical global impacts in the 21st century.

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