Chapter 1
Energy Demand and Supply

Abstract The use of energy defines the beginning of human civilization: when the prehistoric human mastered the use of fire for domestic comfort and cooking, human civilization began and evolved to reach the age of the locomotive, the nuclear power plant, the automobile, the airplane, the personal computer and the wireless internet. Throughout the centuries, the human society has evolved by increasingly using energy to the point where the consumption of energy is necessary for the functioning of the contemporary society, the prosperity of the nations and the survival of our civilization. Energy is produced and is being used in different forms: airplanes and automobiles use liquid hydrocarbon fuels; electric power plants convert primarily the energy in coal, natural gas, nuclear and hydroelectric into electricity; and a contemporary household uses electricity and natural gas for domestic comfort, entertainment and the preparation of meals. Because most functions of our society are based on the use of energy, elaborate networks of energy supply have been developed in the last three centuries: electricity is fed into communities by the transmission lines of the electric grid at high voltage; natural gas by a complex system of pipelines, which transcend national boundaries; and tanker ships crisscross the oceans daily to supply crude oil to refineries. The economic impact of the energy supply and the energy trade is of paramount importance to all nations. The geopolitical activities of most modern nations are significantly influenced by their need for a constant and secure energy supply. Most of modern wars (those after 1950) have been fought for the control and security of energy supplies and many treaties and international agreements have been cemented with energy resources as the primary issue. This is a general chapter on energy, not just alternative energy, which explains in a quantitative way what is the quantity we call "energy," whence it comes and where it goes. The forms that energy is produced and consumed are, first, explained. The several units that are commonly used for different energy forms and quantities are listed and their equivalencies are explained. Secondly, the importance of energy in the economic activities of the contemporary society is described qualitatively and the

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primary energy resources are identified. The current energy trade between groups of nations is also described briefly and the main flow of primary energy resources is identified. Thirdly, historical data on energy production and consumption in several groups of nations are offered as well as some acceptable predictions for the future demand and supply of energy.

1.1 Forms and Units of Work, Heat and Energy

From the theory of Newtonian Mechanics, work has been defined as the scalar product of a force and the distance its point of application moves during a period of time. Power is the work per unit time. In the case of a force that is variable, the work is given by an integral, which describes the motion of the force between two end points, *a* and *b*. The work and its time derivative, the instantaneous power, are defined as follows:

$$W = \int_a^b \vec{F} \bullet d\vec{x} \quad and \quad \dot{W} = \vec{F} \bullet \frac{d\vec{x}}{dt} = \vec{F} \bullet \vec{V}. \tag{1.1}$$

Power is the scalar product of the force and of the velocity its point of application moves. For an engine to produce or consume power there must be forceful motion of some of its components. Usually, this motion is circular and is converted by gears to linear motion.

All the engines that are currently used for the performance of the several tasks desired by the human society produce work and consume energy resources. For example, the internal combustion engine consumes gasoline or diesel and produces work, which is used in propulsion. "Energy" is a very broad concept and is defined as the potential of materials and systems to perform useful work. Energy is measured in the same units as work and comes in several forms. Heat or thermal energy is a form of energy that is transferred from materials at higher temperatures to materials at lower temperatures. It is usually produced by the combustion of fuels, which are regarded as "energy sources." There are several engineering systems, such as the power plants and the internal combustion engines, which convert heat into work. Other forms of energy, which are commonly met in engineering practice and everyday applications, are:

1. The potential energy (mgz) of matter, at a higher level.
2. The kinetic energy ($1/2\ m\ |\vec{V}|^2$) of matter that moves with velocity $\vec{V}$.
3. The chemical energy (ΔG) of substances, such as coal and hydrocarbons.
4. The elastic energy ($Vm\sigma\varepsilon$) of a stressed solid with volume V and strain ε.
5. The electric energy (qV) of a charge q in a voltage difference V.
6. The magnetic energy (HM) of a magnetic quantity M in a magnetic field with intensity H.
7. The wave energy ($1/2A\rho g\alpha^2$) of waves on an area A with amplitude α.

8. The nuclear energy (mc^2) which is equivalent to the mass, m.
9. The surface energy (γA) of fluids with surface tension γ and area A.

Our society uses the energy content of several substances to produce work and to accomplish several tasks and activities. Different forms of energy undergo conversions and produce work during these activities. The energy conversions are subjected to the Laws of Thermodynamics. Details of these laws, a general overview of the subject of Thermodynamics, and examples on the conversions of energy forms are given in Chap. 3.

1.1.1 Units of Energy

From the kinetic energy of a single electron that may have been created during the "electron–hole" pair process in a photovoltaic cell, to the net power produced in a large nuclear power station, the units of energy span a very large range. Although they are different concepts and are not interchangeable, work, heat and energy are measured by the same units. The unit of energy in the *Systeme Internationale* (S.I.) is the Joule (J) and is defined as the work done when a constant force of 1 Newton (N) moves its point of application by 1 meter (m). One Joule is also performed when a charge of 1 Coulomb (1 Cb) moves through an electric potential difference of 1 Volt (1 V). Multiples of the Joule—as well as of all the other S.I. units—have been defined by international convention and are as follows:

- 1 yocto-Joule (yJ) = 10^{-24} J
- 1 zepto-Joule (zJ) = 10^{-21} J
- 1 atto-Joule (aJ) = 10^{-18} J
- 1 femto-Joule (fJ) = 10^{-15} J.
- 1 pico-Joule (pJ) = 10^{-12} J.
- 1 nano-Joule (nJ) = 10^{-9} J.
- 1 micro-Joule (μJ) = 10^{-6} J.
- 1 milli-Joule (mJ) = 10^{-3} J.
- 1 kilo-Joule (kJ) = 10^{3} J.
- 1 mega-Joule (MJ) = 10^{6} J.
- 1 giga-Joule (GJ) = 10^{9} J.
- 1 tera-Joule (TJ) = 10^{12} J.
- 1 peta-Joule (PJ) = 10^{15} J.
- 1 exa-Joule (EJ) = 10^{18} J
- 1 zetta-Joule (ZJ) = 10^{21} J
- 1 yotta-Joule (YJ) = 10^{24} J

It must be noted that all these prefixes may be applied to all other units of the S.I. Also that the S.I. units and their multiples have very precise notation and that differences in notation between lower case letters and capital letters denote differences of several orders of magnitude. For example, while mJ/mJ = 1 by definition, MJ/mJ = 10^9, and PJ/pJ = 10^{27}. All science and engineering students have to be very careful and precise with the notation of units.

The unit of power in the S.I. is the Watt (W). When an engine performs one Joule of work per second, it produces a power of one Watt (1 W). The multiples of the Watt as well as for all other units in the *Systeme Internationale* are the same as those of the unit Joule, as listed above.

Because energy is such a ubiquitous and practical subject of significant economic importance and everyday use, several other units of energy have been defined in the past and are still in common use:

- In the c.g.s. system of units the erg is the main energy unit, with 1 erg being equal to 10^{-7} J.
- In the British system of units, the British thermal unit (1 Btu) is very commonly used in the heating and air-conditioning industries and is equal to 1.055 kJ. One Btu is defined as the amount of energy needed to increase the temperature of 1 lb of water from 14.5 to 15.5°F.
- A larger unit in the British system is the Therm (1 therm), which is equal to 10^5 Btu or $1.055*10^8$ J.
- The calorie (cal) is equal to 4.184 J.
- An extremely large amount of energy is the Quad (1 Q), which is equal to 10^{15} Btu or, approximately, 10^{18} J. The total energy consumed in the USA in 2009 was approximately 100 Q and in the entire world approximately 490 Q.
- For extremely small amounts of energy, usually related to atoms or nuclei, the electron-volt (eV) has been defined as the potential energy gained by an electron when it moves through an electric potential difference of 1 Volt. Given that the charge of an electron is $1.6*10^{-19}$ Cb, 1 eV is equal to $1.6*10^{-19}$ J.

A third type of energy units is related to the chemical energy content of fuels, such as coal, crude oil and natural gas. Because the chemical composition and energy content of actual fuels, e.g. sweet East Texas crude or Saudi Arabian crude, depends largely on the location the fuels are extracted from, these units have been fixed according to international convention. Among these units their S.I. equivalents are the following:

- 1 ton of coal equivalent (1 tce) which is equal to $2.931 * 10^{10}$ J.
- 1 barrel of oil (1 bbl) which is equal to $6.119 * 10^9$ J.
- 1 cubic foot of natural gas (1 scf), measured at standard pressure and temperature (1 atm and 25°C), which is equal to $1.072 * 10^6$ J. 1 scf is often approximated as 10^6 J.

Table 1.1 shows the conversion factors for several energy units that are commonly used. For example, 1 cal = 4.18 J, 1 ton of coal is equivalent to $2.78 * 10^7$ Btu, etc. The diagonal terms of this table are equal to 1 by definition, and each term is equal to the reciprocal of its diagonally mirror term, that is $c_{ij} = 1/c_{ji}$.

Table 1.1 Conversion factors for energy units

	eV	calorie	erg	J	Btu	gallon of gasoline	barrel of oil
eV	1	3.82E − 20	1.60E − 12	1.60E − 19	1.52E − 22	1.21E − 27	2.61E − 29
calorie	2.62E + 19	1	4.19E + 07	4.18	3.97E − 03	3.17E − 08	6.84E − 10
erg	6.25E + 11	2.39E − 08	1	1.00E − 07	9.48E − 11	7.58E − 16	1.63E − 17
J	6.25E + 18	0.24	1.00E + 07	1	9.48E − 04	7.58E − 09	1.63E − 10
Btu	6.59E + 21	252	1.06E + 10	1,055	1	8.00E − 06	1.72E − 07
gallon of gasoline	8.25E + 26	3.15E + 07	1.32E + 15	1.32E + 08	1.25E + 05	1	2.16E − 02
barrel of oil	3.82E + 28	1.46E + 09	6.12E + 16	6.12E + 09	5.80E + 06	46.4	1
kw-h	2.25E + 25	8.60E + 05	3.6E + 13	3.60E + 06	3,412	2.73E − 02	5.88E − 04
ft-lb	8.48E + 18	0.32	1.36E + 07	1.36	1.29E − 03	1.03E − 08	2.22E − 10
therm	2.62E + 28	2.52E + 07	1.06E + 15	1.06E + 08	1.00E + 05	0.8	1.72E − 02
ton-TNT	2.62E + 28	1.00E + 09	4.18E + 16	4.18E + 09	3.97E + 06	31.73	0.68
quad	6.59E + 36	2.5E + 17	1.06E + 25	1.06E + 18	1E + 15	8.00E + 09	1.72E + 08
ton of coal	1.83E + 29	7.00E + 09	2.93E + 17	2.93E + 10	2.78E + 07	2.22E + 02	4.79E + 00
scf of nat. gas	1.01E + 25	2.56E + 05	1.07E + 13	1.07E + 06	1,016	8.12E − 03	1.75E − 04

	kw-h	ft-lb	therm	ton-TNT	quad	ton of coal	scf naturalgas
eV	4.44E − 26	1.18E − 19	3.82E − 29	3.82E − 29	1.52E − 37	5.46E − 30	9.89E − 26
calorie	1.16E − 06	3.09	3.97E − 08	1.00E − 09	3.97E − 18	1.43E − 10	3.90E − 06
erg	2.78E − 14	7.37E − 08	9.48E − 16	2.39E − 17	9.48E − 26	3.41E − 18	9.33E − 14
J	2.78E − 07	0.74	9.48E − 09	2.39E − 10	9.48E − 19	3.41E − 11	9.33E − 07
Btu	2.93E − 04	7.78E + 02	1.00E − 05	2.52E − 07	1.00E − 15	3.60E − 08	9.84E − 04
gallon of gasoline	3.66E + 01	9.73E + 07	1.25	3.15E − 02	1.25E − 10	4.50E − 03	123.1
barrel of oil	1.70E + 03	4.51E + 09	5.80E + 01	1.46	5.80E − 09	2.09E − 01	5,708
kw-h	1	2.66E + 06	3.41E − 02	8.61E − 04	3.41E − 12	1.23E − 04	3.358
ft-lb	3.77E − 07	1	1.29E − 08	3.24E − 10	1.29E − 18	4.63E − 11	1.27E − 06
therm	29.31	7.78E + 07	1	2.52E − 02	1.00E − 10	3.60E − 03	98.42
ton-TNT	1162	3.09E + 09	39.66	1	3.97E − 09	1.43E − 01	3,899
quad	2.93E + 11	7.78E + 17	1.00E + 10	2.52E + 08	1	3.60E + 07	9.84E + 11
ton of coal	8.14E + 03	2.16E + 10	2.78E + 02	7.00	2.78E − 08	1	2.73E + 04
scf of nat. gas	0.2978	7.88E + 05	1.02E − 02	2.56E − 04	1.02E − 12	3.66E − 05	1

1.2 Energy Demand and Supply

The beginning of human civilization is marked by the use of energy. When the prehistoric humans started using fire for cooking, heating, and protection from wild animals, the human civilization began. A few millennia later, the human society evolved and used the various forms of energy for heating during the winter, air-conditioning for summer comfort, cooking, transportation, and other activities that define the contemporary civilization. In the twenty-first century, the era of factories, individual houses, airplanes, automobiles and personal computers, energy is being increasingly used for the production of consumer goods, living comfort, transportation and entertainment.

It is hard to envision the human society of the twenty-first century without the use of energy in its several forms: on a typical working day, a man in Paris, France will wake up to the sound of his electric alarm; will make a cup of coffee and breakfast, using gas or electricity; will take the electric elevator to the ground floor of his apartment; will walk to the closest *metropolitaine* (metro) station and, after descending in the electric escalator will take one or more of the electrically powered metro lines towards his working place. If he does not use the metro system, he will use one of the many diesel-powered buses. When he reaches his destination will ascend again in an electric escalator; will walk to his place of work, which is heated by burning natural gas and lit by a system of fluorescent lights. Most of the tasks he will perform during a typical working day, for example, telephone calls, writing, e-mails, power-point presentations, involve the use of significant amounts of electric energy. The day of a typical woman in Los Angeles, California, has a very similar energy-use pattern. One difference may be that, instead of using public transportation, she will use her own automobile to drive to work and that her office is typically air-conditioned instead of heated. Men or women in developing countries may use fewer energy consuming devices and engines in their everyday lives, but, nevertheless, still use a significant amount of energy for living comfort, cooking, transportation and the production of goods.

The contemporary human society depends to a large extent on the use of energy in its various forms. The importance of energy in the human society is accentuated by cases when the supply of sufficient energy has been interrupted: the coal miners' strike in Britain in the winter of 1973–1974 resulted in the disruption of the transportation system, the reduction of the working week to a three-day week, economic recession and several deaths, which were due to lack of heating, electricity and lack of transportation. During the oil embargo of the mid 1970s, shortage of gasoline in Europe and North America resulted in the rationing of oil products, industrial production disruption, long waiting lines in the gas stations and, in a few instances in USA, shootings and murders. The interruption of the electric power supply in New York City on July 13, 1977 and in the entire eastern part of the USA on August 14, 2003 resulted in two infamous blackouts: in both cases the loss of electric power in several American cities resulted in the disruption of civic power, lootings, and large-scale municipal unrest. During these two blackouts, the interruption of electric power supply clearly signaled the disruption of the rule of law and brought social disorder. On such occasions there is always clear evidence that the temporary interruption of electric power and energy supply is accompanied by a disruption of civilization as we know it. The use of energy in its different forms clearly has defined the contemporary human civilization and the uninterrupted and secure supply of energy is essential for the preservation of human civilization.

1.2.1 Energy Demand

Humans use energy in several different forms in order to run machinery and accomplish different tasks: An air-conditioner unit uses electric energy to drive its compressor and provide cool air in a building in Miami, Florida; a burner demands heating oil or coal to heat up the cold air in a factory in Nanjing, China; a stove uses natural gas to prepare food in Germany; a car assembly line in Japan uses electricity to weld parts of cars and trucks; cars, trucks and buses use gasoline or diesel fuel in their internal combustion engines to transport people and goods; airplanes use kerosene to also transport people and goods.

The modern human society needs the accomplishment of such tasks, since the machinery to perform these tasks only runs on energy. The air-conditioner, the kiln of a cement factory, the welding equipment of a shipyard, the train locomotive that brings food to a city and the ship that transports goods between continents, all operate because they use various forms of energy. In the absence of energy supply, these equipment would not operate and the societal tasks would not be performed: when ships do not have fuel, food is not shipped and rots in ports; when the factory does not have electricity, cars are not manufactured to be sold later; with a scarcity of heating fuel, homes in Berlin are very cold in January and the inhabitants do not have the expected domestic comfort; without air-conditioning, working is very difficult during the summer months of Fort Worth, Texas and productivity suffers; without kerosene for airplanes or gasoline for cars, families do not re-unite for holidays.

Energy is demanded in different forms, the most important of which are: electricity, gaseous fuels, liquid fuels and solid fuels. Global energy demand has been constantly growing since the industrial revolution and is affected by two factors:

a) The increase of the global population.
b) The increasing energy demand per capita as agrarian and less affluent societies transform to industrial and more affluent societies.

In general, the more affluent a society is the more energy it consumes per capita. Citizens of the more affluent nations, as a group, buy more energy-intensive consumer goods; use more frequently private means of transportation and travel more; and have higher levels of energy-intensive comfort in their homes. All these activities require higher amounts of energy per person. Figure 1.1 shows the relationship between affluence and energy use in the plot of the consumption of electricity, measured in MWh/per year per capita, versus the Gross Domestic Product

(GDP) per capita for several countries.[1] The GDP values in the figure have been adjusted to take into account the different purchasing power of the US dollar in the respective countries.

It is apparent in this figure that there is a direct relationship between the affluence of a nation and the average energy its citizens consume. Nations in the Organization for Economic Cooperation and Development group[2] (OECD), which encompasses most of the industrialized and more affluent nations have significantly higher GDP per capita and consume significantly more electricity per capita than developing nations. The United States of America, Canada, Switzerland, most European Union countries, Japan, Australia and New Zealand appear at the top of the figure. At the bottom are several developing countries, primarily in the African continent, where societies are in general less affluent and the energy consumption is significantly less. In the middle of the diagram, there are several countries in intermediate stages of economic development, which are commensurate with their energy consumption. Among these, the economies of several countries including China, India and Brazil have improved significantly in the first ten years of the twenty-first century. Citizens of these countries have become more affluent and, as a result, both the total energy consumption and the electric energy consumption per capita have increased significantly.

A correlation of the variables in Fig. 1.1 yields the following relationship between GDP and the electric mega-watt-hours per capita consumed:

$$MWh = 0.06*(GDP)^{1.184}. \tag{1.2}$$

The correlation coefficient of the data is 0.8279, which signifies that the correlation between the MWh consumed per capita and GDP (adjusted for purchasing power) is very significant.

Figure 1.2 presents an interesting consequence of affluence and energy consumption for all nations. This figure depicts the average life expectancy in the chosen countries versus the electric energy consumption per capita. The outlier countries in this figure are essentially countries with high incidence of cases of the AIDS epidemic (several sub-Saharan countries), war-torn countries (Afghanistan) or countries with exceptionally good preventive health care (Cuba, Costa Rica, Sri Lanka and Nicaragua). It is obvious from this figure that a significant and positive correlation exists between the energy consumption and the average longevity of the citizens of a nation. Since the latter is connected to the "quality of life," one may reasonably correlate the energy consumption per capita with the quality of the life of the citizens in a nation.

Regarding Fig. 1.2 and the contemporary use of energy, it is important to note that energy consumption is not the *cause* of affluence and longevity in the nations,

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[1] The ordinate of Figs. 1.1 and 1.2 is the electric energy consumption per capita. The same trends are observed and the same conclusions may be drawn with the total primary energy consumption per capita being the ordinate of the figures.

[2] The OECD group of countries comprises most of the European Union countries, Switzerland, Canada, the USA, Australia and New Zealand. The countries in this group are sometimes referred to as the "developed" countries.

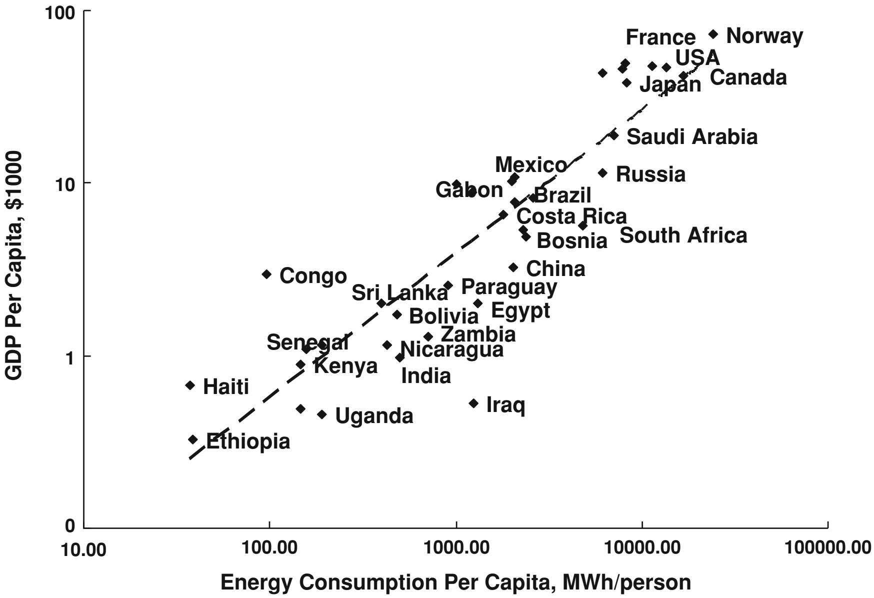

Fig. 1.1 Relationship between electric energy demand and GDP adjusted according to purchasing power. (Data from *Key World Energy Statistics,* IEA, 2009)

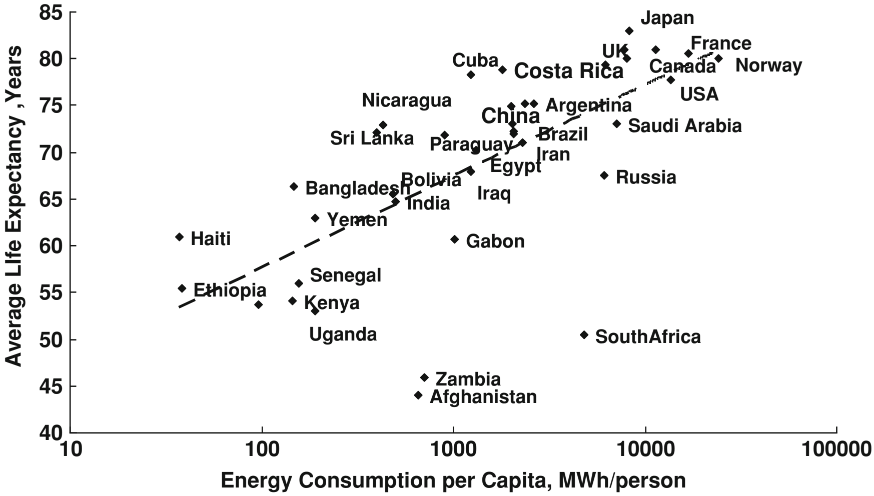

Fig. 1.2 The relationship between electric energy consumption and average life expectancy for several countries. (Data from *Key World Energy Statistics,* IEA, 2009 and the World Bank)

but the *effect* of this affluence: A more affluent society demands more goods and services, travels more, and typically has better public or private health care than a poorer society. Hence, citizens of the affluent nations consume more energy and live longer as the last two figures demonstrate.[3] One may also establish a cause and effect relationship by looking at the use of energy since the beginnings of humans: the prehistoric humans had to perform all the tasks by themselves. As a result the fossils of their bones show a great deal of "wear and tear" and their life expectancy was approximately 20 years. The early historic-period humans domesticated certain animals that performed most heavy tasks for them, but worked hard in agriculture. The life expectancy of these humans increased to 30–35 years. The humans of the early twenty-first century are employing mechanical engines to do most of their work, use machinery in agriculture, do not physically stress their bodies and, as a result, their life expectancy has increased to more than 70 years.

From the public administration point of view, governments look after the welfare of their citizens and, through long-term strategic planning, aim to increase the economic prosperity of their people. By doing so, they also aim to increase the total consumption of energy as well as of electric energy in particular. For this reason, national, regional and local governments adopt long-term plans to secure the adequate supply of energy products and the production of sufficient electric power, in order to sustain their growing economies. Three notable examples of rapid economic development in the recent past accompanied by significantly increased energy demand are: the Peoples Republic of China (PRC), India and Brazil. Figure 1.3 shows the GDP per capita (adjusted for the purchasing power of the US dollar) and electric energy consumption per capita in these three countries in the thirty years from 1980 to 2010.

It is apparent in Fig. 1.3 that the road to affluence for these three emerging economies was accompanied by an immediate increase of the electric energy consumption.[4] The trend is particularly evident in the case of the Peoples Republic of China, where the rapid industrialization and rise in GDP in the first decade of the twenty-first century was accompanied by an equally rapid increase of the use of energy. It must also be noted that these three countries account for more than 40% of the entire population of the Earth and that their further industrialization, increased affluence and increased energy use are expected to continue in the near future.

Similar developmental patterns were followed in the past by the countries of the OECD group when they were in their early development stages and very likely will be followed by most developing countries. The desire and tendency of all nations to become more affluent and the dramatic increase of energy consumption that follows have had very significant implications on the total world energy consumption growth. This trend is depicted in Fig. 1.4, which shows the total energy demand in the entire world from 1970 to 2010 according to the form of energy demanded and used. The values for years 2009 and 2010 are projections.

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[3] While it may be true that "money does not buy happiness," Fig. 1.2 and this cause-effect relationship demonstrate that, at least, money can buy a longer life.

[4] The fluctuations of the GDP of Brazil are due to the devaluation of the *Real,* the national currency of the country in 1998 and the short-term disruption of the economic activities that followed.

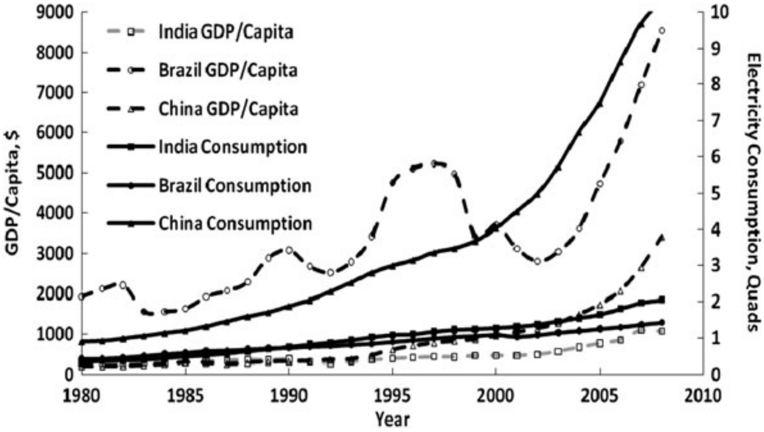

Fig. 1.3 Electric energy demand and GDP for Brazil, China and India. (Data from *Key World Energy Statistics,* IEA)

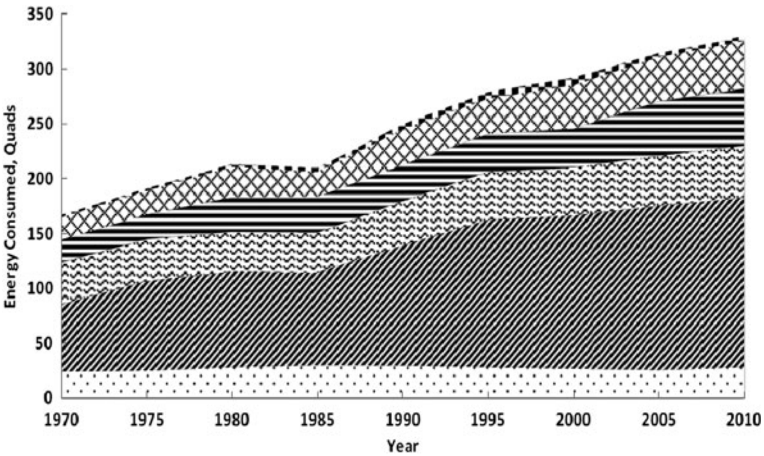

Fig. 1.4 Total global energy demand by energy form from 1970 to 2010. The areas (from *bottom* to *top*) represent coal, petroleum, natural gas, wood and waste, electricity and other energy forms. (Data from *Key World Energy Statistics,* IEA, 2009)

It is apparent that the global energy demand more than doubled in these 40 years. This growth is accounted for by two factors:

a) The improved economic prosperity in the entire world, and
b) The increase of the world's population.

These two factors are expected to continue their upward trends in the foreseeable future, thus driving the global energy demand continuously to higher levels. Energy conservation and improved efficiency in engineering processes

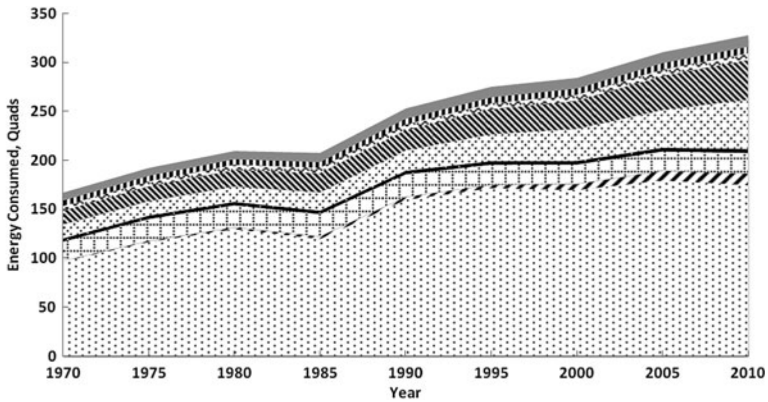

Fig. 1.5 The evolution of the global energy demand by region and groups of countries (data from *Key World Energy Statistics,* IEA, 2009). The areas (from *bottom* to *top*) represent OECD, Middle East, Former Soviet Union, non-OECD Europe, China, Rest of Asia, Latin America and Bunker fuel (the latter is used in transportation internationally)

simply cannot keep up with the growing world population and the increasing affluence. For the continuation of the "global economic progress" the world will need more energy to produce and to consume in the near future.

The rise in the energy demand has not been uniform among nations and geographical regions. Given the characteristics of energy demand according to the affluence of nations, it is not surprising that the OECD countries consume a significantly larger proportion of the world energy. Figure 1.5 shows the evolution of the energy demand from 1970 to 2010 (values for 2009 and 2010 are projections) in several regions of the planet. It is apparent in this figure that the relative energy demand in the OECD countries has fallen from approximately 60% of the total to 45%. However, and because the total global energy demand more than doubled during this period, the absolute energy consumed by the OECD countries increased by 44%, from 101 to 144 Q.

While the energy consumed in the OECD countries increased, the rate of growth in these countries was less than the average rate of growth of the global energy demand. The Peoples Republic of China[5] and the rest of Asia almost doubled their share of the total energy demand, while the share of Latin American and African nations also increased by 50 and 60% respectively. As the economies of the countries in these developing regions grow and the populations become more affluent, the consumption of energy increases according to the trends shown in Fig. 1.1. The only geographical region that has experienced a decrease of energy demand is the former Soviet Union during the years that followed the split

[5] Although the P.R. of China is an Asian country, it merits separate mention because of the size of its population—in 2009 the country had 12% more inhabitants than the entire OECD group—and because of the tremendous economic and energy demand growth it has shown since 1990.

of the Union into several countries. The lower energy consumption in these new countries was a consequence of the economic recession that followed the break-up of the Soviet Union. The improved economic activity in these countries during the first decade of the twenty-first century was immediately followed by increased energy consumption. Once again, this demonstrates the cause-effect relationship between economic prosperity, reflected in the higher GDP, and energy use.

A rather somber conclusion about the energy demand trends in the OECD countries is that, despite the energy conservation and improved energy efficiency measures that were adopted since 1970, the total energy consumed in these nations increased significantly. The global energy demand and the environmental effects associated with energy consumption have continued growing at an accelerated pace in the first decade of the twenty-first century. The current trends indicate that the global energy demand is not going to decrease in any geographic region, during the foreseeable future. On the contrary, the energy demand will grow significantly in several regions. The growth of energy consumption will occur primarily in Asia, Africa and Latin America, where most of the Earth's population lives and where most of the economic growth occurred in the beginning of the twenty-first century. The combined factors of increasing affluence and population growth will be the driving forces for the growth of energy demand in these continents and the entire planet.

1.2.2 Energy Supply

The national energy demand as a total must be met by the global energy supply. Since the natural laws dictate that energy may neither be created nor destroyed, all the energy that is consumed must be produced from energy sources, which exist in the natural environment. These natural energy sources are:

1. Fossil fuels, such as the various forms of coal, crude oil and natural gas.
2. Nuclear fuels, such as uranium and thorium.
3. Renewable energy forms such as solar, wind, biomass, geothermal, wave, and hydroelectric energy.

The first two forms of energy are essentially minerals that were formed several millennia ago. Their formation processes take place over very long periods of time (geological periods). Because these minerals may not be reproduced naturally in the foreseeable future, they will be exhausted at some point in the future. The category in the third item represents renewable energy forms that are reproduced and are inexhaustible. Humankind may expect that these energy forms will continue to supply energy to the humans in the foreseeable and far future.

The human society demands energy in different forms, such as electricity, transportation fuels, natural gas etc. Depending on the form of energy they supply, we distinguish the sources of energy supply as:

1. *Primary* energy encompasses the forms of energy that are directly consumed as they are found in nature, without any processing. The various forms of coal,

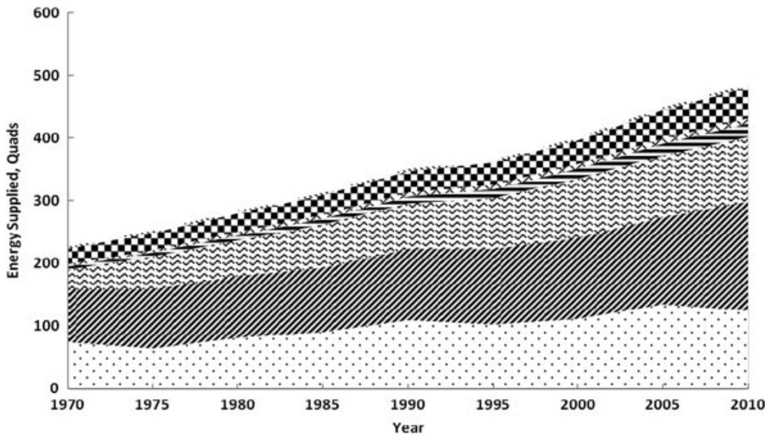

Fig. 1.6 The primary energy sources that supplied the global demand between 1970 and 2010. The areas (from *bottom* to *top*) represent coal, petroleum, natural gas, wood and waste, electricity and other energy forms (data from *Key World Energy Statistics,* IEA, 2009)

crude oil, natural gas, hydraulic energy and passive solar energy are among these forms.

2. *Secondary* energy forms are used by the consumers in a refined, processed form. The liquid petroleum products derived from crude oil, such as gasoline, diesel and kerosene; fuel from biomass; biodiesel; solar collector energy; and thermal geothermal are among the secondary energy forms.
3. *Tertiary* energy forms involve one or more transformations of energy. Electric energy, in any way it is produced, is a tertiary form of energy. Nuclear energy, wind power and most of the other renewable energy sources when they are used to produce electricity contribute to the supply of tertiary energy. In general, the transformations leading to the production of tertiary energy involve a significant percentage of dissipation, which is governed by the 2nd Law of Thermodynamics as explained in Chap. 3.

Secondary and tertiary forms of energy must be produced from primary sources. The main primary energy sources that have satisfied the global energy demand since 1970 are shown in Fig. 1.6 (the values for 2009 and 2010 are estimates). These primary sources are classified as:

a) The various forms of coal (anthracite, bituminous, lignite, peat)
b) Crude oil/petroleum
c) Natural gas
d) Nuclear
e) Hydroelectric energy or water energy
f) Biomass and waste, which primarily comprises trees, and
g) Other renewable forms such as solar, wind and geothermal.

Table 1.2 Evolution of the world primary energy supply between 1973 and 2007

	1973 (total 243 Quads)	2007 (total 475 Quads)
Coal and coal products	24.5	26.5
Crude oil	46.1	34.0
Natural gas	16.0	20.9
Nuclear	0.9	5.9
Hydraulic	1.8	2.2
Wood, biomass and wastes	10.6	9.8
Solar, wind, geothermal	0.1	0.7

All values are in percentages (data from *Key World Energy Statistics,* IEA, 2009)

It is apparent from this figure that the energy supply more than doubled between 1970 and 2010, following the increased energy demand. It is of interest to know the contributions of the several primary energy sources to the total global energy demand during the period covered in Fig. 1.6. Table 1.2, which was produced from the same data shows two "snapshots" of the total global energy supply in the years 1973 and 2007 and elucidates the changes that occurred in the consumption of the several primary energy forms.

A number of conclusions may be drawn from Table 1.2 regarding the trends of the use of primary energy sources in the recent past:

1. The relative amount of coal and its products that have been used primarily for the production of electricity has remained almost the same. Because the total energy consumption almost doubled, the coal consumption also doubled.
2. While the relative amount of crude oil consumption decreased significantly between 1973 and 2007, from 46.1 to 34% of the total, the absolute amount of crude oil consumed actually increased from 112 Quads to 162 Quads, or from 2,819 million tons of crude oil (19,264 million bbl) to 4,090 million tons (27,864 million bbl). This implies that, despite all the campaigns for the reduction of oil consumption and policy measures for energy independence in the OECD countries, the demand for crude oil is still very strong and its use will likely grow significantly in the near future.
3. Most of the global energy supply, 81.4%, comes from fossil fuels (coal, oil and natural gas) which are finite and will be exhausted at some point in the future. For a sustainable future energy supply, the supply and consumption of non-fossil forms of energy must increase significantly.
4. Both the relative and the actual amount of nuclear energy used have increased significantly. However, most of the increase occurred during the 1970s and early 1980s. Only a handful of nuclear reactors have been built in the OECD countries since 1986, when the Chernobyl accident occurred.

5. A great deal of the world energy supply (10%) stems from the burning of trees and other biomass products. This practice occurs primarily in the developing countries, where biomass is the main source of fuel for cooking and heating.
6. The production of hydroelectric energy, in kWh, has more than doubled.
7. Even though the relative use of solar, wind and geothermal energy have increased by a factor of 7 and the energy supplied by them increased by a factor of 15, these renewable energy sources, still contribute less than 1% of the total energy supply. The world has to make significant technological progress and great strides in order to achieve a sustainable energy future that is based on renewable energy sources.

An important conclusion that may be deduced from the data of Table 1.2 and Fig. 1.6 is that the global primary energy demand is satisfied principally by exhaustible energy sources, such as coal, oil, natural gas, and nuclear. The time-scale of replenishment of these fuels is of the order of thousands of years, and the rate of their consumption by far exceeds the rate of their replenishment. Because of this, it is apparent that these fuels will become scarce and will be exhausted in the future. Since the entire contemporary human civilization is based on the consumption of energy, the continuation of our civilization demands that humans must ensure the adequate supply of renewable energy in the near future. Technologies for the utilization of solar, wind, geothermal, and hydrogen fusion energy[6] must become widely available in the future to satisfy the global energy demand and to ensure the continuation of our civilization.

All of the world's countries utilize and promote domestic energy sources to satisfy their energy demand to the extent possible. For the production of electricity, most countries use their domestic coal supply, supplemented by nuclear fuels and a small percentage of fluid hydrocarbons and renewable sources. The Peoples Republic of China has launched a very ambitious electrification program, based on domestic coal supply and the USA has relied on domestic coal to provide more than 70% of its electric consumption. On the other hand, countries with smaller coal reserves, such as France and Japan, have aggressively promoted nuclear programs that supply most of their electric energy. Unlike their neighbor France, Germany and the United Kingdom, two countries with significant coal deposits, rely more on their domestic coal to produce electricity than their nuclear reactors.

The situation is different in the transportation sector, which demands liquid fuels: crude oil and natural gas exist in only a few regions of the world and are in very high demand in Europe and North America. There is a significant trade in fluid hydrocarbons, both crude oil and natural gas, which primarily flow towards the OECD countries. The Middle East, the countries of the former Soviet Union and some countries of Latin America supply most of the crude oil and the natural

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[6] Hydrogen is not a renewable energy source. However, the amount of hydrogen on Earth is very high and the energy released by fusion is large enough to make this energy source virtually inexhaustible (Chap. 6).

Table 1.3 World population, GDP, and primary energy production, imports and total supply

Region	Population, (Million)	GDP (billion, $US)	Production, (Quads)	Imports, (Quads)	TPES, (Quads)
OECD and rest of Europe	1,238	32,870	155	74	229
Middle East	193	1,552	61	−38	23
Former Soviet Union	284	2,472	65	−24	41
P. R. China	1,327	10,156	72	8	80
Rest of Asia	2,148	8,292	49	8	57
Latin America	461	3,714	28	−5	23
Africa	958	2,372	45	−19	26
Total world	6,609	61,424	475	0	475

Data of the year 2007 from *Key World Energy Statistics,* IEA, 2009

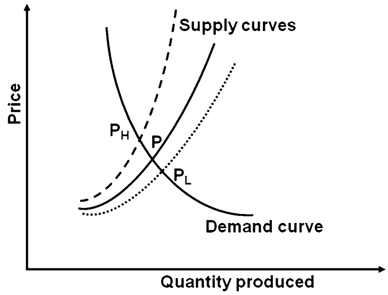
gas consumed in Europe and the USA. The flow of primary energy forms in the several regions of the world is shown in Table 1.3 together with the population of the regions and the average Gross Domestic Product adjusted for the purchasing power of the US dollar in the respective region. The Total Primary Energy Supply (TPES) is the sum of the domestic production and all imports. In national statistics, it is the TPES that is commonly referred to as "energy."

It is apparent from Table 1.3 that energy imports are primarily directed to the OECD countries and the rest of Europe. It is also of interest to note that these countries also have the highest energy consumption per capita. The energy consumption in the OECD countries is 0.185 Quads per million inhabitants, while the average for the world is 0.072 Quads per million inhabitants. If the entire world had the same level of affluence and consumed energy at the same rate as the OECD countries, in 2007 the total world primary energy demand would have been 1,223 Quads or 2.57 times higher than it actually was. In the absence of serious efforts in conservation and energy efficiency as well as of internationally mandated measures for the curtailment of energy consumption globally, it is likely that the future global energy consumption will reach these levels.

1.2.3 Energy Prices, OPEC and Politics

According to microeconomic theory, price is what connects the supply and demand of a commodity. The demand curve of a commodity is inversely related to its price, because consumers buy less of the commodity if the price increases. Supply curves are positively correlated with price because suppliers produce more of the commodity when the commodity price rises. At the intersection of the supply and demand curves, the supply and demand of a given commodity are at equilibrium. The intersection point of the two curves determines the price of the commodity at equilibrium. Figure 1.7 depicts typical demand and supply curves for a relatively inelastic commodity such as petroleum. The equilibrium price, P,

Fig. 1.7 Typical demand and supply curves of a commodity such as petroleum



is also shown at the intersection of the demand and supply curves, which are represented by the solid curves.

Now let us assume that a political event happens that affects one of the oil producing regions—a war, an embargo, or a political unrest—that disrupts the petroleum production in the region and decreases the produced quantity.[7] Other suppliers or other methods may enter the market to supply the demand, but the supply curve shifts to the left as denoted by the dashed line in Fig. 1.7. A new equilibrium is reached with a higher price, P_H. It must be noted that, because of the higher price, the quantity demanded and produced has slightly decreased at this equilibrium state. On the other hand if, again as result of an international political event, the suppliers decide to increase the quantity of the commodity produced, the supply curve shifts to the right and is represented by the dotted curve in Fig. 1.7. The new equilibrium is reached at a lower price, P_L. At this equilibrium, the consumption of the commodity is higher than that at the original equilibrium position because consumers respond to the lower price and use more of this commodity.

The price of crude oil and other hydrocarbons fluctuates almost daily, responding to demand and supply conditions. Absolute crude oil prices are historically much more volatile than prices of other commodities for two reasons:

(a) They are significantly influenced by international politics and events; and
(b) A group of relatively few countries, which effectively control the petroleum production, supply most of the imports to the OECD countries.

The prices of the rest of the energy forms also fluctuate, following the petroleum prices, but with lower variability. Political events in the Middle East—the major supply region of crude oil to the OECD countries—have significant influence on production and the prices, not only of petroleum, but also of all liquid hydrocarbons. Between 1960 and 2010 the price of crude oil jumped by more than

[7] The political upheavals of the first three months of 2011 in Tunisia, Egypt, Libya and other Arab nations caused a temporary disruption to the petroleum supply from North Africa. The immediate result was a jump in the oil price from approximately \$80/bbl in January 2011 to more than \$110/bbl in April 2011. When the political situation in these countries became more stable, in June 2011 the price of crude dropped to approximately \$95/bbl.

100% within a few months in the aftermath of the following political events: the Arab–Israeli war of 1973 and the following oil embargo; the aftermath of the Iranian revolution in 1979; the Iraqi invasion of Kuwait and the Persian Gulf war of 1990–1991; the production reduction of the mid 1990s by the Organization of Petroleum Exporting Countries (OPEC). In the twenty-first century the higher oil prices have been principally driven by the tight control of crude oil supply by OPEC, the war in Iraq, the increased demand in China and India and the domestic/national strifes in several Arab countries for more political freedom.

The OPEC is an economic cartel composed of Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela. The cartel has quarterly meetings in Vienna, Austria, where they try to regulate the crude oil supply by issuing quotas among the member countries. In 2007 the OPEC accounted for the production of 29,600,000 bbl of crude oil per day, most of which was exported to the OECD countries. This is equal to 62.8 Quads and, according to Table 1.3, it represents 85% of the oil imports of the OECD countries and the rest of Europe. By regulating the crude oil supply, the actions of OPEC have a very important effect on the world production of crude oil and shift the supply curves. By the supply–demand mechanism shown in Fig. 1.7, the equilibrium position of the market and the price of crude oil are also affected significantly. Consequently, the OPEC's actions affect the price of all the other energy commodities in the world.

Regarding the price of all energy commodities, we distinguish between *real* and *nominal* prices. The nominal prices are those quoted in everyday transactions and frequently appear on the gasoline station billboards. For example the nominal price of one liter of gasoline in Oxford, England was £0.21 in 1976 and £1.56 in 2008. The real price of gasoline and other petroleum products accounts for the inflation that has occurred during a time interval and differs from the nominal price. The real price is often quoted in constant currency of a particular year, such as constant 1990 US dollars or constant 2000 British pounds.[8] The official inflation rate in a country, which is often given by the respective national Treasury Department, determines the annual rate of inflation of the currency for the corrections to be made.

The fluctuations of the liquid hydrocarbon prices from the end of the 2nd World War to 2010 are shown in Fig. 1.8, which depicts the nominal and real crude oil prices, the former measured in constant 2010 US dollars.[9] Several of the important political events that influenced the price of liquid hydrocarbons are also noted in the figure. The following conclusions may be drawn from Fig. 1.8:

[8] The conversion to Euro in many European nations, which occurred between 1995 and 2005, makes this computation more cumbersome. Most of the energy resources are quoted in constant US dollars or British pounds.

[9] The price of crude oil (petroleum) is a well-publicized economic parameter. This price is followed daily and appears in most news outlets of the globe. This price is usually quoted per barrel of oil, \$/bbl (1 bbl = 42.0 gallons = 159 l).

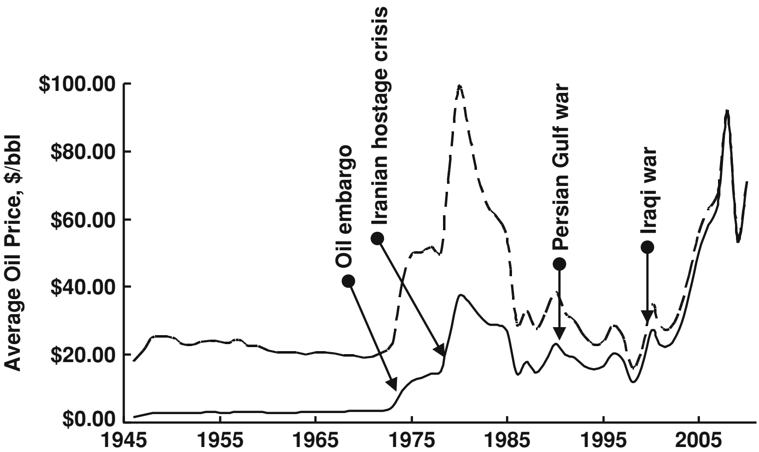


Fig. 1.8 Nominal price (*solid line*) and real price in 2010 $US (*dashed line*) of crude oil. Data obtained from the International Energy Agency and the US Bureau of Labor Statistics

- The effect of major international events in the price of crude oil is significant, but, typically, of short duration. Prices are restored close to their previous level once the "political crisis" is over.
- Despite the significant fluctuations in its nominal price, the real price of crude oil, measured in constant 2010 US dollars, has been historically almost constant in the range $20–$40 per barrel. The exception to this was the decade 1975–1985, when the OPEC yielded significant political influence, and the first decade of the twenty-first century, when the demand from several developing nations became significant enough to affect the global crude oil prices.

The prices of the other fuels and other energy commodities have a high, positive correlation to the price of crude oil. Usually, the price of crude oil leads the trends in the prices of other fuels. However, the prices of the other fuels have higher inertia and do not exhibit the wild fluctuations of crude oil prices. The economic phenomenon of *substitution* becomes important and drives the consumption of alternative energy sources, energy efficiency and conservation: When energy prices rise, the society strives to satisfy its energy needs with other sources of energy, such as wind, solar, geothermal or reduces the energy consumption using conservation and higher efficiency measures. For example, ordinary citizens switch to cars with higher mileage, drive less and use less energy at home; electricity corporations invest more in higher efficiency power plants or in power plants that use alternative energy sources; and nations initiate and promote policy measures that favor alternative energy sources, more energy conservation and higher efficiency. When crude oil and the other conventional energy sources become expensive, alternative energy sources become viable, economic alternatives to satisfy the energy demand of the society.

The experience of the years 2006–2010 demonstrates how the significant energy price increase resulted in more conservation measures and increased use of alternative energy sources at the individual, the corporate, the national and the global levels. On the other hand, when there is an "oil glut" and the energy prices drop to a low level, energy conservation, alternative energy and higher efficiency projects become relatively more costly and less important to the general population. The period 1984–2000 is an example of such low energy prices era: during this period there was very little investment in solar and wind energy projects; conservation and higher efficiency efforts were relaxed or abandoned; and the automobile companies throughout the world introduced vehicles with very low mileage, such as the family caravan, the SUV and the "Hummer," which became very popular with affluent consumers in several countries.

1.3 Reserves, Resources and Future Demand for Energy

It is apparent that the global TPES consumption has been continuously increasing during the last two centuries and that this increase is expected to continue at least in the near future. The growth of the world's population and the improving economic conditions are expected to accelerate the global energy consumption, while the nominal rise in the prices of fuels is expected to promote conservation and to slow the growth of TPES use. One of the factors that contribute to this growth is the increasing energy demand in developing countries, and especially in China and India, which together account for almost 40% of the Earth's population.

The globally-averaged compounded annual rate of the TPES growth between 1970 and 2009 was 1.91%. During this period, the TPES growth rate in the OECD countries was a mere 0.85%. These numbers signify that the developing countries account for most of this TPES growth rate. Given that the developing countries have most of the world's population and, in addition, have the highest GDP growth rates, it is expected that the global energy consumption will continue to increase in the near future. The global energy consumption is expected to grow, with a rate that is similar to the rate of the last forty years despite any reasonable rise in the energy prices and energy conservation measures, which may be adopted by individual nations or the global community.

One of the reasons that the TPES consumption growth rate may become lower in the future is international regulations and international agreements designed to curtail the global greenhouse gas emissions. As it will be seen in more detail in Chap. 2, the combustion of fossil fuels produces large quantities of carbon dioxide, which cause the warming of the atmosphere and global environmental change. Several countries have already adopted measures for the curtailment of carbon dioxide emissions. It is possible that other countries will follow with such regulations and the world will have meaningful restrictions on the production of carbon dioxide. If this occurs, the consumption of fossil fuels, such as coal, liquid and gaseous hydrocarbons, will be reduced significantly and the total TPES will also be

Table 1.4 **a** Expected primary energy demand in 2030

	RS-2030 Total TPES	Percentage	450 PS-2030 Total TPES	Percentage
a In Quads (data from *Key World Energy Statistics,* IEA, 2009)				
OECD countries	250.4	37.1	222.3	39.0
OME countries	308.5	45.7	240.5	42.2
Rest of world	108.0	16.0	98.6	17.3
Transportation fuel	8.1	1.2	8.6	1.5
Total	675.0		570.0	
b By energy sources in Quads (data from *Key World Energy Statistics,* IEA, 2009)				
Coal	194.4	28.8	94.6	16.6
Petroleum	203.2	30.1	171.0	30
Gas	145.8	21.6	116.9	20.5
Nuclear	35.8	5.3	54.2	9.5
Hydroelectric	16.2	2.4	22.2	3.9
Renewables	79.7	11.8	111.2	19.5
Total	675.0		570.0	

reduced significantly. The *International Energy Authority* (IEA)*,* an agency of the United Nations, has prepared two scenarios for the future energy consumption that extend to the year 2030: The first scenario assumes that there will not be a significant regulatory intervention by the international community. The second scenario assumes that an international treaty will reduce carbon dioxide emissions significantly to stabilize the concentration of the gas at 450 parts per million (450 ppm). The effect of this action will be a reduction of the TPES growth, especially that of fossil fuels and the substitution of fossil fuels by alternative energy and conservation measures. The first scenario is often called Reference Scenario (RS-2030) and the latter is often called the Scenario 450 PS (450 PS-2030).

Tables 1.4a and b show the expected consumption of TPES in the year 2030 under these two IAE scenarios. The first table depicts the expected energy demand in 2030 in the various regions of the globe and the second table gives the supply of primary energy forms that would satisfy this demand. In Table 1.4a the designation of OECD countries also include the rest of Europe. OME denotes the Other Major Economies, which comprise Brazil, the P.R. of China, India, Indonesia, the Russian Federation and the countries of the Middle East. These economies are expected to play an important role in the future energy consumption and the growth of TPES between 2010 and 2030.

It must be noted that the term "renewables" in these Tables comprise: human and animal wastes; solar energy; wind energy; geothermal energy; and biomass, which includes the combustion of timber from live trees. By analyzing the numbers in the two tables, one will draw the following conclusions:

1. Despite all the conservation measures that were adopted in the recent past, the TPES consumption is continuously increasing and is not expected to decrease

in the near future. Under the reference scenario, the expected compound annual growth rate of TPES consumption is 1.75% and under the more restrictive 450 policy scenario this annual growth rate is 0.9%.
2. Given that the 2010 TPES consumption in the OECD countries is approximately 230 Quads, it is apparent that the expected TPES consumption in these countries will remain almost constant between now and 2030. The consumption will slightly increase to 250 Quads under the reference scenario or will slightly decrease to 222 quads under the more restrictive 450-PS scenario. Most of the increase of the TPES consumption is expected to occur in the Other Major Economies (OME) and, to a lesser extent, in the rest of the world. The OME are expected to surpass the OECD countries in TPES consumption by 2030.
3. Comparing the 2030-RS and the more restrictive 450-PS scenario, the majority of relative TPES savings are expected to come from the OME countries (22%). This is expected to occur from the reduction of the rate of growth of TPES consumption in the OME countries. The OECD reduction will be only 11% and the reduction in the rest of the world will be 7%.[10] Given this disparity in the burden of efficiency and conservation, the current rates of economic and population growth in the OME countries, and the current political realities, it is rather unlikely that the OME countries will consent to adopt such an international treaty or scenario.
4. The fossil fuels, coal, petroleum and gas, are still expected to provide the bulk of the energy demand, even under the 450-PS.
5. If the 450-PS restrictions or similar restrictions are adopted, the use of nuclear energy and renewable energy is expected to increase significantly. The fractional contributions of both are expected to double in comparison to the reference scenario contributions. The use of hydroelectric energy is not expected to double, primarily because the best and most significant hydroelectric resources have already been utilized or are expected to have been utilized by 2030 under the reference scenario.

1.3.1 Energy Reserves and Resources

The fossil fuels, coal, natural gas and petroleum are mineral resources, which have been formed eons ago and are currently extracted from the Earth's interior. The current rate of extraction and combustion of the fossil fuels exceeds by far the rate of the replenishment of these resources. Because the mass of the Earth's crust is finite, it is reasonable to deduce that the total amount of the fossil fuels that exist in the crust and may be recoverable must be finite too. With the continuous and

[10] Such assumptions do not appear to be acceptable to the OEM countries and may become reasons for not reaching an international agreement on CO_2 stabilization in the future. The OEM countries have repeatedly denounced international accords that do not include significant TPES reductions in the OECD countries.

increasing mining of these finite resources, it is also reasonable to deduce that these resources will be depleted in the near or far future.

Of the total amount of the existing fossil resources, a small fraction is located in known areas and may be extracted economically with the existing technology. The fraction, which may be economically extracted under present conditions, is called the *proven reserves.* Another part of the resources is known to exist, but may not be recovered economically at present. These are the *potential reserves.* If the price of the fuel rises or if a technological breakthrough that lowers the cost of extraction is achieved, potential reserves become proven reserves and are mined economically.

In addition to the reserves, there are also large quantities of the mineral/fuel resources, which are located in the vicinity of the proven and the potential reserves. Such resources have not been fully explored and quantified at present, but, from past experience with mining, it may be reasonably assumed that when they are explored and quantified they will be recovered economically with the currently known technology. These are the *inferred resources.* Finally, there are additional resources that might exist in the crust of the Earth, but have not been discovered yet and may not be extracted economically or with known technology at present. These resources may become available at a future date and they are the *undiscovered* or *hypothetical resources*.

The concepts of *reserves* and *resources* are strongly tied to the technology and economics of mineral extraction. For this reason, their numbers are not fixed by a scientific method. Reports of their quantities fluctuate significantly by year and by nation. When the price of a fuel rises, and technology improves, potential reserves become proven reserves. Inferred or hypothetical resources eventually become proven resources with additional exploration and technological improvements. For example, during the 1960s, most of the oilfields in the North Sea were classified as potential reserves or inferred resources. With the technological advances in offshore exploration, drilling and oil production as well as with the significant increase of crude oil prices during the 1970s, these reserves became economical to be exploited and were promoted to proven reserves. By 2000, most of these potential reserves have yielded oil-producing fields. Similarly, the technological advances of the 1990s that allowed deep sea drilling operations resulted in the promotion of several off-shore oilfields in the Gulf of Mexico from resources to proven reserves.

Because of the strong dependence of the reserves and resources on the current technology and prices, and because the quantities of the reserves suffer from a great deal of uncertainty, reports on them fluctuate significantly and are not scientifically reliable. An additional source of uncertainty stems from inaccuracies of national governments in reporting their energy reserves and resources: Some governments or governmental agencies deliberately under-report or underestimate their national resources, while others over-estimate them.[11]

[11] Over-reporting or reporting very optimistic estimates was prevalent until the 1990 s in the former Soviet Union and the Eastern European nations. This gave an inaccurate picture of the global reserves in the 1970 and 1980 s.

1.3.2 The Finite Life of a Resource

All mineral resources including fossil energy resources exist in the crust of the Earth in finite amounts. The molecules and the total quantities of coal, petroleum and natural gas are finite. It is self-evident that, if we continue to mine them and use them for the production of energy, these fossil fuels will be exhausted at some point in the future. Therefore, the question for a society, which overwhelmingly relies on the fossil fuel resources for the production of its energy, is not *if the resources will be exhausted* but *when the resources will be exhausted.* One of the mitigating and rather fortunate factors for the human society is that, since 1950, with the advances of technology and the intensified exploration in all the Continents, new mineral energy resources have been discovered and many of these resources have been mined and exploited. Among these are the near-surface coal deposits in Wyoming, USA, the oil deposits of Alaska and the North Sea. The discovery, development and exploitation of these natural resources has contributed to the lower nominal and real prices of energy resources during the 1980 and 1990s and to the dramatic rise in the consumption of fossil fuels in the first decade of the twenty-first century, which is apparent in Table 1.2. However, it is also apparent that, since the fossil fuel resources are finite, they will be exhausted in the future.

The increasing rate of fossil fuel consumption, if continued unchecked, will accelerate the depletion of these energy resources. Figure 1.9 depicts schematically this depletion scenario. The figure pertains to a hypothetical resource of finite total amount, equal to 32,000 units. This resource was consumed at an annual rate of 10 units from the beginning of the industrial revolution to 1850; at a rate of 20 units from 1850 to 1900; and at a rate of 30 units from 1900 to 1950. From that point in time onwards, the consumption of the hypothetical resource doubles every 20 years (the global crude oil consumption has followed similar trends in the past). The calculations and the figure show that, because of the continuing increase in the consumption, this finite resource is going to be exhausted by 2110. Although this resource and the consumption scenario are hypothetical, it becomes apparent from Fig. 1.9 that:

(a) The most significant drop in the proven reserves of this resource occurs in the last 20 years of its use; and
(b) In 2090, 20 years before the depletion of this resource, one may observe that there is still as much of this resource available for consumption (16,080 units) as it was consumed in the past 240 years. Thus, twenty years before the depletion of the resource, a society may be lulled into a false sense of security by statements such as "…we have as much of this resource left as we have consumed in the last two-and-a-half centuries." When the potential of an energy resource is to be evaluated, it is the current and future consumption of the resource that matter and not the past history of utilization of the resource.

The *lifetime* of a resource is often used as a measure of the time in the future when the resource will be exhausted. This lifetime depends on the total amount of

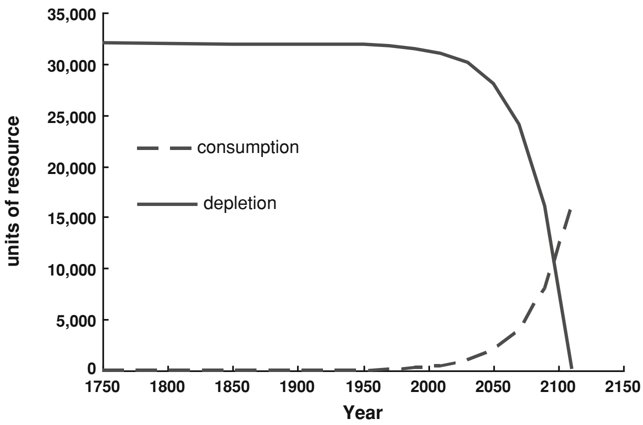


Fig. 1.9 The life cycle of a hypothetical energy resource, whose consumption doubles every 20 years since 1950

the reserves of the resource, M_T, as well as the annual consumption of the resource, M_A. In the simple case when the consumption of the resource is constant, the lifetime of the reserves, T, is simply equal to the ratio M_T/M_A. In most cases though, the consumption of the resources grows at an annual rate, r. In this case of growing consumption, the lifetime of the resource, in years, may be calculated from the following expression:

$$T = \frac{1}{r}\ln\left[r\frac{M_T}{M_A} + 1\right]. \tag{1.3}$$

Predictions for the lifetime of several fossil fuel resources have been made using this expression. A glance in the predictions of the past fifty years, however, proves that these predictions have been inaccurate.[12] The main reason for this is that the total reserves, M_T, is actually a variable that is adjusted upwards as potential reserves and inferred or hypothetical resources are promoted to reserves.

1.3.3 *The Hubbert Curve and the Hubbert Peak*

The life cycle and the consumption of actual energy resources may somehow differ from the trends shown in Fig. 1.9 because of price adjustments, new discoveries and technological breakthroughs. According to a theory, which is frequently

[12] For example, during the energy crisis of the 1970 s there was an almost unanimous belief by the "experts," which was promulgated in the popular press, that the lifetime of the petroleum reserves was 30–35 years and that, hence, petroleum would have been almost exhausted by 2015. The same "experts" were predicting $12 per gallon of gasoline in the USA by 2010.

referenced in the popular press, the life cycle of a resource should have the shape of a curve that approximates the *bell-shaped curve.* This curve is sometimes called the *Hubbert curve* [1, 2] and its functional form is:

$$y = \frac{e^{-t}}{(1 + e^{-t})^2} = \frac{1}{2(1 + \cosh t))}, \tag{1.4}$$

where t is the time and y the normalized fraction of the resource that is consumed. The shape of this curve is bell-shaped. It is apparent that the Hubbert curve is not a Gaussian, but its shape has a similar form and approaches zero more slowly than a Gaussian curve. According to Hubbert's theory, during the first stages of the utilization of any resource, its consumption rises exponentially because it is accelerated by two factors:

1. Relatively low nominal price.
2. New technologies and new uses are developed for this resource to perform several societal functions and tasks that were accomplished using another resource before. This increases significantly the demand and consumption of the resource.

At the initial stages of the utilization of the resource, there is an increasing growth in its consumption. During the first stages of its consumption the resource is defined as a *new* or *emerging resource.*

It is well known that, given the finite amount of all materials and resources, an exponential growth in the consumption of any commodity cannot be indefinitely sustained. This ushers the second stage of the growth in the consumption of the resource. The rate of growth of the consumption slows down because of two other factors:

1. There are no more new applications that make use of this resource.
2. The price of the resource increases significantly because of profit-taking and because of the realization that the resource may be depleted and may become more valuable in the future.

Following the slowing of the rate of growth, the resource becomes a *mature resource* and its consumption is governed by its price, which is determined by demand and supply. The total production and consumption of the resource starts decreasing during this stage, depending on the price level. Thus, the production of all resources passes through a maximum, which is often called *Hubbert peak.*

The third stage in the theoretical life-cycle of the energy resource occurs when there is a realization that there are few reserves of the resource left. At this point, the resource is classified as a *rare* or *depleting resource.* After this stage, the real and nominal prices of the resource rise continuously and significantly. The widespread use of the resource becomes uneconomical and new technologies are developed to substitute this resource with other, more abundant, longer lasting, more secure and more affordable resources. The immediate consequence of this *substitution effect,* which is driven by the commodity's price increase, is that the consumption of the resource slows down and finally diminishes when the resource is about to be depleted.

An example of the life cycle of an energy resource in the United States is the production and consumption of natural gas. The production and consumption of this energy resource was very low at the beginning of the twentieth century. Discoveries of several large deposits of natural gas were made in the beginning of that century and several applications of this energy resource were invented and adopted. The development of a national distribution network of pipelines for natural gas brought this resource into the major urban centers, thus, reaching new consumers and creating high demand. Natural gas substituted coal and wood for domestic heating and cooking in most of the USA cities during the first half of the twenty first century. Gas turbines were invented and natural gas started being used in gas turbines for the production of electricity, again substituting coal and petroleum products. The driving force behind this substitution was the relatively low price of the resource, the relative safety, the wide availability and the significant convenience of its use. The further development and optimization of the distribution network across the country made this energy resource widely available to the American consumer. As a result, the use of natural gas increased almost exponentially in the first seventy years of the twenty-first century, from 23 billion scf in 1900 to more than 20 trillion scf in 1970 (1 scf of gas provides approximately 10^6 J).

Following this initial growth period, during the energy crisis of the 1970s, the real price of natural gas started increasing continuously, even though several new discoveries of natural gas were made. In addition, no new domestic applications for the use of natural gas were adopted, because most of the households in the USA already were using gas for heating, hot water supply and cooking. As a result, the rate of growth of production and consumption of this resource diminished and actually became slightly negative. The consumption of natural gas slightly decreased, between 1978 and 1990, when energy conservation and the use of relatively cheap electricity substituted for the use of natural gas in some households. Between 1990 and 2010, the price of the natural gas fluctuated significantly and its consumption also fluctuated, largely following the price and the increase of the population in the USA. One reason behind these fluctuations is the relatively ease of substitution of natural gas by other energy forms, especially electricity. Thus, between 1970 and 2010, the demand of natural gas in the USA has followed its price in an inverse manner. It may be said that the natural gas consumption in the USA follows the trend of a *mature resource.*

Figure 1.10 depicts the consumption of natural gas in the USA and shows the trends that were described above. The figure also depicts a *Hubbert curve* that best fits the scenario of gas production and consumption. It is observed that in the early stages of the development of this energy resource, the production followed rather faithfully the shape of the *Hubbert curve.* However, after the peak production was reached in the 1970s, there has been a significant diversion from this analytical

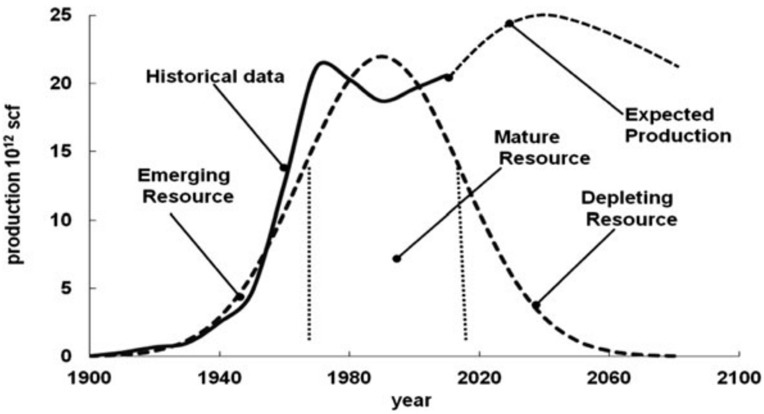


Fig. 1.10 The Hubbert curve life cycle of an energy resource (*bell*-shaped curve) and the production of natural gas in the USA

shape. The actual natural gas consumption in the USA decreased temporarily and then increased again, fueled by new domestic discoveries, such as the Barnett field in Texas, and the significant increase of new family house construction between 1995 and 2008. In addition, liquefaction of natural gas, which is abundant abroad, has made possible the transoceanic transportation of this resource. These imports have also provided additional, albeit limited, supplies of natural gas in the USA market. The figure shows that a local maximum was reached in the 1970s followed by a local minimum in the early 1990s and a continuous but slow consumption increase since then. The more recent discoveries of vast natural gas resources in several regions from the East Coast to the Tennessee Valley in the USA are expected to keep prices low and to further increase the consumption of natural gas in the United States. The expected production part of the curve from 2010 to 2100 reflects these recent resource discoveries and the reaction of the consumers to the expected stable price of natural gas in the USA.

It is also observed in Fig. 1.10 that, neither the curve obtained by the actual data until 2010 nor its extension with the expected production fit well with the entire *Hubbert curve* and, especially, with the rather sharp and well defined *Hubbert peak.* The actual consumption of natural gas in the USA seems to have reached a plateau close to $20*10^{12}$ scf per year. What is more important for the comparison of the two curves is that the demand for natural gas does not show any signs of sharp reduction as the *Hubbert curve* predicts. The main reason for this trend is the new exploration and drilling activities that resulted in the development of new natural gas fields. The more recent discovery of additional resources in the middle of the country indicates that the price of the natural gas will not rise dramatically so as to discourage demand in the foreseeable future. The trends indicate that the natural gas production will stay at the approximately same level in the near future, rather than show a sharp maximum and a significant, sharp reduction as the *Hubbert curve* predicts. Therefore, based on the recent natural gas production data, there is no clear evidence that a well-defined *Hubbert peak* exists in the consumption of natural gas.

The crude oil consumption in the Unites States follows a similar pattern. The domestic production of oil in the USA shows that a maximum was reached in the 1980s and that this production has been decreasing since that decade. However, the consumption of petroleum and liquid hydrocarbons in the USA continued to increase as the domestic production and the increased demand was satisfied by relatively cheap petroleum imports from the Middle East and the South American countries. Even though the domestic production of petroleum in the USA has decreased since the 1980s, this decrease has been gradual and does not fit well to a *Hubbert curve*. The offshore oil production in the Gulf of Mexico and the opening of the Alaska oilfields has contributed to the flattening of the domestic oil production curve. In addition, imports have contributed to an ever-increasing demand for petroleum in the USA. Actually, Hubbert [1] predicted that the domestic petroleum production will peak in the 1970s and that petroleum will be substituted by nuclear power. While the first part may be partly correct, the second prediction was proven to be wrong.

It must be emphasized that the *Hubbert curve* and the *Hubbert peak* are not part of a physical law, which has universal validity, but only a hypothesis that was promulgated in the 1960s and is based on the limited data at the time. While the early part in the consumption of energy resources may be well approximated by this curve, all the empirical data we have collected since the 1980s show that the consumption of natural resources does not follow this curve. In particular, the *Hubbert peak* does not exist as a sharp and well defined maximum, beyond which a substitute must be found for the resource. Instead, the production and consumption curves of the resource reach a rather flat level and fluctuate close to this level. Price adjustments and technological advances in exploration and production make possible the augmentation of the resources and the addition to the proven reserves. In addition, the ease of transportation and the worldwide trade of primary energy sources have made possible the almost continuous supply of energy resources in the world economies. For this reason all the predictions for future production, consumption and pricing that have been made in the past, based on the existence of a *Hubbert peak* have proven to be unreliable. As with all predictions about the future, future energy production and, especially, future energy prices may not be forecasted with any degree of certainty. Based on the existence of a finite quantity of fossil fuels, what is certain is that *eventually* the fossil fuels will be exhausted. However, at present, science cannot tell us with any degree of certainty, when in the future and in what way the depletion of the fossil fuels will occur.

1.4 Concluding Remarks

The supply of sufficient energy has become very important to the affluence of nations and the well-being of the global society. Securing energy supplies for the present and the future has become a prime consideration of all the governments and plays an important role in regional and global political considerations. Energy sources have become prime commodities, on which economic growth and national prosperity are based. The control of vital energy supplies becomes the principal reason for regional conflicts and wars. Because of this, the subject of alternative energy sources is not simply technological, but also extends into areas of economics, history, political science and public policy. As a result, a great deal of complexity and a certain degree of mystery surround the subject of energy. Other factors that make this subject complex and multifaceted are: the multitude of the scientific units that have been used; the significant price fluctuations of the primary and secondary energy sources; the discovery of new resources; and the unpredictability of future supplies.

While simple predictions on the energy production and prices, such as the *Hubbert curve,* are not reliable, it is certain that at some point in the future—very likely the far future—the fossil fuels, which now satisfy more than 80% of the world primary energy demand, will be exhausted. Alternative energy sources, which include nuclear energy, will have to substitute the fossil fuel consumption and provide the human society with sufficient energy to maintain the desired standards of living. In addition, societal concerns about global climate change may impose regulatory limitations on the consumption of fossil fuels in the near future. For this reason it is very important to know: what are the alternative energy sources that may be harnessed with the current technology; what are the engineering systems that will harness this energy; how the alternative energy sources may satisfy the energy demand of the human society; and what is the potential of these sources to supply energy on a large scale.

This book provides the means to understand the scientific principles of energy conversion and the operation of the technical systems that are employed for the harnessing of all the currently known alternative energy sources. The students of the book will become familiar with the governing principles for the harnessing of alternative energy sources and will be able to apply this knowledge to conduct feasibility studies and to design engineering systems in order to make the best use of these energy resources. At the same time, the students will become familiar with the political, social and economic issues that surround the use of alternative energy sources and the global climatic change and will be able to participate as experts in the ongoing societal debates related to these issues.

Problems

1. Convert to Btu the following quantities: 300 kWh; 450 bbl of oil; 25 scf of natural gas.
2. Convert to MJ the following: 500 MeV; 15 Therm; 15 tce.
3. What was the energy demand in your country in 2010 and which primary sources supplied the demand?
4. How much was the electricity production in your country in 2009 and which primary energy resources produced it?

5. The GDP of the Peoples Republic of China is expected to increase by an average rate of 9.7% in the next ten years. What is expected to be the corresponding increase of the rate of electricity consumption?
6. How many kWh of energy were produced in 2007 from solar, wind and geothermal energy? How do these compare to the energy from coal?
7. Oil sands abound in several provinces of Canada. Oil sands contain bitumen, trapped in the sandstone. The best oil sand resources contain close to 0.7 bbl of oil per ton of sand. One method of extracting this resource is to inject high temperature steam or carbon dioxide into the oil reservoir to liquefy the bitumen and bring it to the surface in a pipeline. The heat capacity of the sandstone is 1.1 kJ/kgK. The sand and bitumen are heated from 45 to 250°C for the bitumen to melt and flow into the pipeline. Assuming that all the heat supplied to the extracted bitumen part is recovered at the wellhead, how much heat must be supplied to the sandstone for this process? What percentage of the heating value of the extracted oil does this represent?
8. What is the projected demand for oil, in bbl, in 2030 according to the RS-2030 and 450-PS-2030? Based on your knowledge of oil consumption, suggest four systems or methods that will result in decreasing the future oil energy demand.
9. "Based on the average oil demand of the last hundred years, we have enough petroleum reserves to last us for another three centuries." Comment in an essay of 300–350 words.
10. The world total coal reserves (adjusted for the heating value of the various types of coal) are estimated to be approximately 10^{12} tons. The current annual consumption rate is $6.62*10^9$ tons and the consumption of coal increases by 0.85% per year. Estimate the lifetime of this resource.
11. The world's petroleum reserves are approximately $1.7*10^{12}$ bbl. From outside sources obtain the current global consumption of petroleum and its average rate of growth in the last five years. Based on these, calculate the lifetime of petroleum reserves.

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