CHAPTER

Introduction

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1.1 General introduction to renewable energy technologies

The sun is the only star of our solar system located at its center. The earth and other planets orbit the sun. Energy from the sun in the form of solar radiation supports almost all life on earth via photosynthesis and drives the earth's climate and weather.

About 74% of the sun's mass is hydrogen, 25% is helium, and the rest is made up of trace quantities of heavier elements. The sun has a surface temperature of approximately 5500 K, giving it a white color, which, because of atmospheric scattering, appears yellow. The sun generates its energy by nuclear fusion of hydrogen nuclei to helium. Sunlight is the main source of energy to the surface of the earth that can be harnessed via a variety of natural and synthetic processes. The most important is photosynthesis, used by plants to capture the energy of solar radiation and convert it to chemical form. Generally, photosynthesis is the synthesis of glucose from sunlight, carbon dioxide, and water, with oxygen as a waste product. It is arguably the most important known biochemical pathway, and nearly all life on earth depends on it.

Basically all the forms of energy in the world as we know it are solar in origin. Oil, coal, natural gas, and wood were originally produced by photosynthetic processes, followed by complex chemical reactions in which decaying vegetation was subjected to very high temperatures and pressures over a long period of time. Even the energy of the wind and tide has a solar origin, since they are caused by differences in temperature in various regions of the earth.

Since prehistory, the sun has dried and preserved humankind's food. It has also evaporated seawater to yield salt. Since humans began to reason, they have recognized the sun as a motive power behind every natural phenomenon. This is why many of the prehistoric tribes considered the sun as a god. Many scripts of ancient Egypt say that the Great Pyramid, one of humankind's greatest engineering achievements, was built as a stairway to the sun (Anderson, 1977).

From prehistoric times, people realized that a good use of solar energy is beneficial. The Greek historian Xenophon in his "memorabilia" records some of the teachings of the Greek philosopher Socrates (470–399 BC) regarding the correct orientation of dwellings to have houses that were cool in summer and warm in winter.

The greatest advantage of solar energy compared with other forms of energy is that it is clean and can be supplied without environmental pollution. Over the past century, fossil fuels provided most of our energy, because these were much cheaper and more convenient than energy from alternative energy sources, and until recently, environmental pollution has been of little concern.

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Twelve autumn days of 1973, after the Egyptian army stormed across the Suez Canal on October 12, changed the economic relation of fuel and energy as, for the first time, an international crisis was created over the threat of the “oil weapon” being used as part of Arab strategy. Both the price and the political weapon issues were quickly materialized when the six Gulf members of the Organization of Petroleum Exporting Countries (OPEC) met in Kuwait and abandoned the idea of holding any more price consultations with the oil companies, announcing at the same time that they were raising the price of their crude oil by 70%.

The rapid increase in oil demand occurred mainly because increasing quantities of oil, produced at very low cost, became available during the 1950s and 1960s from the Middle East and North Africa. For the consuming countries, imported oil was cheap compared with indigenously produced energy from solid fuels.

The proven world oil reserves are equal to 1341 billion barrels (2009), the world coal reserves are 948,000 million tons (2008), and the world natural gas reserves are 178.3 trillion m^3 (2009). The current production rate is equal to 87.4 million barrels per day for oil, 21.9 million tons per day for coal and 9.05 billion m^3 per day for natural gas. Therefore, the main problem is that proven reserves of oil and gas, at current rates of consumption, would be adequate to meet demand for only another 42 and 54 years, respectively. The reserves for coal are in a better situation; they would be adequate for at least the next 120 years.

If we try to see the implications of these limited reserves, we are faced with a situation in which the price of fuels will accelerate as the reserves are decreased. Considering that the price of oil has become firmly established as the price leader for all fuel prices, the conclusion is that energy prices will increase continuously over the next decades. In addition, there is growing concern about the environmental pollution caused by burning fossil fuels. This issue is examined in Section 1.3.

The sun’s energy has been used by both nature and humankind throughout time in thousands of ways, from growing food to drying clothes; it has also been deliberately harnessed to perform a number of other jobs. Solar energy is used to heat and cool buildings (both actively and passively), heat water for domestic and industrial uses, heat swimming pools, power refrigerators, operate engines and pumps, desalinate water for drinking purposes, generate electricity, for chemistry applications, and many more operations. The objective of this book is to present various types of systems used to harness solar energy, their engineering details, and ways to design them, together with some examples and case studies.

1.2 Energy demand and renewable energy

Many alternative energy sources can be used instead of fossil fuels. The decision as to what type of energy source should be utilized in each case must be made on the basis of economic, environmental, and safety considerations. Because of the desirable environmental and safety aspects it is widely believed that solar energy should be utilized instead of other alternative energy forms because it can be provided sustainably without harming the environment.

If the world economy expands to meet the expectations of countries around the globe, energy demand is likely to increase, even if laborious efforts are made to increase the energy use efficiency. It is now generally believed that renewable energy technologies can meet much of the growing demand at prices that are equal to or lower than those usually forecast for conventional energy. By the middle of the twenty-first century, renewable sources of energy could account for three-fifths of the world's electricity market and two-fifths of the market for fuels used directly.[1] Moreover, making a transition to a renewable energy-intensive economy would provide environmental and other benefits not measured in standard economic terms. It is envisaged that by 2050 global carbon dioxide (CO_2) emissions would be reduced to 75% of their levels in 1985, provided that energy efficiency and renewables are widely adopted. In addition, such benefits could be achieved at no additional cost, because renewable energy is expected to be competitive with conventional energy (Johanson et al., 1993).

This promising outlook for renewables reflects impressive technical gains made during the past two decades as renewable energy systems benefited from developments in electronics, biotechnology, material sciences, and in other areas. For example, fuel cells developed originally for the space program opened the door to the use of hydrogen as a non-polluting fuel for transportation.

Moreover, because the size of most renewable energy equipment is small, renewable energy technologies can advance at a faster pace than conventional technologies. While large energy facilities require extensive construction in the field, most renewable energy equipment can be constructed in factories, where it is easier to apply modern manufacturing techniques that facilitate cost reduction. This is a decisive parameter that the renewable energy industry must consider in an attempt to reduce cost and increase the reliability of manufactured goods. The small scale of the equipment also makes the time required from initial design to operation short; therefore, any improvements can be easily identified and incorporated quickly into modified designs or processes.

According to the renewable energy-intensive scenario, the contribution of intermittent renewables by the middle of this century could be as high as 30% (Johanson et al., 1993). A high rate of penetration by intermittent renewables without energy storage would be facilitated by emphasis on advanced natural gas-fired turbine power-generating systems. Such power-generating systems—characterized by low capital cost, high thermodynamic efficiency, and the flexibility to vary electrical output quickly in response to changes in the output of intermittent power-generating systems—would make it possible to backup the intermittent renewables at low cost, with little, if any, need for energy storage.

The key elements of a renewable energy-intensive future are likely to have the following key characteristics (Johanson et al., 1993):

1. There would be a diversity of energy sources, the relative abundance of which would vary from region to region. For example, electricity could be provided by various combinations of hydroelectric power, intermittent renewable power sources (wind, solar thermal electric, and photovoltaic (PV)), biomass,[2] and geothermal sources. Fuels could be provided by methanol, ethanol, hydrogen, and methane (biogas) derived from biomass, supplemented with hydrogen derived electrolytically from intermittent renewables.

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[1] This is according to a renewable energy-intensive scenario that would satisfy energy demands associated with an eightfold increase in economic output for the world by the middle of the twenty-first century. In the scenario considered, world energy demand continues to grow in spite of a rapid increase in energy efficiency.

[2] The term *biomass* refers to any plant matter used directly as fuel or converted into fluid fuel or electricity. Biomass can be produced from a wide variety of sources such as wastes of agricultural and forest product operations as well as wood, sugarcane, and other plants grown specifically as energy crops.

2. Emphasis would be given to the efficient mixing of renewable and conventional energy supplies. This can be achieved with the introduction of energy carriers such as methanol and hydrogen. It is also possible to extract more useful energy from such renewable resources as hydropower and biomass, which are limited by environmental or land-use constraints. Most methanol exports could originate in sub-Saharan Africa and Latin America, where vast degraded areas are suitable for revegetation that will not be needed for cropland. Growing biomass on such lands for methanol or hydrogen production could provide a powerful economic driver for restoring these lands. Solar-electric hydrogen exports could come from the regions in North Africa and the Middle East that have good insolation.
3. Biomass would be widely used. Biomass would be grown sustainably and converted efficiently to electricity and liquid and gaseous fuels using modern technology without contributing to deforestation.
4. Intermittent renewables would provide a large quantity of the total electricity requirements cost-effectively, without the need for new electrical storage technologies.
5. Natural gas would play a major role in supporting the growth of a renewable energy industry. Natural gas-fired turbines, which have low capital costs and can quickly adjust their electrical output, can provide excellent backup for intermittent renewables on electric power grids. Natural gas would also help launch a biomass-based methanol industry.
6. A renewables-intensive energy future would introduce new choices and competition in energy markets. Growing trade in renewable fuels and natural gas would diversify the mix of suppliers and the products traded, which would increase competition and reduce the possibility of rapid price fluctuations and supply disruptions. This could also lead eventually to a stabilization of world energy prices with the creation of new opportunities for energy suppliers.
7. Most electricity produced from renewable sources would be fed into large electrical grids and marketed by electric utilities, without the need for electrical storage.

A renewable energy-intensive future is technically feasible, and the prospects are very good that a wide range of renewable energy technologies will become competitive with conventional sources of energy in a few years' time. However, to achieve such penetration of renewables, existing market conditions need to change. If the following problems are not addressed, renewable energy will enter the market relatively slowly:

- Private companies are unlikely to make the investments necessary to develop renewable technologies because the benefits are distant and not easily captured.
- Private firms will not invest in large volumes of commercially available renewable energy technologies because renewable energy costs will usually not be significantly lower than the costs of conventional energy.
- The private sector will not invest in commercially available technologies to the extent justified by the external benefits that would arise from their widespread deployment.

Fortunately, the policies needed to achieve the goals of increasing efficiency and expanding renewable energy markets are fully consistent with programs needed to encourage innovation and productivity growth throughout the economy. Given the right policy environment, energy industries will adopt innovations, driven by the same competitive pressures that revitalized other major manufacturing businesses around the world. Electric utilities have already shifted from being protected monopolies, enjoying economies of scale in large generating plants, to being competitive managers of investment portfolios that combine a diverse set of technologies, ranging from advanced generation, transmission, distribution, and storage equipment to efficient energy-using devices on customers' premises.

Capturing the potential for renewables requires new policy initiatives. The following policy initiatives are proposed by Johanson et al. (1993) to encourage innovation and investment in renewable technologies:

1. Subsidies that artificially reduce the price of fuels that compete with renewables should be removed or renewable energy technologies should be given equivalent incentives.
2. Taxes, regulations, and other policy instruments should ensure that consumer decisions are based on the full cost of energy, including environmental and other external costs not reflected in market prices.
3. Government support for research, development, and demonstration of renewable energy technologies should be increased to reflect the critical roles renewable energy technologies can play in meeting energy and environmental objectives.
4. Government regulations of electric utilities should be carefully reviewed to ensure that investments in new generating equipment are consistent with a renewables-intensive future and that utilities are involved in programs to demonstrate new renewable energy technologies.
5. Policies designed to encourage the development of the biofuels industry must be closely coordinated with both national agricultural development programs and efforts to restore degraded lands.
6. National institutions should be created or strengthened to implement renewable energy programs.
7. International development funds available for the energy sector should be increasingly directed to renewables.
8. A strong international institution should be created to assist and coordinate national and regional programs for increased use of renewables, support the assessment of energy options, and support centers of excellence in specialized areas of renewable energy research.

The integrating theme for all such initiatives, however, should be an energy policy aimed at promoting sustainable development. It will not be possible to provide the energy needed to bring a decent standard of living to the world's poor or sustain the economic well-being of the industrialized countries in environmentally acceptable ways if the use of present energy sources continues. The path to a sustainable society requires more efficient energy use and a shift to a variety of renewable energy sources. Generally, the central challenge to policy makers in the next few decades is to develop economic policies that simultaneously satisfy both socioeconomic developmental and environmental challenges.

Such policies could be implemented in many ways. The preferred policy instruments will vary with the level of the initiative (local, national, or international) and the region. On a regional level, the preferred options will reflect differences in endowments of renewable resources, stages of economic development, and cultural characteristics. Here the region can be an entire continent. One example of this is the declaration of the European Union (EU) for the promotion of renewable energies as a key measure to ensure that Europe meets its climate change targets under the Kyoto Protocol.

According to the decision, central to the European Commission's (EC) action to ensure that the EU and member states meet their Kyoto targets is the European Climate Change Programme launched in

2000. Under this umbrella, the Commission, member states, and stakeholders identified and developed a range of cost-effective measures to reduce emissions.

To date, 35 measures have been implemented, including the EU Emissions Trading Scheme and legislative initiatives to promote renewable energy sources for electricity production, to expand the use of biofuels in road transport, and to improve the energy performance of buildings. Previously, the EC proposed an integrated package of measures to establish a new energy policy for Europe that would increase actions to fight climate change and boost energy security and competitiveness in Europe, and the proposals put the EU on course toward becoming a low-carbon economy. The new package sets a range of ambitious targets to be met by 2020, including improvement of energy efficiency by 20%, increasing the market share of renewables to 20%, and increasing the share of biofuels in transport fuels to 10%. On greenhouse gas (GHG) emissions, the EC proposes that, as part of a new global agreement to prevent climate change from reaching dangerous levels, developed countries should reduce their emissions by an average of 30% from 1990 levels.

As a concrete first step toward this reduction, the EU would make a firm independent commitment to cut its emissions by at least 20% even before a global agreement is reached and irrespective of what others do.

Many scenarios describe how renewable energy will develop in coming years. In a renewable energy-intensive scenario, global consumption of renewable resources reaches a level equivalent to 318 EJ (exa, $E = 10^{18}$) per annum (a) of fossil fuels by 2050—a rate comparable with the 1985 total world energy consumption, which was equal to 323 EJ. Although this figure seems to be very large, it is less than 0.01% of the 3.8 million EJ of solar energy reaching the earth's surface each year. The total electric energy produced from intermittent renewable sources ($\sim$34 EJ/a) would be less than 0.003% of the sunlight that falls on land and less than 0.1% of the energy available from wind. The amount of energy targeted for recovery from biomass could reach 206 EJ/a by 2050, which is also small compared with the rate (3800 EJ/a) at which plants convert solar energy to biomass. The production levels considered are therefore not likely to be constrained by resource availability. A number of other practical considerations, however, do limit the renewable resources that can be used. The renewable energy-intensive scenario considers that biomass would be produced sustainably, not harvested in virgin forests. About 60% of the biomass supply would come from plantations established on degraded land or excess agricultural land and the rest from residues of agricultural or forestry operations. Finally, the amounts of wind, solar thermal, and PV power that can be economically integrated into electric generating systems are very sensitive to patterns of electricity demand and weather conditions. The marginal value of these intermittent electricity sources typically declines as their share of the total electric market increases.

By making efficient use of energy and expanding the use of renewable technologies, the world can expect to have adequate supplies of fossil fuels well into the twenty-first century. However, in some instances regional declines in fossil fuel production can be expected because of resource constraints. Oil production outside the Middle East would decline slowly under the renewables-intensive scenario, so that one-third of the estimated ultimately recoverable conventional resources will remain in the ground in 2050. Under this scenario, the total world conventional oil resources would decline from about 9900 EJ in 1988 to 4300 EJ in 2050. Although remaining conventional natural gas resources are comparable with those for conventional oil, with an adequate investment in pipelines and other infrastructure components, natural gas could be a major energy source for many years.

The next section reviews some of the most important environmental consequences of using conventional forms of energy. This is followed by a review of renewable energy technologies not included in this book.

1.3 Energy-related environmental problems

Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. The importance of energy in economic development is recognized universally and historical data verify that there is a strong relationship between the availability of energy and economic activity. Although in the early 1970s, after the oil crisis, the concern was on the cost of energy, during the past two decades the risk and reality of environmental degradation have become more apparent. The growing evidence of environmental problems is due to a combination of several factors since the environmental impact of human activities has grown dramatically. This is due to the increase of the world population, energy consumption, and industrial activity. Achieving solutions to the environmental problems that humanity faces today requires long-term potential actions for sustainable development. In this respect, renewable energy resources appear to be one of the most efficient and effective solutions.

A few years ago, most environmental analysis and legal control instruments concentrated on conventional pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulates, and carbon monoxide (CO). Recently, however, environmental concern has extended to the control of hazardous air pollutants, which are usually toxic chemical substances harmful even in small doses, as well as to other globally significant pollutants such as carbon dioxide (CO_2). Additionally, developments in industrial processes and structures have led to new environmental problems. Carbon dioxide as a GHG plays a vital role in global warming. Studies show that it is responsible for about two-thirds of the enhanced greenhouse effect. A significant contribution to the CO_2 emitted to the atmosphere is attributed to fossil fuel combustion (EPA, 2007).

The United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro, Brazil, in June 1992, addressed the challenges of achieving worldwide sustainable development. The goal of sustainable development cannot be realized without major changes in the world's energy system. Accordingly, Agenda 21, which was adopted by UNCED, called for "new policies or programs, as appropriate, to increase the contribution of environmentally safe and sound and cost-effective energy systems, particularly new and renewable ones, through less polluting and more efficient energy production, transmission, distribution, and use".

The division for sustainable development of the United Nations Department of Economics and Social Affairs defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Agenda 21, the *Rio Declaration on Environment and Development*, was adopted by 178 governments. This is a comprehensive plan of action to be taken globally, nationally, and locally by organizations of the United Nations system, governments, and major groups in every area in which there are human impacts on the environment (United Nations, 1992). Many factors can help to achieve sustainable development. Today, one of the main factors that must be considered is energy and one of the most important issues is the requirement for a supply of energy that is fully sustainable (Rosen, 1996; Dincer and Rosen, 1998). A secure supply of energy is generally agreed to be a necessary but not a sufficient requirement for development within a society. Furthermore, for a sustainable development within a society, it is required that a sustainable supply of energy and an effective and efficient utilization of energy resources are secure. Such a supply in the long term should be readily available at reasonable cost, sustainable, and able to be utilized for all the required tasks without causing negative societal impacts. This is the reason why there is a close connection between renewable sources of energy and sustainable development.

Sustainable development is a serious policy concept. In addition to the definition just given, it can be considered as a development that must not carry the seeds of destruction, because such a development is unsustainable. The concept of sustainability has its origin in fisheries and forest management in which prevailing management practices, such as overfishing or single-species cultivation, work for limited time, then yield diminishing results and eventually endanger the resource. Therefore, sustainable management practices should not aim for maximum yield in the short run but for smaller yields that can be sustained over time.

Pollution depends on energy consumption. In 2011, the world daily oil consumption is 87.4 million barrels. Despite the well-known consequences of fossil fuel combustion on the environment, this is expected to increase to 123 million barrels per day by the year 2025 (Worldwatch, 2007). A large number of factors are significant in the determination of the future level of energy consumption and production. Such factors include population growth, economic performance, consumer tastes, and technological developments. Furthermore, government policies concerning energy and developments in the world energy markets certainly play a key role in the future level and pattern of energy production and consumption (Dincer, 1999).

In 1984, 25% of the world population consumed 70% of the total energy supply, while the remaining 75% of the population was left with 30%. If the total population were to have the same consumption per inhabitant as the Organization for Economic Cooperation and Development member countries have on average, it would result in an increase in the 1984 world energy demand from 10 TW (tera, $T = 10^{12}$) to approximately 30 TW. An expected increase in the population from 4.7 billion in 1984 to 8.2 billion in 2020 would raise the figure to 50 TW.

The total primary energy demand in the world increased from 5536 GTOE[3] in 1971 to 11,235 GTOE in 2007, representing an average annual increase of about 2%. It is important, however, to note that the average worldwide growth from 2001 to 2004 was 3.7%, with the increase from 2003 to 2004 being 4.3%. The rate of growth is rising mainly due to the very rapid growth in Pacific Asia, which recorded an average increase from 2001 to 2004 of 8.6%.

The major sectors using primary energy sources include electrical power, transportation, heating, and industry. The International Energy Agency data shows that the electricity demand almost tripled from 1971 to 2002. This is because electricity is a very convenient form of energy to transport and use. Although primary energy use in all sectors has increased, their relative shares have decreased, except for transportation and electricity. The relative share of primary energy for electricity production in the world increased from about 20% in 1971 to about 30% in 2002 as electricity became the preferred form of energy for all applications.

Fueled by high increases in China and India, worldwide energy consumption may continue to increase at rates between 3% and 5% for at least a few more years. However, such high rates of increase cannot continue for too long. Even at a 2% increase per year, the primary energy demand of 2002

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[3] TOE = Tons of oil equivalent = 41.868 GJ (giga, $G = 10^9$).

would double by 2037 and triple by 2057. With such high energy demand expected 50 years from now, it is important to look at all the available strategies to fulfill the future demand, especially for electricity and transportation.

At present, 95% of all energy for transportation comes from oil. Therefore, the available oil resources and their production rates and prices greatly influence the future changes in transportation. An obvious replacement for oil would be biofuels such as ethanol, methanol, biodiesel, and biogases. It is believed that hydrogen is another alternative because, if it could be produced economically from renewable energy sources, it could provide a clean transportation alternative for the future.

Natural gas will be used at rapidly increasing rates to make up for the shortfall in oil production; however, it may not last much longer than oil itself at higher rates of consumption. Coal is the largest fossil resource available and the most problematic due to environmental concerns. All indications show that coal use will continue to grow for power production around the world because of expected increases in China, India, Australia, and other countries. This, however, would be unsustainable, from the environmental point of view, unless advanced clean coal technologies with carbon sequestration are deployed.

Another parameter to be considered is the world population. This is expected to double by the middle of this century and as economic development will certainly continue to grow, the global demand for energy is expected to increase. For example, the most populous country, China, increased its primary energy consumption by 15% from 2003 to 2004. Today, much evidence exists to suggest that the future of our planet and the generations to come will be negatively affected if humans keep degrading the environment. Currently, three environmental problems are internationally known: acid precipitation, the stratospheric ozone depletion, and global climate change. These issues are analyzed in more detail in the following subsections.

1.3.1 Acid rain

Acid rain is a form of pollution depletion in which SO_2 and NO_x produced by the combustion of fossil fuels are transported over great distances through the atmosphere, where they react with water molecules to produce acids deposited via precipitation on the earth, causing damage to ecosystems that are exceedingly vulnerable to excessive acidity. Therefore, it is obvious that the solution to the issue of acid rain deposition requires an appropriate control of SO_2 and NO_x pollutants. These pollutants cause both regional and transboundary problems of acid precipitation.

Recently, attention also has been given to other substances, such as volatile organic compounds (VOCs), chlorides, ozone, and trace metals that may participate in a complex set of chemical transformations in the atmosphere, resulting in acid precipitation and the formation of other regional air pollutants.

It is well known that some energy-related activities are the major sources of acid precipitation. Additionally, VOCs are generated by a variety of sources and comprise a large number of diverse compounds. Obviously, the more energy we expend, the more we contribute to acid precipitation; therefore, the easiest way to reduce acid precipitation is by reducing energy consumption.

1.3.2 Ozone layer depletion

The ozone present in the stratosphere, at altitudes between 12 and 25 km, plays a natural equilibrium-maintaining role for the earth through absorption of ultraviolet (UV) radiation (240–320 nm) and absorption of infrared radiation (Dincer, 1998). A global environmental problem is the depletion of the stratospheric ozone layer, which is caused by the emissions of chlorofluorocarbons (CFCs), halons (chlorinated and brominated organic compounds), and NO_x. Ozone depletion can lead to increased levels of damaging UV radiation reaching the ground, causing increased rates of skin cancer and eye damage to humans, and is harmful to many biological species. It should be noted that energy-related activities are only partially (directly or indirectly) responsible for the emissions that lead to stratospheric ozone depletion. The most significant role in ozone depletion is played by the CFCs, which are mainly used in air-conditioning and refrigerating equipment as refrigerants, and NO_x emissions, which are produced by the fossil fuel and biomass combustion processes, natural denitrification, and nitrogen fertilizers.

In 1998, the size of the ozone hole over Antarctica was 25 million km^2 whereas in 2012 it is 18 million km^2. It was about 3 million km^2 in 1993 (Worldwatch, 2007). Researchers expect the Antarctic ozone hole to remain severe in the next 10–20 years, followed by a period of slow healing. Full recovery is predicted to occur in 2050; however, the rate of recovery is affected by the climate change (Dincer, 1999).

1.3.3 Global climate change

The term *greenhouse effect* has generally been used for the role of the whole atmosphere (mainly water vapor and clouds) in keeping the surface of the earth warm. Recently, however, it has been increasingly associated with the contribution of CO_2, which is estimated to contribute about 50% to the anthropogenic greenhouse effect. Additionally, several other gases, such as CH_4, CFCs, halons, N_2O, ozone, and peroxyacetylnitrate (also called *GHGs*), produced by the industrial and domestic activities can contribute to this effect, resulting in a rise of the earth's temperature. Increasing atmospheric concentrations of GHGs increase the amount of heat trapped (or decrease the heat radiated from the earth's surface), thereby raising the surface temperature of the earth. According to Colonbo (1992), the earth's surface temperature has increased by about 0.6 °C over the past century, and as a consequence the sea level is estimated to have risen by perhaps 20 cm. These changes can have a wide range of effects on human activities all over the world. The role of various GHGs is summarized by Dincer and Rosen (1998).

According to the EU, climate change is happening. There is an overwhelming consensus among the world's leading climate scientists that global warming is being caused mainly by carbon dioxide and other GHGs emitted by human activities, chiefly the combustion of fossil fuels and deforestation.

A reproduction of the climate over the past 420,000 years was made recently using data from the Vostok ice core in Antarctica. An ice core is a core sample from the accumulation of snow and ice over many years that has recrystallized and trapped air bubbles from previous time periods. The composition of these ice cores, especially the presence of hydrogen and oxygen isotopes, provides a picture of the climate at the time. The data extracted from this ice core provide a continuous record of temperature and atmospheric composition. Two parameters of interest are the concentration of CO_2 in the atmosphere and the temperature. These are shown in Figure 1.1, considering 1950 as the reference year. As can be seen, the two parameters follow a similar trend and have a periodicity of about 100,000 years. If one considers, however, the present (December 2012) CO_2 level, which is 392.92 ppm (www.co2now.org), the highest ever recorded, one can understand the implication that this would have on the temperature of the planet.

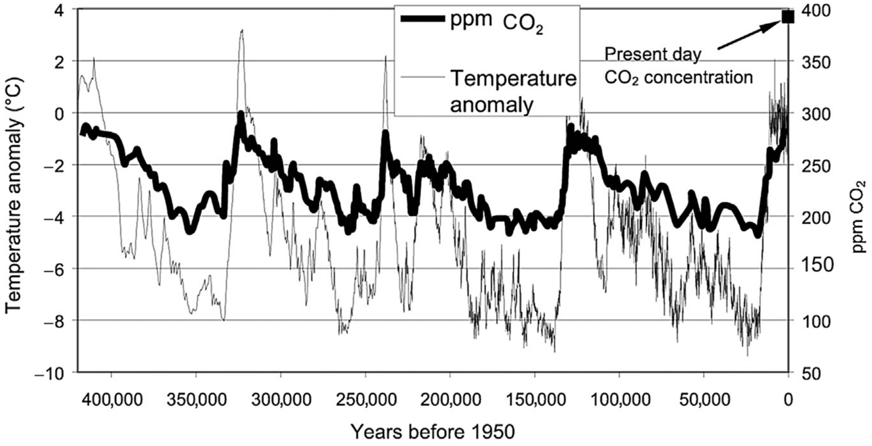

FIGURE 1.1

Temperature and CO_2 concentration from the Vostok ice core.

Humans, through many of their economic and other activities, contribute to the increase of the atmospheric concentrations of various GHGs. For example, CO_2 releases from fossil fuel combustion, methane emissions from increased human activities, and CFC releases contribute to the greenhouse effect. Predictions show that if atmospheric concentrations of GHGs, mainly due to fossil fuel combustion, continue to increase at the present rates, the earth's temperature may increase by another 2–4 °C in the next century. If this prediction is realized, the sea level could rise by 30–60 cm before the end of this century (Colonbo, 1992). The impacts of such sea level increase can easily be understood and include flooding of coastal settlements, displacement of fertile zones for agriculture to higher latitudes, and decrease in availability of freshwater for irrigation and other essential uses. Thus, such consequences could put in danger the survival of entire populations.

1.3.4 Nuclear energy

Nuclear energy, although non-polluting, presents a number of potential hazards during the production stage and mainly for the disposal of radioactive waste. Nuclear power environmental effects include the effects on air, water, ground, and the biosphere (people, plants, and animals). Nowadays, in many countries, laws govern any radioactive releases from nuclear power plants. In this section some of the most serious environmental problems associated with electricity produced from nuclear energy are described. These include only the effects related to nuclear energy and not the emissions of other substances due to the normal thermodynamic cycle.

The first item to consider is radioactive gases that may be removed from the systems supporting the reactor cooling system. The removed gases are compressed and stored. The gases are periodically sampled and can be released only when the radioactivity is less than an acceptable level, according to certain standards. Releases of this nature are done very infrequently. Usually, all potential paths where radioactive materials could be released to the environment are monitored by radiation monitors (Virtual Nuclear Tourist, 2007).

Nuclear plant liquid releases are slightly radioactive. Very low levels of leakage may be allowed from the reactor cooling system to the secondary cooling system of the steam generator. However, in any case where radioactive water may be released to the environment, it must be stored and radioactivity levels reduced, through ion exchange processes, to levels below those allowed by the regulations.

Within the nuclear plant, a number of systems may contain radioactive fluids. Those liquids must be stored, cleaned, sampled, and verified to be below acceptable levels before release. As in the gaseous release case, radiation detectors monitor release paths and isolate them (close valves) if radiation levels exceed a preset set point (Virtual Nuclear Tourist, 2007).

Nuclear-related mining effects are similar to those of other industries and include generation of tailings and water pollution. Uranium milling plants process naturally radioactive materials. Radioactive airborne emissions and local land contamination were evidenced until stricter environmental rules aided in forcing cleanup of these sites.

As with other industries, operations at nuclear plants result in waste; some of it, however, is radioactive. Solid radioactive materials leave the plant by only two paths:

- Radioactive waste (e.g. clothes, rags, wood) is compacted and placed in drums. These drums must be thoroughly dewatered. The drums are often checked at the receiving location by regulatory agencies. Special landfills must be used.
- Spent resin may be very radioactive and is shipped in specially designed containers.

Generally, waste is distinguished into two categories: low-level waste (LLW) and high-level waste (HLW). LLW is shipped from nuclear plants and includes such solid waste as contaminated clothing, exhausted resins, or other materials that cannot be reused or recycled. Most anti-contamination clothing is washed and reused; however, eventually, as with regular clothing, it wears out. In some cases, incineration or super-compaction may be used to reduce the amount of waste that has to be stored in the special landfills.

HLW is considered to include the fuel assemblies, rods, and waste separated from the spent fuel after removal from the reactor. Currently the spent fuel is stored at the nuclear power plant sites in storage pools or in large metal casks. To ship the spent fuel, special transport casks have been developed and tested.

Originally, the intent had been that the spent fuel would be reprocessed. The limited amount of highly radioactive waste (also called HLW) was to be placed in glass rods surrounded by metal with low long-term corrosion or degradation properties. The intent was to store those rods in specially designed vaults where the rods could be recovered for the first 50–100 years and then made irretrievable for up to 10,000 years. Various underground locations can be used for this purpose, such as salt domes, granite formations, and basalt formations. The objective is to have a geologically stable location with minimal chance for groundwater intrusion. The intent had been to recover the plutonium and unused uranium fuel and then reuse it in either breeder or thermal reactors as mixed oxide fuel. Currently, France, Great Britain, and Japan are using this process (Virtual Nuclear Tourist, 2007).

1.3.5 Renewable energy technologies

Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of energy. These technologies use the sun's energy and its direct and indirect effects on the earth (solar radiation, wind, falling water, and various plants; i.e., biomass), gravitational forces (tides), and the heat of the earth's core (geothermal) as the resources from which energy is produced. These resources have massive energy potential; however, they are generally diffused and not fully accessible, and most of them are intermittent and have distinct regional variabilities. These characteristics give rise to difficult, but solvable, technical and economical challenges. Nowadays, significant progress is made by improving the collection and conversion efficiencies, lowering the initial and maintenance costs, and increasing the reliability and applicability of renewable energy systems.

Worldwide research and development in the field of renewable energy resources and systems has been carried out during the past two decades. Energy conversion systems that are based on renewable energy technologies appeared to be cost-effective compared with the projected high cost of oil. Furthermore, renewable energy systems can have a beneficial impact on the environmental, economic, and political issues of the world. At the end of 2001 the total installed capacity of renewable energy systems was equivalent to 9% of the total electricity generation (Sayigh, 2001). As was seen before, by applying the renewable energy-intensive scenario, the global consumption of renewable sources by 2050 would reach 318 EJ (Johanson et al., 1993).

The benefits arising from the installation and operation of renewable energy systems can be distinguished into three categories: energy saving, generation of new working posts, and decrease in environmental pollution.

The energy-saving benefit derives from the reduction in consumption of the electricity and diesel used conventionally to provide energy. This benefit can be directly translated into monetary units according to the corresponding production or avoiding capital expenditure for the purchase of imported fossil fuels.

Another factor of considerable importance in many countries is the ability of renewable energy technologies to generate jobs. The penetration of a new technology leads to the development of new production activities, contributing to the production, market distribution, and operation of the pertinent equipment. Specifically for the case of solar energy collectors, job creation is mainly related to the construction and installation of the collectors. The latter is a decentralized process, since it requires the installation of equipment in every building or for every individual consumer.

The most important benefit of renewable energy systems is the decrease in environmental pollution. This is achieved by the reduction of air emissions due to the substitution of electricity and conventional fuels. The most important effects of air pollutants on the human and natural environment are their impact on the public health, agriculture, and on ecosystems. It is relatively simple to measure the financial impact of these effects when they relate to tradable goods, such as the agricultural crops; however, when it comes to non-tradable goods, such as human health and ecosystems, things become more complicated. It should be noted that the level of the environmental impact and therefore the social pollution cost largely depend on the geographical location of the emission sources. Contrary to the conventional air pollutants, the social cost of CO_2 does not vary with the geographical characteristics of the source, as each unit of CO_2 contributes equally to the climate change thread and the resulting cost.

All renewable energy sources combined account for only 22.5% share of electricity production in the world (2010), with hydroelectric power providing almost 90% of this amount. However, as the renewable energy technologies mature and become even more cost competitive in the future, they will be in a position to replace a major fraction of fossil fuels for electricity generation. Therefore, substituting fossil fuels with renewable energy for electricity generation must be an important part of any strategy of reducing CO_2 emissions into the atmosphere and combating global climate change.

In this book, emphasis is given to solar thermal systems. Solar thermal systems are non-polluting and offer significant protection of the environment. The reduction of GHG pollution is the main advantage of utilizing solar energy. Therefore, solar thermal systems should be employed whenever possible to achieve a sustainable future.

The benefits of renewable energy systems can be summarized as follows (Johanson et al., 1993):

- *Social and economic development*. Production of renewable energy, particularly biomass, can provide economic development and employment opportunities, especially in rural areas, that otherwise have limited opportunities for economic growth. Renewable energy can thus help reduce poverty in rural areas and reduce pressure for urban migration.
- *Land restoration*. Growing biomass for energy on degraded lands can provide the incentive and financing needed to restore lands rendered nearly useless by previous agricultural or forestry practices. Although lands farmed for energy would not be restored to their original condition, the recovery of these lands for biomass plantations would support rural development, prevent erosion, and provide a better habitat for wildlife than at present.
- *Reduced air pollution*. Renewable energy technologies, such as methanol or hydrogen for fuel cell vehicles, produce virtually none of the emissions associated with urban air pollution and acid deposition, without the need for costly additional controls.
- *Abatement of global warming*. Renewable energy use does not produce carbon dioxide or other greenhouse emissions that contribute to global warming. Even the use of biomass fuels does not contribute to global warming, since the carbon dioxide released when biomass is burned equals the amount absorbed from the atmosphere by plants as they are grown for biomass fuel.
- *Fuel supply diversity*. There would be substantial interregional energy trade in a renewable energy-intensive future, involving a diversity of energy carriers and suppliers. Energy importers would be able to choose from among more producers and fuel types than they do today and thus would be less vulnerable to monopoly price manipulation or unexpected disruptions of supply. Such competition would make wide swings in energy prices less likely, leading eventually to stabilization of the world oil price. The growth in world energy trade would also provide new opportunities for energy suppliers. Especially promising are the prospects for trade in alcohol fuels, such as methanol, derived from biomass and hydrogen.
- *Reducing the risks of nuclear weapons proliferation*. Competitive renewable resources could reduce incentives to build a large world infrastructure in support of nuclear energy, thus avoiding major increases in the production, transportation, and storage of plutonium and other radioactive materials that could be diverted to nuclear weapons production.

Solar systems, including solar thermal and PVs, offer environmental advantages over electricity generation using conventional energy sources. The benefits arising from the installation and operation of solar energy systems fall into two main categories: environmental and socioeconomical issues.

From an environmental viewpoint, the use of solar energy technologies has several positive implications that include (Abu-Zour and Riffat, 2006):

- Reduction of the emission of the GHGs (mainly CO_2 and NO_x) and of toxic gas emissions (SO_2, particulates),

- Reclamation of degraded land,
- Reduced requirement for transmission lines within the electricity grid, and
- Improvement in the quality of water resources.

The socioeconomic benefits of solar technologies include:

- Increased regional and national energy independence,
- Creation of employment opportunities,
- Restructuring of energy markets due to penetration of a new technology and the growth of new production activities,
- Diversification and security (stability) of energy supply,
- Acceleration of electrification of rural communities in isolated areas, and
- Saving foreign currency.

It is worth noting that no artificial project can completely avoid some impact to the environment. The negative environmental aspects of solar energy systems include:

- Pollution stemming from production, installation, maintenance, and demolition of the systems,
- Noise during construction,
- Land displacement, and
- Visual intrusion.

These adverse impacts present difficult but solvable technical challenges.

The amount of sunlight striking the earth's atmosphere continuously is 1.75×10^5 TW. Considering a 60% transmittance through the atmospheric cloud cover, 1.05×10^5 TW reaches the earth's surface continuously. If the irradiance on only 1% of the earth's surface could be converted into electric energy with a 10% efficiency, it would provide a resource base of 105 TW, while the total global energy needs for 2050 are projected to be about 25–30 TW. The present state of solar energy technologies is such that single solar cell efficiencies have reached more than 20%, with concentrating PVs at about 40%, and solar thermal systems provide efficiencies of 40–60%.

Solar PV panels have come down in cost from about $30/W to about $0.8/W in the past three decades. At $0.8/W panel cost, the overall system cost is around $2.5-5/W (depending on the size of the installation), which is still too high for the average consumer. However, solar PV is already cost-effective in many off-grid applications. With net metering and governmental incentives, such as feed-in laws and other policies, even grid-connected applications such as building-integrated PV have become cost-effective. As a result, the worldwide growth in PV production has averaged more than 30% per year during the past 5 years.

Solar thermal power using concentrating solar collectors was the first solar technology that demonstrated its grid power potential. A total of 354 MWe solar thermal power plants have been operating continuously in California since 1985. Progress in solar thermal power stalled after that time because of poor policy and lack of R&D. However, the past 5 years have seen a resurgence of interest in this area, and a number of solar thermal power plants around the world are constructed and more are under construction. The cost of power from these plants (which so far is in the range of $0.12–$0.16/kWh) has the potential to go down to $0.05/kWh with scale-up and creation of a mass market. An advantage of solar thermal power is that thermal energy can be stored efficiently and fuels such as natural gas or biogas may be used as backup to ensure continuous operation.

1.4 State of the climate

A good source of information on the state of climate in the year 2011 is the report published by the U.S. National Climatic Data Center (NCDC), which summarizes global and regional climate conditions and places them in the context of historical records (Blunden and Arndt, 2012). The parameters examined are global temperature and various gases found in the atmosphere.

1.4.1 Global temperature

Based on the National Oceanic and Atmospheric Administration and the U.S. NCDC records, the global temperature has been rising gradually at a rate between 0.71 and 0.77 °C per century since 1901 and between 0.14 and 0.17 °C per decade since 1971. Data show that 2011 was the ninth warmest year since records began in 1979; 0.13 °C above the 1981–2010 average whereas the upward trend for 1979–2011 was 0.12 °C per decade (Blunden and Arndt, 2012). Unusually high temperatures affected most land areas during 2011 with the most prominent effect taking place in Russia, while unusually low temperatures were observed in parts of Australia, north-western United States, and central and south-eastern Asia. Averaged globally, the 2011 land surface temperature was, according to the institution performing the analysis, ranged between 0.20 and 0.29 °C above the 1981–2010 average, ranking from 5th to 10th warmest on record, depending on the choice of data set.

Despite two La Niña episodes (the first strong and the second weaker), global average sea surface temperatures remained above average throughout the year, ranking as either 11th or 12th warmest on record. The global sea surface temperature in 2011 was between 0.02 and 0.09 °C above the 1981–2010 average depending on the choice of data set. Annual mean sea surface temperatures were above average across the Atlantic, Indian, and western Pacific Oceans, and below average across the eastern and equatorial Pacific Ocean, southern Atlantic Ocean, and some regions of the Southern Oceans (Blunden and Arndt, 2012).

The majority of the top 10 warmest years on record have occurred in the past decade. The global temperature from 1850 until 2006 is shown in Figure 1.2, together with the 5-year average values. As can be seen there is an upward trend that is more serious from the 1970s onward.

1.4.2 Carbon dioxide

Carbon dioxide emitted from natural and anthropogenic (i.e., fossil fuel combustion) sources is partitioned into three reservoirs: atmosphere, oceans, and the terrestrial biosphere. The result of increased fossil fuel combustion has been that atmospheric CO_2 has increased from about 280 ppm (parts per million by dry air mole fraction) at the start of the industrial revolution to about 392.9 ppm in December 2012 (see Figure 1.3). Carbon dioxide in fact has increased by 2.10 ppm since 2010 and exceeded 390 ppm for the first time since instrumental records began. Roughly half of the emitted CO_2 remains in the atmosphere and the remainder goes into the other two sinks: oceans and the land biosphere (which includes plants and soil carbon).

In 2010, anthropogenic carbon emissions to the atmosphere have increased globally to more than 9.1 ± 0.5 Pg/a (piga, $P = 10^{15}$). Most of this increase resulted from a 10% increase in emissions from China, the world's largest fossil fuel CO_2 emitter. During the 1990s, net uptake by the oceans was estimated at 1.7 ± 0.5 Pg/a, and by the land biosphere at 1.4 ± 0.7 Pg/a. The gross atmosphere–ocean

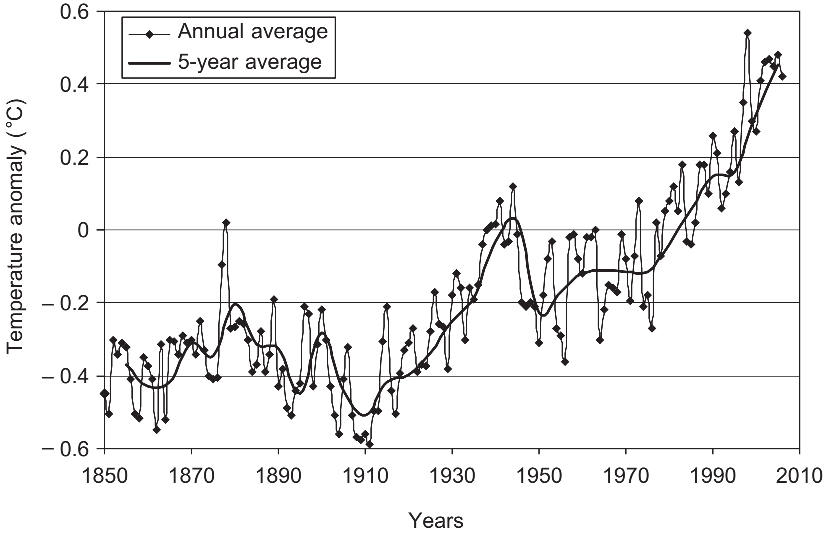

FIGURE 1.2

Global temperature since 1850.

and atmosphere–terrestrial biosphere (i.e., photosynthesis and respiration) fluxes are on the order of 100 Pg/a. Inter-annual variations in the atmospheric increase of CO_2 are not attributed to variations in fossil fuel emissions but rather to small changes in these net fluxes. Most attempts to explain the interannual variability of the atmospheric CO_2 increase have focused on short-term climate fluctuations (e.g. the El Niño/Southern Oscillation and post-mountain Pinatubo cooling), but the mechanisms,

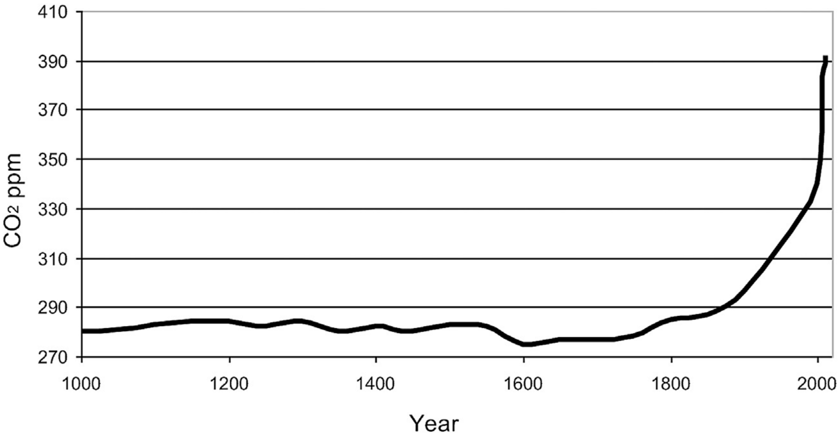

FIGURE 1.3

CO_2 levels in the past 1000 years.

especially the role of the terrestrial biosphere, are poorly understood. To date, about 5% of conventional fossil fuels have been combusted. If combustion is stopped today, it is estimated that after a few hundred years, 15% of the total carbon emitted would remain in the atmosphere, and the remainder would be in the oceans.

In 2011, the globally averaged atmospheric CO_2 mole fraction was 390.4 ppm, just more than a 2.1 ± 0.09 ppm increase from 2010. This was slightly larger than the average increase from 2000 to 2010 of 1.96 ± 0.36 ppm/a. The record CO_2 concentration in 2012 (392.92 ppm) continues a trend toward increased atmospheric CO_2 since before the industrial era values of around 280 ppm. This continues the steady upward trend in this abundant and long-lasting GHG. Since 1900, atmospheric CO_2 has increased by 94 ppm (132%), with an average annual increase of 4.55 ppm since 2000.

1.4.3 Methane

The contribution of methane (CH_4) to anthropogenic radiative forcing, including direct ($\approx 70\%$) and indirect ($\approx 30\%$) effects, is about 0.7 W/m^2, or roughly half that of CO_2. Also, changes in the load of CH_4 feed back into atmospheric chemistry, affecting the concentrations of hydroxyl (OH) and ozone (O_3). The increase in CH_4 since the pre-industrial era is responsible for about half of the estimated increase in background tropospheric O_3 during that time. It should be noted that changes in OH concentration affect the lifetimes of other GHGs such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). Methane has a global warming potential (GWP) of 25; this means that, integrated over a 100-year timescale, the radiative forcing from a given pulse of CH_4 emissions is estimated to be 25 times greater than a pulse of the same mass of CO_2.

In 2011, CH_4 increased by about 5 ± 2 ppb (parts per billion, 10^9, by dry air mole fraction), primarily due to increases in the Northern Hemisphere. The globally averaged methane (CH_4) concentration in 2011 was 1803 ppb.

Stratospheric ozone over Antarctica in October 2012 reached a value of 139 Dobson units (DU) and the world average is about 300 DU. A DU is the most basic measure used in ozone research. The unit is named after G. M. B. Dobson, one of the first scientists to investigate atmospheric ozone. He designed the Dobson spectrometer, which is the standard instrument used to measure ozone from the ground. The Dobson spectrometer measures the intensity of solar UV radiation at four wavelengths, two of which are absorbed by ozone and two of which are not. One Dobson unit is defined to be 0.01 mm thickness at STP (standard temperature and pressure = 0 °C and 1 atmosphere pressure). For example, when in an area all the ozone in a column is compressed to STP and spread out evenly over the area and forms a slab of 3 mm thick, then the ozone layer over that area is 300 DU.

1.4.4 Carbon monoxide

Unlike CO_2 and CH_4, carbon monoxide (CO) does not strongly absorb terrestrial infrared radiation but affects climate through its chemistry. The chemistry of CO affects OH (which influences the lifetimes of CH_4 and HFCs) and tropospheric O_3 (which is by itself a GHG); so emissions of CO can be considered equivalent to emissions of CH_4. Current emissions of CO may contribute more to radiative forcing over decade timescales than emissions of anthropogenic nitrous oxide.

Because the lifetime of CO is relatively short (a few months), the anomaly of increased levels of CO in the atmosphere quickly disappeared and CO quickly returned to pre-1997 levels. Carbon monoxide levels in 2011 were comparable with those found in the early 2000s. The globally averaged CO mole fraction in 2011 was about 80.5 ppb, slightly less than the 2010 value. Since 1991, little trend in globally averaged CO has been observed.

1.4.5 Nitrous oxide and sulfur hexafluoride

Atmospheric nitrous oxide (N_2O) and sulfur hexafluoride (SF_6) are present in lower concentrations than CO_2, but the radiative forcing of each is far greater. Nitrous oxide is the third strongest GHG, while each SF_6 molecule is 23,900 times more effective as an infrared absorber than one CO_2 molecule and has an atmospheric lifetime of between 500 and 3200 years.

The concentration of both species has grown at a linear rate, N_2O at 0.76 ppb/a (0.25% per year) since 1978 and SF_6 at a rate of 0.22 ppt (parts per trillion, 10^{12}, by dry air mole fraction) per year (~5%/a) since 1996. The concentration of 324.3 ppb N_2O in 2011 has added a radiative forcing of around 0.17 W/m^2 over the pre-industrial N_2O concentration of around 270 ppb. The 2011 value represents an increase of 1.1 ppb over the 2010 value and is higher than the average growth rate of 0.76 ppb/a shown above. Atmospheric N_2O is also a major source of stratospheric nitric oxide (NO), a compound that helps to catalytically destroy stratospheric O_3. The atmospheric concentration of SF_6 has grown due to its use as an electrical insulator for power transmission throughout the world. Its global mean concentration was 7.31 ppt at the end of 2011, an increase of 0.28 ppt over the 2010 value. While total radiative forcing of SF_6 from pre-industrial times to the present is relatively small, its long atmospheric lifetime, high atmospheric growth rate, and high GWP are a concern for the future.

1.4.6 Halocarbons

Concern over stratospheric ozone depletion has restricted or eliminated production of many halocarbons. The phase-out of human-produced halocarbons was the result of the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. As a result of these efforts, mixing ratios of many ozone-depleting gases have been declining at the earth's surface in recent years; this decline continued in 2011. Reports from many laboratories around the world that perform measurements of halocarbons show that tropospheric mixing ratios of CFC-12, the longest lived and most abundant human-made ozone-depleting gas in the atmosphere, peaked within the past few years. These measurements also show that mixing ratios of some halogenated gases continue to increase globally. The most rapid increases are in HCFCs and HFCs, which are chemicals commonly used as replacements for CFCs, halons, and other ozone-depleting gases. Although HCFCs contain chlorine (Cl) and deplete O_3 with a reduced efficiency compared with CFCs, HFCs do not participate in O_3 destroying reactions.

Changes in the direct radiative influence of long-lived halocarbons can be estimated from observed changes in atmospheric mixing ratios with knowledge of trace-gas radiative efficiencies. Such an analysis suggests that the direct radiative forcing of these gases was still increasing in 2011, though at a much slower rate than observed from 1970 to 1990.

1.4.7 Sea level

The average global rate of sea level change computed over the years 1993–2011 is 3.2 ± 0.4 mm/a. Relative to the long-term trend, global sea level dropped noticeably in mid-2010 and reached a local minimum in 2011. The drop has been linked to the strong La Niña conditions that have prevailed throughout 2010–2011. Global sea level increased sharply during the second half of 2011. The global value for 2011 is 50 mm above the 1995 value. The largest positive anomalies were in the equatorial Pacific off South America. Annual sea levels were generally high in the tropical Indian Ocean, with the exception of the strong negative anomaly in the eastern Indian Ocean. Sea level deviations in the Atlantic Ocean showed bands of relatively high sea level in the South Atlantic just north of the equator, and in the sub-polar North Atlantic.

1.5 A brief history of solar energy

Solar energy is the oldest energy source ever used. The sun was adored by many ancient civilizations as a powerful god. The first known practical application was in drying for preserving food (Kalogirou, 2004).

Probably the oldest large-scale application known to us is the burning of the Roman fleet in the bay of Syracuse by Archimedes, the Greek mathematician and philosopher (287–212 BC). Scientists discussed this event for centuries. From 100 BC to 1100 AD, authors made reference to this event, although later it was criticized as a myth because no technology existed at that time to manufacture mirrors (Delyannis, 1967). The basic question was whether Archimedes knew enough about the science of optics to devise a simple way to concentrate sunlight to a point at which ships could be burned from a distance. Nevertheless, Archimedes had written a book, *On Burning Mirrors* (Meinel and Meinel, 1976), which is known only from references, since no copy survived.

The Greek historian Plutarch (46–120 AD) referred to the incident, saying that the Romans, seeing that indefinite mischief overwhelmed them from no visible means, began to think they were fighting with the gods.

In his book, *Optics*, Vitelio, a Polish mathematician, described the burning of the Roman fleet in detail (Delyannis and Belessiotis, 2000; Delyannis, 1967): “The burning glass of Archimedes composed of 24 mirrors, which conveyed the rays of the sun into a common focus and produced an extra degree of heat.”

Proclus repeated Archimedes’ experiment during the Byzantine period and burned the war fleet of enemies besieging Byzance in Constantinople (Delyannis, 1967).

Eighteen hundred years after Archimedes, Athanasius Kircher (1601–1680) carried out some experiments to set fire to a woodpile at a distance to see whether the story of Archimedes had any scientific validity, but no report of his findings survives (Meinel and Meinel, 1976).

Many historians, however, believe that Archimedes did not use mirrors but the shields of soldiers, arranged in a large parabola, for focusing the sun’s rays to a common point on a ship. This fact proved that solar radiation could be a powerful source of energy. Many centuries later, scientists again considered solar radiation as a source of energy, trying to convert it into a usable form for direct utilization.

Amazingly, the very first applications of solar energy refer to the use of concentrating collectors, which are, by their nature (accurate shape construction) and the requirement to follow the sun, more “difficult” to apply. During the eighteenth century, solar furnaces capable of melting iron, copper, and other metals were being constructed of polished iron, glass lenses, and mirrors. The furnaces were in use throughout Europe and the Middle East. One of the first large-scale applications was the solar

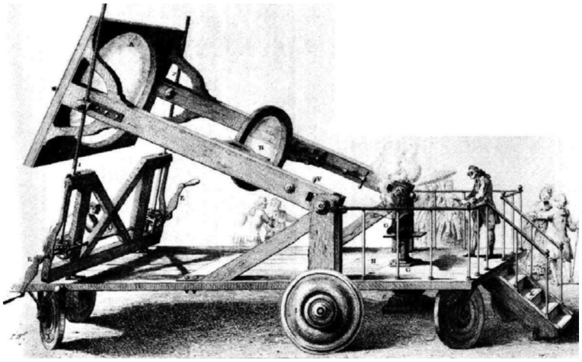

FIGURE 1.4

Solar furnace used by Lavoisier in 1774.

furnace built by the well-known French chemist Lavoisier, who, around 1774, constructed powerful lenses to concentrate solar radiation (see Figure 1.4). This attained the remarkable temperature of 1750 °C. The furnace used a 1.32 m lens plus a secondary 0.2 m lens to obtain such temperature, which turned out to be the maximum achieved for 100 years. Another application of solar energy utilization in this century was carried out by the French naturalist Boufon (1747–1748), who experimented with various devices that he described as "hot mirrors burning at long distance" (Delyannis, 2003).

During the nineteenth century, attempts were made to convert solar energy into other forms based upon the generation of low-pressure steam to operate steam engines. August Mouchot pioneered this field by constructing and operating several solar-powered steam engines between the years 1864 and 1878 in Europe and North Africa. One of them was presented at the 1878 International Exhibition in Paris (see Figure 1.5). The solar energy gained was used to produce steam to drive a printing machine (Mouchot, 1878, 1880). Evaluation of one built at Tours by the French government showed that it was

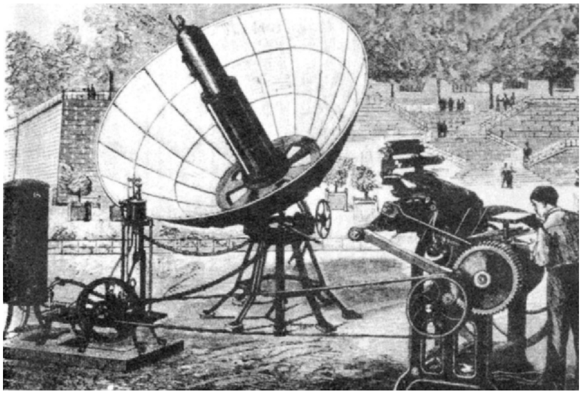

FIGURE 1.5

Parabolic collector powering a printing press at the 1878 Paris Exposition.

too expensive to be considered feasible. Another one was set up in Algeria. In 1875, Mouchot made a notable advance in solar collector design by making one in the form of a truncated cone reflector. Mouchot's collector consisted of silver-plated metal plates and had a diameter of 5.4 m and a collecting area of 18.6 m^2. The moving parts weighed 1400 kg.

Abel Pifre, a contemporary of Mouchot, also made solar engines (Meinel and Meinel, 1976; Kreider and Kreith, 1977). Pifre's solar collectors were parabolic reflectors made of very small mirrors. In shape they looked rather similar to Mouchot's truncated cones.

The efforts were continued in the United States, where John Ericsson, an American engineer, developed the first steam engine driven directly by solar energy. Ericsson built eight systems that had parabolic troughs by using either water or air as the working medium (Jordan and Ibele, 1956).

In 1901 A.G. Eneas installed a 10 m diameter focusing collector that powered a water-pumping apparatus at a California farm. The device consisted of a large umbrella-like structure opened and inverted at an angle to receive the full effect of the sun's rays on the 1788 mirrors that lined the inside surface. The sun's rays were concentrated at a focal point where the boiler was located. Water within the boiler was heated to produce steam, which in turn powered a conventional compound engine and centrifugal pump (Kreith and Kreider, 1978).

In 1904, a Portuguese priest, Father Himalaya, constructed a large solar furnace. This was exhibited at the St. Louis World's Fair. This furnace appeared quite modern in structure, being a large, off-axis, parabolic horn collector (Meinel and Meinel, 1976).

In 1912, Frank Shuman, in collaboration with C.V. Boys, undertook to build the world's largest pumping plant in Meadi, Egypt. The system was placed in operation in 1913, using long parabolic cylinders to focus sunlight onto a long absorbing tube. Each cylinder was 62 m long, and the total area of the several banks of cylinders was 1200 m^2. The solar engine developed as much as 37–45 kW continuously for a 5-h period (Kreith and Kreider, 1978). Despite the plant's success, it was completely shut down in 1915 due to the onset of World War I and cheaper fuel prices.

During the past 50 years, many variations were designed and constructed using focusing collectors as a means of heating the heat-transfer or working fluid that powered mechanical equipment. The two primary solar technologies used are central receivers and distributed receivers employing various point and line focus optics to concentrate sunlight. Central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver (SERI, 1987). Distributed receiver technology includes parabolic dishes, Fresnel lenses, parabolic troughs, and special bowls. Parabolic dishes track the sun in two axes and use mirrors to focus radiant energy onto a point focus receiver. Troughs and bowls are line focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Receiver temperatures range from 100 °C in low-temperature troughs to close to 1500 °C in dish and central receiver systems (SERI, 1987).

Today, many large solar plants have output in the megawatt range to produce electricity or process heat. The first commercial solar plant was installed in Albuquerque, New Mexico, in 1979. It consisted of 220 heliostats and had an output of 5 MW. The second was erected at Barstow, California, with a total thermal output of 35 MW. Most of the solar plants produce electricity or process heat for industrial use and they provide superheated steam at 673 K. Thus, they can provide electricity or steam to drive small-capacity conventional desalination plants driven by thermal or electrical energy.

Another area of interest, hot water and house heating, appeared in the mid-1930s but gained interest in the last half of the 1940s. Until then, millions of houses were heated by coal-burning boilers. The idea was to heat water and feed it to the radiator system that was already installed.

The manufacture of solar water heaters began in the early 1960s. The industry of solar water heater manufacturing expanded very quickly in many countries of the world. Typical solar water heaters in many cases are of the thermosiphon type and consist of two flat plate solar collectors having an absorber area between 3 and 4 m^2 and a storage tank with capacity between 150 and 180 l, all installed on a suitable frame. An auxiliary electric immersion heater or a heat exchanger, for central heating-assisted hot water production, is used in winter during periods of low solar insolation. Another important type of solar water heater is the forced circulation type. In this system, only the solar panels are visible on the roof, the hot water storage tank is located indoors in a plant room, and the system is completed with piping, a pump, and a differential thermostat. Obviously, this type is more appealing, mainly for architectural and aesthetic reasons, but it is also more expensive, especially for small installations (Kalogirou, 1997). More details on these systems are given in Chapter 5.

1.5.1 Photovoltaics

Becquerel discovered the PV effect in selenium in 1839. The conversion efficiency of the “new” silicon cells, developed in 1958, was 11%, although the cost was prohibitively high ($1000/W). The first practical application of solar cells was in space, where cost was not a barrier, since no other source of power is available. Research in the 1960s resulted in the discovery of other PV materials such as gallium arsenide (GaAs). These could operate at higher temperatures than silicon but were much more expensive. The global installed capacity of PVs at the end of 2011 was 67 GWp (Photon, 2012). PV cells are made of various semiconductors, which are materials that are only moderately good conductors of electricity. The materials most commonly used are silicon (Si) and compounds of cadmium sulfide (CdS), cuprous sulfide (Cu_2S), and gallium arsenide (GaAs).

Amorphous silicon cells are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon; so the cells can be thinner. For this reason, amorphous silicon is also known as a *thin-film* PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible, which makes it ideal for curved surfaces and “foldaway” modules. Amorphous cells are, however, less efficient than crystalline-based cells, with typical efficiencies of around 6%, but they are easier and therefore cheaper to produce. Their low cost makes them ideally suited for many applications where high efficiency is not required and low cost is important.

Amorphous silicon (a-Si) is a glassy alloy of silicon and hydrogen (about 10%). Several properties make it an attractive material for thin-film solar cells:

1. Silicon is abundant and environmentally safe.
2. Amorphous silicon absorbs sunlight extremely well, so that only a very thin active solar cell layer is required (about 1 μm compared with 100 μm or so for crystalline solar cells), thus greatly reducing solar cell material requirements.
3. Thin films of a-Si can be deposited directly on inexpensive support materials such as glass, sheet steel, or plastic foil.

A number of other promising materials, such as cadmium telluride (CdTe) and copper indium diselenide (CIS), are now being used for PV modules. The attraction of these technologies is that they can be manufactured by relatively inexpensive industrial processes, in comparison to crystalline silicon technologies, yet they typically offer higher module efficiencies than amorphous silicon.

The PV cells are packed into modules that produce a specific voltage and current when illuminated. PV modules can be connected in series or in parallel to produce larger voltages or currents. PV systems can be used independently or in conjunction with other electrical power sources. Applications powered by PV systems include communications (both on earth and in space), remote power, remote monitoring, lighting, water pumping, and battery charging.

The two basic types of PV applications are the stand-alone and the grid-connected systems. Stand-alone PV systems are used in areas that are not easily accessible or have no access to mains electricity grids. A stand-alone system is independent of the electricity grid, with the energy produced normally being stored in batteries. A typical stand-alone system would consist of PV module or modules, batteries, and a charge controller. An inverter may also be included in the system to convert the direct current (DC) generated by the PV modules to the alternating current (AC) form required by normal appliances.

In the grid-connected applications, the PV system is connected to the local electricity network. This means that during the day, the electricity generated by the PV system can either be used immediately (which is normal for systems installed in offices and other commercial buildings) or sold to an electricity supply company (which is more common for domestic systems, where the occupier may be out during the day). In the evening, when the solar system is unable to provide the electricity required, power can be bought back from the network. In effect, the grid acts as an energy storage system, which means the PV system does not need to include battery storage.

When PVs started to be used for large-scale commercial applications about 20 years ago, their efficiency was well below 10%. Nowadays, their efficiency has increased to about 15%. Laboratory or experimental units can give efficiencies of more than 30%, but these have not been commercialized yet. Although 20 years ago PVs were considered a very expensive solar system, the present cost is around \$2500–5000/kW$_e$ (depending on the size of the installation), and there are good prospects for further reduction in the coming years. More details on PVs are included in Chapter 9 of this book.

1.5.2 Solar desalination

The lack of water was always a problem to humanity. Therefore, among the first attempts to harness solar energy was the development of equipment suitable for the desalination of seawater. Solar distillation has been in practice for a long time (Kalogirou, 2005).

As early as in the fourth century BC, Aristotle described a method to evaporate impure water and then condense it to obtain potable water. However, historically, probably one of the first applications of seawater desalination by distillation is depicted in the drawing shown in Figure 1.6. The need to produce freshwater onboard emerged by the time the long-distance trips were possible. The drawing illustrates an account by Alexander of Aphrodisias in 200 AD, who said that sailors at sea boiled seawater and suspended large sponges from the mouth of a brass vessel to absorb what evaporated. In drawing this liquid off the sponges, they found that it was sweet water (Kalogirou, 2005).

Solar distillation has been in practice for a long time. According to Malik et al. (1985), the earliest documented work is that of an Arab alchemist in the fifteenth century, reported by Mouchot in 1869. Mouchot reported that the Arab alchemist had used polished Damascus mirrors for solar distillation.

Until medieval times, no important applications of desalination by solar energy existed. During this period, solar energy was used to fire alembics to concentrate dilute alcoholic solutions or herbal extracts for medical applications and to produce wine and various perfume oils. The stills, or alembics,

FIGURE 1.6

Sailors producing freshwater with seawater distillation.

were discovered in Alexandria, Egypt, during the Hellenistic period. Cleopatra the Wise, a Greek alchemist, developed many distillers of this type (Bittel, 1959). One of them is shown in Figure 1.7 (Kalogirou, 2005). The head of the pot was called the *ambix*, which in Greek means the "head of the still", but this word was applied very often to the whole still. The Arabs, who overtook science and especially alchemy about the seventh century, named the distillers *Al-Ambiq*, from which came the name *alembic* (Delyannis, 2003).

Mouchot (1879), the well-known French scientist who experimented with solar energy, in one of his numerous books mentions that, in the fifteenth century, Arab alchemists used polished Damascus concave mirrors to focus solar radiation onto glass vessels containing saltwater to produce freshwater. He also reports on his own solar energy experiments to distill alcohol and an apparatus he developed with a metal mirror having a linear focus in which a boiler was located along its focal line.

Later on, during the Renaissance, Giovani Batista Della Porta (1535–1615), one of the most important scientists of his time, wrote many books, which were translated into French, Italian, and German. In one of them, *Magiae Naturalis*, which appeared in 1558, he mentions three desalination systems (Delyannis, 2003). In 1589, he issued a second edition in which, in the volume on distillation, he mentions seven methods of desalination. The most important of them is a solar distillation apparatus that converted brackish water into freshwater. In this, wide earthen pots were used, exposed to the intense heat of the solar rays to evaporate water, and the condensate collected into vases placed underneath (Nebbia and Nebbia-Menozzi, 1966). He also describes a method to obtain freshwater from the air (what is known today as the *humidification–dehumidification method*).

Around 1774, the great French chemist Lavoisier used large glass lenses, mounted on elaborate supporting structures, to concentrate solar energy on the contents of distillation flasks. The use of

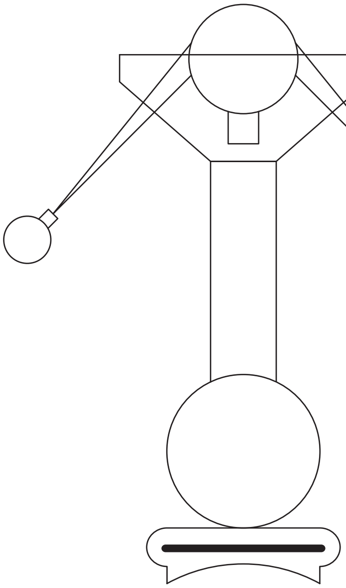

FIGURE 1.7

Cleopatra's alembic.

silver- or aluminum-coated glass reflectors to concentrate solar energy for distillation has also been described by Mouchot.

In 1870, the first American patent on solar distillation was granted to the experimental work of Wheeler and Evans. Almost everything we know about the basic operation of the solar stills and the corresponding corrosion problems is described in that patent. The inventors described the greenhouse effect, analyzed in detail the cover condensation and re-evaporation, and discussed the dark surface absorption and the possibility of corrosion problems. High operating temperatures were claimed as well as means of rotating the still to follow the solar incident radiation (Wheeler and Evans, 1870).

Two years later, in 1872, an engineer from Sweden, Carlos Wilson, designed and built the first large solar distillation plant, in Las Salinas, Chile (Harding, 1883); thus, solar stills were the first to be used on large-scale distilled water production. The plant was constructed to provide freshwater to the workers and their families at a saltpeter mine and a nearby silver mine. They used the saltpeter mine effluents, of very high salinity (140,000 ppm), as feed-water to the stills. The plant was constructed of wood and timber framework covered with one sheet of glass. It consisted of 64 bays having a total surface area of 4450 m^2 and a total land surface area of 7896 m^2. It produced 22.70 m^3 of freshwater per day (about 4.9 l/m^2). The still was operated for 40 years and was abandoned only after a freshwater pipe was installed, supplying water to the area from the mountains.

In the First World Symposium on Applied Solar Energy, which took place in November 1955, Maria Telkes described the Las Salinas solar distillation plant and reported that it was in operation for about 36 continuous years (Telkes, 1956a).

The use of solar concentrators in solar distillation was reported by Louis Pasteur, in 1928, who used a concentrator to focus solar rays onto a copper boiler containing water. The steam generated from the boiler was piped to a conventional water-cooled condenser in which distilled water was accumulated.

A renewal of interest in solar distillation occurred after the First World War, at which time several new devices had been developed, such as the roof-type, tilted wick, inclined tray, and inflated stills.

Before the Second World War only a few solar distillation systems existed. One of them, designed by C.G. Abbot, is a solar distillation device, similar to that of Mouchot (Abbot, 1930, 1938). At the same time some research on solar distillation was undertaken in the USSR (Trofimov, 1930; Tekutchev, 1938). During the years 1930–1940, the dryness in California initiated the interest in desalination of saline water. Some projects were started, but the depressed economy at that time did not permit any research or applications. Interest grew stronger during the Second World War, when hundreds of Allied troops suffered from lack of drinking water while stationed in North Africa, the Pacific islands, and other isolated places. Then a team from MIT, led by Maria Telkes, began experiments with solar stills (Telkes, 1943). At the same time, the U.S. National Research Defense Committee sponsored research to develop solar desalters for military use at sea. Many patents were granted (Delano, 1946a, b; Delano and Meisner, 1946) for individual small plastic solar distillation apparatuses that were developed to be used on lifeboats or rafts. These were designed to float on seawater when inflated and were used extensively by the U.S. Navy during the war (Telkes, 1945). Telkes continued to investigate various configurations of solar stills, including glass-covered and multiple-effect solar stills (Telkes, 1951, 1953, 1956b).

The explosion of urban population and the tremendous expansion of industry after the Second World War again brought the problem of good-quality water into focus. In July 1952, the Office of Saline Water (OSW) was established in the United States, the main purpose of which was to finance basic research on desalination. The OSW promoted desalination application through research. Five demonstration plants were built, and among them was a solar distillation plant in Daytona Beach, Florida, where many types and configurations of solar stills (American and foreign) were tested (Talbert et al., 1970). G.O.G. Loef, as a consultant to the OSW in the 1950s, also experimented with solar stills, such as basin-type stills, solar evaporation with external condensers, and multiple-effect stills, at the OSW experimental station in Daytona Beach (Loef, 1954).

In the following years, many small-capacity solar distillation plants were erected on Caribbean islands by McGill University of Canada. Everett D. Howe, from the Sea Water Conversion Laboratory of the University of California, Berkeley, was another pioneer in solar stills who carried out many studies on solar distillation (Kalogirou, 2005).

Experimental work on solar distillation was also performed at the National Physical Laboratory, New Delhi, India, and the Central Salt and Marine Chemical Research Institute, Bhavnagar, India. In Australia, the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne carried out a number of studies on solar distillation. In 1963, a prototype bay-type still was developed, covered with glass and lined with black polyethylene sheet (CSIRO, 1960). Solar distillation plants were constructed using this prototype still in the Australian desert, providing freshwater from saline well water for people and livestock. At the same time, V. A. Baum in the USSR was experimenting with solar stills (Baum, 1960, 1961; Baum and Bairamov, 1966).

Between 1965 and 1970, solar distillation plants were constructed on four Greek islands to provide small communities with freshwater (Delyannis, 1968). The design of the stills, done at the Technical University of Athens, was of the asymmetric glass-covered greenhouse type with aluminum frames.

The stills used seawater as feed and were covered with single glass. Their capacity ranged from 2044 to 8640 m^3/day. In fact, the installation in the island of Patmos is the largest solar distillation plant ever built. On three more Greek islands, another three solar distillation plants were erected. These were plastic-covered stills (Tedlar) with capacities of 2886, 388, and 377 m^3/day, which met the summer freshwater needs of the Young Men's Christian Association campus.

Solar distillation plants were also constructed on the islands of Porto Santo and Madeira, Portugal, and in India, for which no detailed information exists. Today, most of these plants are not in operation. Although a lot of research is being carried out on solar stills, no large-capacity solar distillation plants have been constructed in recent years.

A number of solar desalination plants coupled with conventional desalination systems were installed in various locations in the Middle East. The majority of these plants are experimental or demonstration scale. A survey of these simple methods of distilled water production, together with some other, more complicated ones, is presented in Chapter 8.

1.5.3 Solar drying

Another application of solar energy is solar drying. Solar dryers have been used primarily by the agricultural industry. The objective in drying an agricultural product is to reduce its moisture contents to a level that prevents deterioration within a period of time regarded as the safe storage period. Drying is a dual process of heat transfer to the product from a heating source and mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air. For many centuries farmers were using open sun drying. Recently, however, solar dryers have been used, which are more effective and efficient.

Drying by exposure to the sun is one of the oldest applications of solar energy, used for food preservation, such as vegetables, fruits, and fish and meat products. From the prehistoric times mankind used solar radiation as the only available thermal energy source to dry and preserve all necessary foodstuffs, to dry soil bricks for their homes and to dry animal skins for dressing.

The first known drying installation is in South of France and is dated at about 8000 BC. This is in fact a stone paved surface used for drying crops. Breeze or natural moderate wind velocities were combined with solar radiation to accelerate drying (Kroll and Kast, 1989).

Various other installations have been found around the world, dated between the years 7000 and 3000 BC. There are various combined installations, utilizing solar radiation combined with natural air circulation, used mainly for drying food. In Mesopotamia various sites have been found, for solar air drying of colored textile material and written clay plates. The first solely air drying installation for crops was found in Hindu river valley and is dated at about 2600 BC (Kroll and Kast, 1989).

The well-known Greek philosopher and physician, Aristotle (384–322 BC), described in detail the drying phenomena, and gave for first time, theoretical explanations of drying. Later on, biomass and wood were used to fire primitive furnaces to dry construction material, such as bricks and roof tiles, but food was exposed only to direct solar radiation (Belessiotis and Delyannis, 2011). The industry of conventional drying started about the eighteenth century but despite any modern methods developed, drying by exposure to the sun continues to be the main method for drying small amounts of agricultural products worldwide.

The objective of a dryer is to supply the product with more heat than is available under ambient conditions, increasing sufficiently the vapor pressure of the moisture held within the crop, thus enhancing moisture migration from within the crop and decreasing significantly the relative humidity of the drying air, hence increasing its moisture-carrying capability and ensuring a sufficiently low equilibrium moisture content.

In solar drying, solar energy is used as either the sole heating source or a supplemental source, and the air flow can be generated by either forced or natural convection. The heating procedure could involve the passage of the preheated air through the product or by directly exposing the product to solar radiation, or a combination of both. The major requirement is the transfer of heat to the moist product by convection and conduction from surrounding air mass at temperatures above that of the product, by radiation mainly from the sun and to a little extent from surrounding hot surfaces, or by conduction from heated surfaces in conduct with the product. More information on solar dryers can be found in Chapter 7.

1.5.4 Passive solar buildings

Finally, another area of solar energy is related to passive solar buildings. The term *passive system* is applied to buildings that include, as integral parts of the building, elements that admit, absorb, store, and release solar energy and thus reduce the need for auxiliary energy for comfort heating. These elements have to do with the correct orientation of buildings, the correct sizing of openings, the use of overhangs and other shading devices, and the use of insulation and thermal mass.

Before the advent of mechanical heating and cooling, passive solar building design was practiced for thousands of years as a means to provide comfortable indoor conditions and protect inhabitants from extreme weather conditions. People at those times considered factors such as solar orientation, thermal mass, and ventilation in the construction of residential dwellings, mostly by experience and the transfer of knowledge from generation to generation. The first solar architecture and urban planning methods were developed by both the Greeks and the Chinese. These methods specified that by orienting buildings toward the south, light and warmth can be provided. According to the "memorabilia" of Xenophon, mentioned in Section 1.1, Socrates said: "Now, supposing a house to have a southern aspect, sunshine during winter will steal in under the verandah, but in summer, when the sun traverses a path right over our heads, the roof will afford an agreeable shade, will it not?". These concepts, together with the others mentioned above, are nowadays considered by bioclimatic architecture. Most of these concepts are investigated in Chapter 6 of this book.

1.6 Other renewable energy systems

This section briefly reviews other renewable energy systems. Most of these, except wind energy, are not covered in this book. More details on these systems can be found in other publications.

1.6.1 Wind energy

Wind is generated by atmospheric pressure differences, driven by solar power. Of the total of 175,000 TW of solar power reaching the earth, about 1200 TW (0.7%) are used to drive the atmospheric pressure system. This power generates a kinetic energy reservoir of 750 EJ with a turnover time of 7.4 days (Soerensen, 1979). This conversion process takes place mainly in the upper layers of the atmosphere, at around 12 km height (where the "jet streams" occur). If it is assumed that about 4.6% of the kinetic power is available in the lowest strata of the atmosphere, the world wind potential is on the order of 55 TW. Therefore it can be concluded that, purely on a theoretical basis and disregarding the mismatch between supply and demand, the wind could supply an amount of electrical energy equal to the present world electricity demand.

As a consequence of the cubic (to the third power) relationship between wind speed and wind power (and hence energy), one should be careful in using average wind speed data (m/s) to derive wind power data (W/m^2). Local geographical circumstances may lead to mesoscale wind structures, which have a much higher energy content than one would calculate from the most commonly used wind speed frequency distribution (Rayleigh). Making allowances for the increase of wind speed with height, it follows that the energy available at, say, 25 m varies from around 1.2 MWh/m^2/a to around 5 MWh/m^2/a in the windiest regions. Higher energy levels are possible if hilly sites are used or local topography funnels a prevailing wind through valleys.

A brief historical introduction into wind energy

In terms of capacity, wind energy is the most widely used renewable energy source. Today there are many wind farms that produce electricity. Wind energy is, in fact, an indirect activity of the sun. Its use as energy goes as far back as 4000 years, during the dawn of historical times. It was adored, like the sun, as a god. For the Greeks, wind was the god Aeolos, the "flying man". After this god's name, wind energy is sometimes referred to as Aeolian energy (Delyannis, 2003).

In the beginning, about 4000 years ago, wind energy was used for the propulsion of sailing ships. In antiquity, this was the only energy available to drive ships sailing in the Mediterranean Basin and other seas, and even today, it is used for sailing small leisure boats. At about the same period, windmills, which were used mainly to grind various crops, appeared (Kalogirou, 2005).

It is believed that the genesis of windmills, though not proven, lay in the prayer mills of Tibet. The oldest very primitive windmills have been found at Neh, eastern Iran, and on the Afghanistan border (Major, 1990). Many windmills have been found in Persia, India, Sumatra, and Bactria. It is believed, in general, that many of the windmills were constructed by the Greeks, who immigrated to Asia with the troops of Alexander the Great (Delyannis, 2003). The earliest written document about windmills is a Hindu book of about 400 BC, called *Arthasastra of Kantilys*, in which there is a suggestion for the use of windmills to pump water (Soerensen, 1995). The next known record is from the Hero of Alexandria who described it in the first century AD. In Western Europe, windmills came later, during the twelfth century, with the first written reference in the 1040–1180 AD time frame (Merriam, 1980). Originally in the twelfth century, these were of the post-mill type in which the whole apparatus was mounted on a post so that it could be rotated to face the wind, and later in the fourteenth century, these were of the tower-mill type where only the top part of the windmill carrying the sails could be rotated (Sorensen, 2009a). The industrial revolution and the advent of steam power brought an end to the use of windmills.

A new use of the wind power was connected to the invention of the water pump and used extensively originally by farmers in the United States and subsequently in many parts of the world. This is of the classic lattice metal tower carrying a rotor made from galvanized steel vanes known as the California-type wind pumps (Sorensen, 2009a).

The famous Swiss mathematician, Leonhard Euler, developed the wind wheel theory and related equations, which are, even today, the most important principles for turbogenerators. The ancestor of today's vertical axis wind turbines was developed by Darrieus (1931), but it took about 50 years to be commercialized, in the 1970s. Scientists in Denmark first installed wind turbines during the Second World War to increase the electrical capacity of their grid. They installed 200 kW Gedser mill turbines, which were in operation until the 1960s (Dodge and Thresler, 1989).

Wind energy systems technology

The exploitation of wind energy today uses a wide range of machine sizes and types, giving a range of different economic performances. Today there are small machines up to about 300 kW and large-capacity ones that are in the megawatt range. A photograph of a wind park is shown in Figure 1.8.

The technology of the wind turbine generators currently in use is only 25 years old, and investment in it so far has been rather modest, compared with other energy sources. Nearly all the wind turbines manufactured by industry are of the horizontal axis type, and most of them have a three-bladed rotor. However, for some years now, machines have been constructed with two blades to reduce the costs and prolong the life of machines by making them lighter and more flexible by reducing the number of high-technology components.

Europe installed 9616 MW of wind turbines in 2011, an increase of 11% over the installation levels of 2010. The market for European wind power capacity broke new records in 2011, according to annual statistics from the European Wind Energy Association. The cumulative wind capacity in the EU increased to 93,957 MW, which can generate 190 TWh of electricity in an average wind year, equal to 6.3% of total EU power consumption. Worldwide by the end of 2011, 238 GW were installed, an increase of 40.5 GW from 2010. These wind turbines have the capacity to generate 500 TWh per year electricity, which is equal to about 3% of the world electricity usage. During the period 2005–2010 the installed wind turbines show an average increase of 27.6%.

Germany and Spain continue to be the leading countries in installed wind power with 29,060 and 21,674 MW, respectively. There is however a healthy trend in the European market toward less reliance on Germany and Spain as all other EU countries except Slovenia and Malta are investing in this technology. In 2011, 6480 MW of European wind capacity was installed outside Germany and Spain. On the total installed wind power except Germany and Spain the leading countries are France with 6800 MW, Italy with 6747 MW and United Kingdom with 6540 MW.

FIGURE 1.8

A photograph of a wind park.

It is clear that this investment is due to the strong effect of the EU Renewable Electricity Directive passed in 2001, which urges the EC and the council to introduce safeguard measures that ensure legal stability for renewable electricity in Europe. These figures confirm that sector-specific legislation is the most efficient way to boost renewable electricity production.

Germany installed 2086 MW of turbines in 2011, 39% more than in 2010, and is very near the 30,000 MW mark of total installed wind power. Spain was the second largest market, with 1050 MW (1463 MW in 2010, a drop of 28%), while United Kingdom moved into third place by installing 1293 MW during 2011, 29% more than in 2010. In 2011, Italy installed 950 MW of new capacity, France installed 830 MW and Sweden installed 763 MW. Cyprus, a country with no previous record of wind power, has now 134 MW of installed power. Wind energy in the new EU-12 countries reached 4287 MW in 2011. Fourteen countries in the EU have now surpassed the 1000 MW threshold of wind capacity.

The investments made to achieve this level of development have led to a steady accumulation of field experience and organizational learning. Taken together, many small engineering improvements, better operation and maintenance practices, improved wind prospects, and a variety of other incremental improvements have led to steady cost reductions.

Technological advances promise continued cost reductions. For example, the falling cost of electronic controls has made it possible to replace mechanical frequency controls with electronic systems. In addition, modern computer technology has made it possible to substantially improve the design of blades and other components.

The value of wind electricity depends on the characteristics of the utility system into which it is integrated, as well as on regional wind conditions. Some areas, particularly warm coastal areas, have winds with seasonal and daily patterns that correlate with demand, whereas others have winds that do not. Analyses conducted in the United Kingdom, Denmark, and the Netherlands make it clear that wind systems have greater value if numerous generating sites are connected, because it is likely that wind power fluctuations from a system of turbines installed at many widely separated sites will be less than at any individual site.

More details on wind energy systems can be found in Chapter 13.

1.6.2 Biomass

Biomass energy is a generic term applied to energy production achieved from organic material broken down into two broad categories:

- *Woody biomass*. Forestry timber, residues and co-products, other woody material including thinning and cleaning from woodlands (known as *forestry arisings*), untreated wood products, energy crops such as willow, short rotation coppice, and miscanthus (elephant grass).
- *Non-woody biomass*. Animal wastes, industrial and biodegradable municipal products from food processing, and high-energy crops such as rape, sugarcane, and corn.

Biomass, mainly in the form of industrial and agricultural residues, provided electricity for many years with conventional steam turbine power generators. The United States currently has more than 8000 MWe of generating capacity fueled from biomass. Existing steam turbine conversion technologies are cost competitive in regions where low-cost biomass fuels are available, even though these technologies are comparatively inefficient at the small sizes required for biomass electricity production.

The performance of biomass electric systems can be improved dramatically by adapting to biomass advanced gasification technologies developed originally for coal. Biomass is a more attractive feedstock for gasification than coal because it is easier to gasify and has very low sulfur content; therefore, expensive sulfur removal equipment is not required. Biomass integrated gasifier–gas turbine power systems with efficiencies of more than 40% have been commercially available since the early 1990s. These systems offer high efficiency and low unit capital costs for base load power generation at relatively modest scales of 100 MWe or less and can compete with coal-fired power plants, even when fueled with relatively costly biomass feed stocks.

Another form of energy related to agriculture is biogas. Animal waste is usually used for the generation of electricity from biogas. In these systems, the manure from animals is collected and processed to produce methane, which can be used directly in a diesel engine driving a generator to produce electricity. This can be achieved with two processes; aerobic and anaerobic digestion. Aerobic digestion is the process that takes place in the presence of oxygen, whereas the term anaerobic means without air and hence anaerobic digestion refers to the special type of digestion, which takes place without oxygen. All animal manures are valuable sources of bioenergy. These are usually processed with anaerobic digestion. Anaerobic digestion offers solutions designed to control and accelerate the natural degradation process that occurs in stored manure. An anaerobic digester is a completely closed system, which allows more complete digestion of the odorous organic intermediates found in stored manure to less offensive compounds (Wilkie, 2005). Similar benefits can be obtained also from the aerobic digestion but its operational costs and complexity are greater than the anaerobic systems. Additionally, aerobic methods consume energy and produce large amounts of by-product sludge, which requires disposal compared with significantly less sludge produced in the anaerobic process. From the process engineering point of view, anaerobic digestion is relatively simple, even though the biochemical processes involved are very complex (Wilkie, 2005). Anaerobic digestion applications can be at ambient temperature (15–25 °C), mesophilic temperature (30–40 °C), or thermophilic (50–60 °C) temperature, while farm digesters usually operate at mesophilic temperatures. For these systems to be feasible, large farms or consortiums of farms are required. This method also solves the problem of disposing of the manure, and as a by-product, we have the creation of a very good fertilizer. In the following subsections only biomass and biofuels are examined.

Sustainable biomass production for energy

The renewable energy-intensive global scenario described in Section 1.2 calls for some 400 million hectares of biomass plantations by the second quarter of the twenty-first century. If this magnitude of biomass is used, the questions raised are whether the net energy balances are sufficiently favorable to justify the effort, whether high biomass yields can be sustained over wide areas and long periods, and whether such plantations are environmentally acceptable (Johanson et al., 1993).

Achieving high plantation yields requires energy inputs, especially for fertilizers and harvesting and hauling the biomass. The energy content of harvested biomass, however, is typically 10–15 times greater than the energy inputs.

However, whether such high yields can be achieved year after year is questionable. The question is critical because essential nutrients are removed from a site at harvest; if these nutrients are not replenished, soil fertility and yields will decline over time. Fortunately, replenishment is feasible with good management. Twigs and leaves, the parts of the plant in which nutrients tend to concentrate, should be left at the plantation site at harvest, and the mineral nutrients recovered as ash at energy conversion facilities should be returned to the plantation soils. Nitrogen losses can be restored through the application of chemical fertilizers; make-up requirements can be kept low by choosing species that are especially efficient in the use of nutrients. Alternatively, plantations can be made nitrogen self-sufficient by growing nitrogen-fixing species, perhaps intermixed with other species. In the future, it will be possible to reduce nutrient inputs by matching nutrient applications to a plant's cyclic needs.

Intensive planting and harvesting activities can also increase erosion, leading to productivity declines. Erosion risks for annual energy crops would be similar to those for annual food crops, and so the cultivation of such crops should be avoided on erodible lands. For crops such as trees and perennial grasses, average erosion rates are low because planting is so infrequent, typically once in every 10–20 years.

An environmental drawback of plantations is that they support far fewer species than natural forests. Accordingly, it is proposed here that plantations be established not on areas now occupied by natural forests but instead on deforested and otherwise degraded lands in developing countries and on excess agricultural lands in industrialized countries. Moreover, a certain percentage of land should be maintained in a natural state as sanctuary for birds and other fauna, to help control pest populations. In short, plantations would actually improve the status quo with regard to biological diversity.

Biofuels

Recent advancements in distillation and blending technologies are being widely recognized as influencing the global proliferation of biofuels. The idea of biofuels is not new; in fact, Rudolf Diesel envisaged the significance of biofuels back in the nineteenth century, stating, "The use of vegetable oils for engine fuels may seem insignificant today. But such oils may become in the course of time, as important as petroleum and the coal tar products of the present time" (Cowman, 2007).

Rudolf Diesel's first compression ignition engines ran on peanut oil at the World Exposition in Paris. The current drive toward greater use of biofuels is being pushed by the diversification of energy sources using renewable products, as reliance on carbon-based fuels becomes an issue, and the need to replace the methyl tertiary butyl ether (MTBE) component used in many of the world's petroleum products. The change from fuels with an MTBE component started as an environmental issue in various parts of the world.

Ethanol has been recognized as the natural choice for replacing MTBE, and the need for blending ethanol into petroleum products is now a global requirement. Brazil has long been the world's leader when it comes to fuel ethanol capacity, but the United States is trying to exceed this and other countries in the Western Hemisphere by rapidly growing its production. European legislation has set substantial targets for the coming years, and EU Directive 2003/30/EC promoting the use of biofuels in transport set a target of 5.75% use by 2010. Under the Directive 2009/28/EC on the promotion of the use of energy from renewable sources this share rises to a minimum of 10% in every Member State in 2020. Regarding the expansion of biofuels' use in the EU, the Directive aims to ensure the use of sustainable biofuels only, which generate a clear and net GHG saving without negative impact on biodiversity and land use. Standards for biofuels have already been established, with the undiluted base products being defined as B100 (100% biodiesel) and El00 (100% ethanol). Subsequent blending will modify this number, such as a blend of 80% petrol and 20% ethanol, defined as E20, or a blend of 95% diesel and 5% biodiesel, defined as B5 (Cowman, 2007).

Biodiesel can be used in any concentration with petroleum-based diesel fuel, and little or no modification is required for existing diesel engines. Biodiesel is a domestic renewable fuel for diesel engines and is derived from vegetable oils and animal fats, including used oils and fats. Soybean oil is the leading vegetable oil produced in the United States and the leading feedstock for biodiesel production. Biodiesel is not the same as a raw vegetable oil; rather, it is produced by a chemical process that removes the glycerin and converts the oil into methyl esters.

Utilizing the current petroleum distribution infrastructure, blending is typically carried out at the storage or loading terminal. The most common locations for blending are the storage tank, the load rack headers, or most effectively, at the load arm. The most important requirement for this process is the accurate volume measurement of each product. This can be done through sequential blending or ratio blending but most beneficially utilizing the side stream blending technique.

Although petroleum products containing MTBE could be blended at the refinery and transported to the truck or tanker loading terminals via a pipeline or railcar, ethanol-blended fuel contains properties that make this difficult. Ethanol, by nature, attracts any H_2O encountered on route or found in storage tanks. If this happens in a 10% blend and the concentration of H_2O in the blended fuel reaches 0.4%, the combined ethanol and H_2O drop out of the blend. The exact point of dropout depends on the ethanol percentage, make-up quantity, and temperature. If this dropout occurs, the ethanol combines with the H_2O and separates from the fuel, dropping to the bottom of the storage tank. The resulting blend goes out of specification, and getting back to the correct specification requires sending the contaminated ethanol back to the production plant.

The solution to this problem is to keep the ethanol in a clean, dry environment and blend the ethanol with the petroleum products when loading the transport trucks and tankers. Moving the blend point to the loading point minimizes the risk of fuels being contaminated by H_2O.

In general biodiesel processing, the fat or oil is degummed and then reacted with alcohol, such as methanol, in the presence of a catalyst to produce glycerin and methyl esters (biodiesel). Methanol is supplied in excess to assist in quick conversion, and the unused portion is recovered and reused. The catalyst employed is typically sodium or potassium hydroxide, which has already been mixed with the methanol (Cowman, 2007).

Although fuel produced from agriculture has had only marginal use in today's climate, there are political, environmental, legislative, and financial benefits for using biofuels. With oil prices remaining high and very unlikely to reduce, demand for biofuel will continue to rise and provide exciting growth prospects for both investors and equipment manufacturers.

1.6.3 Geothermal energy

Measurements show that the ground temperature below a certain depth remains relatively constant throughout the year. This is because the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases due to the high thermal inertia of the soil.

There are different geothermal energy sources. They may be classified in terms of the measured temperature as low ($<100\,^{\circ}$C), medium (100–150 °C), and high temperature ($>150\,^{\circ}$C). The thermal gradient in the earth varies between 15 and 75 °C per km depth; nevertheless, the heat flux is anomalous in different continental areas. The cost of electrical energy is generally competitive, 0.6–2.8 U.S. cents/MJ (2–10 U.S. cents/kWh), and 0.3%, or 177.5 billion MJ/a (49.3 billion kWh/a), of the world total electrical energy was generated in the year 2000 from geothermal resources (Baldacci et al., 1998).

Geothermal power based on current hydrothermal technology can be locally significant in those parts of the world where there are favorable resources. About 6 GWe of geothermal power were produced in the early 1990s and 15 GWe may be added during the next decade. If hot dry rock geothermal technology is successfully developed, the global geothermal potential will be much larger.

Deep geothermal heat plants operate with one- or two-hole systems. The high expenditure incurred in drilling holes discourages one from using this method in gaining thermal energy. The one-hole injection system or the use of existing single holes, made during crude oil or natural gas exploration, reduces the capital cost. In one-hole systems, the hole is adapted to locate in it a vertical exchanger with a double-pipe heat exchanger, in which the geothermal water is extracted via the inside pipe. Published characteristics allow the estimation of the gained geothermal heat energy flux as a function of the difference between the temperatures of extracted and injected water at different volume fluxes of the geothermal water. In general, the two-layer systems and two-hole systems are more advantageous than one-hole systems. More details of geothermal systems related to desalination are given in Chapter 8.

Ground coupled heat pumps

In these systems ground heat exchangers (GHE) are employed to exchange heat with the ground (see Chapter 8, Section 8.5.6). The ground can be used as an energy source, an energy sink, or for energy storage (Eckert, 1976). For the efficient use of the ground in energy systems, its temperature and other thermal characteristics must be known. Studies show that the ground temperature varies with depth. At the surface, the ground is affected by short-term weather variations, changing to seasonal variations as the depth increases. At deeper layers, the ground temperature remains almost constant throughout the seasons and years and is usually higher than that of the ambient air during the cold months of the year and lower during the warm months (Florides and Kalogirou, 2008). The ground therefore is divided into three zones:

1. The surface zone where hourly variations of temperature occur,
2. The shallow zone, with monthly variations, and
3. The deep zone, where the temperature is almost constant year round.

The structure and physical properties of the ground are factors affecting temperature, in all zones. The temperature of the ground is a function of the thermal conductivity, specific heat, density, geothermal gradient, water content, and water flow rate through the ground. Studies carried out in several locations in Cyprus (typical Mediterranean climate) show that according to the formation of the ground the surface zone reaches a depth of 0.5 m. The shallow zone penetrates to 7–8 m and there after the deep zone follows. Furthermore, the temperature of the ground of the island at the deep zone has a range between 18 and 23 °C (Florides and Kalogirou, 2008).

GHE or earth heat exchangers (EHE), are devices used for the exploitation of the ground thermal capacity and the difference in temperature between ambient air and ground. A GHE is usually an array of buried pipes installed either horizontally or vertically into the ground. They use the ground as a heat source when operating in the heating mode and as a heat sink when operating in the cooling mode, with a fluid, usually air, water or a water–antifreeze mixture, to transfer the heat from or to the ground. They can contribute to the air-conditioning of a space, for water heating purposes and also for improving the efficiency of a heat pump.

Ground-coupled heat pumps (GCHPs) or geothermal heat pumps are systems combining a heat pump with a GHE for the heat exchange process, which improves the heat pump efficiency. Mainly, they are of two types; namely, the ground-coupled (closed-loop) system or the groundwater (open-loop) system.

The type to be used is chosen according to the ground thermal characteristics, the available land for installation, and the groundwater availability and temperature.

Common heat pumps use an electrically driven compressor that compresses a refrigerant and raises its pressure and thus its temperature. The refrigerant has the ability to change state, from liquid to gas when heated and usually it boils at low temperatures. In the heating mode, the common heat pump's refrigerant absorbs heat from the environment and becomes gas. Then the gas is compressed mechanically and has its temperature increased. The refrigerant at this stage is of high pressure and temperature and exchanges heat with a lower temperature medium (gas or liquid) as it passes through a condenser heating the conditioned space. Having its temperature dropped it returns to the liquid stage and after passing through an expansion valve it becomes liquid at low temperature and pressure. Then the process starts all over again with the refrigerant absorbing heat from the environment cooling it as it passes through an evaporator.

GCHPs exchange heat with the ground instead of the atmosphere. An EHE and a liquid circulating pump are parts that are not included in common heat pumps and are used in the heat exchange process. The heat pumps can be used for both heating and cooling of buildings. This is achieved by reversing the cycle, which means that the condenser and evaporator reverse their roles. The efficiency of heat pumps is described by the coefficient of performance (COP) in the heating mode and the energy efficiency ratio (EER) in the cooling mode. The COP or EER is the ratio of the rate of net heat output to the total energy input expressed in consistent units and under designated rating conditions or is the ratio of the refrigerating capacity to the work absorbed by the compressor per unit time. Sometimes the efficiency is described by the seasonal performance factor, which is the average efficiency of the pump over the heating and cooling period or the seasonal energy efficiency ratio for cooling, which is the total cooling output of an air conditioner during its normal annual usage period for cooling divided by the total electric energy input during the same period. The COP or EER of GCHPs usually is higher than those of the common heat pumps and especially their seasonal performance factor, due to the fact that the ground temperature is more stable during the year, cooler in summer, and hotter in winter than the ambient air (Florides et al., 2011).

Both types of GHEs, open or closed loop, are pollutant free since the only effect they have on the ground is the small increase or decrease of its temperature in a certain distance around the borehole. The efficiency of GCHP depends on the temperature of the cold reservoir (T_C) and the temperature of the hot reservoir (T_H). For the same value of T_C, the efficiency of the refrigerator becomes greater when T_H is lower, that is the smaller the difference between T_H and T_C, the greater the COP. In equation form the ideal reversible Carnot cycle COP is given by:

$$\mathrm{COP} = \frac{T_C}{T_H - T_C} \tag{1.1}$$

For example, calculating the thermodynamic COP of an ideal air-conditioning unit, working at an environmental temperature of 35 °C and a room temperature of 20 °C, with 5 °C expansion temperature and 60 °C compression temperature, we get a thermodynamic COP of 5.05 [= 278/(333 − 278)]. It should be noted that this number will be around 3.7 for an actual unit. By keeping the same variables as above, but reverting into a ground-coupled refrigerator exchanging heat with the ground at 22 °C and with the compression temperature reduced to 35 °C instead of 60 °C, the thermodynamic COP increases to 9.26 [= 278/(308 − 278)] with obvious advantages in electricity consumption. Again in this case, the COP for an actual unit is around 7.7. GCHPs are considered to be improvement on the common water-cooled heat pumps.

1.6.4 Hydrogen

Hydrogen, though the most common element in the universe, is not found in its pure form on earth and must be either electrolyzed from water or stripped out from natural gas, both of which are energy-intensive processes that result in GHG emissions. Hydrogen is an energy carrier and not a fuel, as is usually wrongly asserted. Hydrogen produced electrolytically from wind or direct solar power sources and used in fuel cell vehicles can provide zero-emission transportation. As for any fuel, appropriate safety procedures must be followed. Although the hazards of hydrogen are different from those of the various hydrocarbon fuels now in use, they are not greater.

The basic question is how to produce hydrogen in a clean efficient way. Using natural gas, coal, or even nuclear power to produce hydrogen in many ways defeats the purpose of moving toward a future powered by hydrogen. In the first two instances, GHGs are emitted in the process of producing the hydrogen, whereas in the last case, nuclear waste is generated.

As a nearly ideal energy carrier, hydrogen will play a critical role in a new decentralized energy infrastructure that can provide power to vehicles, homes, and industries. However, the process of making hydrogen with fossil-based power can involve the emission of significant levels of GHGs.

Although the element of hydrogen is the most abundant one in the universe, it must be extracted from biomass, water, or fossil fuels before it can take the form of an energy carrier. A key issue in the future is to promote the generation of electricity from wind and then use that electricity to produce hydrogen.

Extracting hydrogen from water involves a process called *electrolysis*, defined as splitting elements apart using an electric current. Energy supplied from an external source, such as wind or the burning of a fossil fuel, is needed to drive the electrochemical reaction. An electrolyzer uses DC to separate water into its component parts, hydrogen and oxygen. Supplementary components in the electrolyzer, such as pumps, valves, and controls, are generally supplied with AC from a utility connection. Water is "disassociated" and ions are transported through the electrolyte. Hydrogen is collected at the cathode and oxygen at the anode. The process requires pure water.

Electrolysis of water is the decomposition of water (H_2O) into oxygen (O_2) and hydrogen (H_2) gas. This is achieved by passing an electric current through the water.

As shown schematically in Figure 1.9, an electric DC power source is connected to two electrodes, which usually are in the form of plates to increase the surface area, typically made from inert metals (platinum or stainless steel). By doing so hydrogen appears at the cathode, the negatively charged electrode, and oxygen will appear at the anode, the positively charged electrode. Under ideal conditions, the number of moles of hydrogen generated is twice the number of moles of oxygen.

Electrolysis of pure water requires excess energy otherwise the process is very slow. The efficiency of electrolysis is increased with the addition of an electrolyte, such as a salt, an acid, or a base. If electrolysis is applied in pure water, H^+ cations will accumulate at the anode and hydroxyl OH^- anions will accumulate at the cathode. Unless a very large potential is applied electrolysis of pure water is very slow, limited by the overall conductivity.

If a water-soluble electrolyte is added, the conductivity of the water increases considerably. The electrolyte disassociates into cations and anions; the anions move toward the anode and neutralize the buildup of positively charged H^+, whereas the cations move toward the cathode and neutralize the buildup of negatively charged OH^-.

Industrial electrolysis cells are very similar to basic unit shown in Figure 1.9, using platinum plates or honeycombs as electrodes in an attempt to increase the electrode's surface area.

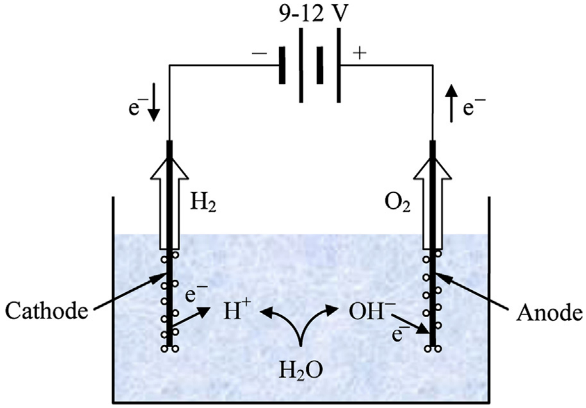

FIGURE 1.9

Schematic diagram of the process of electrolysis.

Two variations of the basic process are the high-pressure and high-temperature electrolysis. In high-pressure electrolysis hydrogen is compressed at around 120–200 bar. By pressurizing the hydrogen in the electrolyzer, the need for an external hydrogen compressor is eliminated whereas the average energy consumption for internal compression is very small of the order of 3%. High-temperature electrolysis, also called *steam electrolysis*, can combine electrolysis with a heat engine. High temperature increases the efficiency of electrolysis reaction and the process is very effective as generally heat energy is cheaper than electricity.

Despite considerable interest in hydrogen, however, there is a significant downside to producing it by means of fossil fuel-generated electricity due to the emissions related to the electrolysis process. Hydrogen fuel promises little GHG mitigation if a developing hydrogen economy increases demand for fossil fuel electricity. On the other hand, using cleanly produced hydrogen can fundamentally change our relationship with the natural environment.

Electrolytic hydrogen may be attractive in regions such as Europe, South and East Asia, North Africa, and the southwestern United States, where prospects for biomass-derived fuels are limited because of either high population density or lack of water. Land requirements are small for both wind and direct solar sources, compared with those for biomass fuels. Moreover, as with wind electricity, producing hydrogen from wind would be compatible with the simultaneous use of the land for other purposes such as ranching or farming. Siting in desert regions, where land is cheap and insolation is good, may be favored for PV–hydrogen systems because little water is needed for electrolysis. The equivalent of 2–3 cm of rain per year on the collectors—representing a small fraction of total precipitation, even for arid regions—would be enough.

Electrolytically produced hydrogen will probably not be cheap. If hydrogen is produced from wind and PV electricity, the corresponding cost of pressurized electrolytic hydrogen to the consumer would be about twice that for methanol derived from biomass; moreover, a hydrogen fuel cell car would cost more than a methanol fuel cell car because of the added cost for the hydrogen storage system. Despite these extra expenses, the life-cycle cost for a hydrogen fuel cell car would be marginally higher than for a gasoline internal combustion engine car, which is about the same as for a battery-powered electric vehicle.

The transition to an energy economy in which hydrogen plays a major role could be launched with hydrogen derived from biomass. Hydrogen can be produced thermochemically from biomass using the same gasifier technology that would be used for methanol production. Although the downstream gas processing technologies would differ from those used for methanol production, in each case the process technologies are well established. Therefore, from a technological perspective, making hydrogen from biomass is no more difficult than making methanol. Biomass-derived hydrogen delivered to users in the transport sector would typically cost only half as much as hydrogen produced electrolytically from wind or PV sources.

Probably the best way to utilize hydrogen is with a fuel cell. A *fuel cell* is an electrochemical energy conversion device in which hydrogen is converted into electricity. Generally, fuel cells produce electricity from external supplies of fuel (on the anode side) and oxidant (on the cathode side). These react in the presence of an electrolyte. Generally, the reactants flow in and reaction products flow out while the electrolyte remains in the cell. Fuel cells can operate continuously as long as the necessary flows are maintained. A hydrogen cell uses hydrogen as fuel and oxygen as an oxidant. Fuel cells differ from batteries in that they consume reactants, which must be replenished, whereas batteries store electrical energy chemically in a closed system. Additionally, while the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are catalytic and relatively stable. More details on fuel cells are given in Chapter 7.

1.6.5 Ocean energy

The various forms of ocean energy are abundant but often available far away from the consumer sites. The world's oceans have the capacity to provide cheap energy. Right now, there are very few ocean energy power plants, and most are fairly small.

The energy of the ocean can be used in three basic ways (Energy Quest, 2007):

- Use the ocean's waves (wave energy conversion).
- Use the ocean's high and low tides and tide currents (tidal energy conversion).
- Use temperature differences in the water (ocean thermal energy conversion (OTEC)).

Unlike other renewable energy sources that rely on sophisticated technologies and advanced materials, such as PVs, most ocean renewable energy systems are inherently simple, since they are made from concrete and steel. Additionally, most of the ocean systems rely on proven technologies, such as hydraulic rams and low-head hydropower turbines and impellers. The ocean's energy resource is large and well understood. It is superior to wind and solar energy, since ocean waves and currents traveling in deep water maintain their characteristics over long distances and the state of the sea can easily be predicted accurately more than 48 h in advance. Therefore, although wave energy is variable, like all renewable energy sources, it is more predictable than solar or wind energy. Similarly, tidal currents are created because of the interaction of the tides and the ocean floor and are thus very predictable and generally more constant than wind and solar energy. Additionally, the high density of water makes the resource concentrated, so moving water carries a lot of energy (Katofsky, 2008). The disadvantage of ocean systems is the need to apply mechanical systems that must be robust and withstand the harsh marine environment.

Wave energy conversion systems convert the kinetic energy of the waves into mechanical energy directly to drive a generator to produce electricity in a special construction, where the oscillating movement of waves is converted into air pressure. This in sequence drives a special wind turbine to produce electricity. Obviously the larger the relative height of the waves, the better. The waves must also be present for many hours of the year.

Tidal energy systems again utilize special turbines or propellers located underwater, which convert the movement of the water due to the tide into mechanical energy to drive an electric generator to produce electricity. Tide is a consequence of the rotation of the moon around the earth and local geography of the seafloor and coastlines. These systems are feasible in places where the tide distance is extended to hundreds of meters. The greatest advantage of these systems is that tides are easily predictable.

Finally, the OTEC systems use the temperature difference of surface and deep water to produce energy. Rankine cycle using a low-pressure turbine is the most employed heat cycle for OTEC. Both closed-cycle and open-cycle engines can be employed. Closed-cycle engines use refrigerants (ammonia or R-134a) as the working fluids, whereas open-cycle engines use vapor produced from the seawater itself as the working fluid. OTEC can also supply cold water as a by-product, which can be used for air-conditioning and refrigeration.

The various ocean energy systems are described briefly in the following sections.

Wave energy

Wave power is the transport of energy by ocean surface waves and the harnessing of that energy to produce useful work such as electricity generation and seawater desalination. The equipment used to exploit wave power is called a wave energy converter (WEC).

Kinetic energy (movement) exists in the moving waves of the ocean and can be used to power a turbine. These systems fundamentally convert the kinetic energy of the waves into electricity by capturing either the vertical oscillation or the linear motion of the waves. Individual devices range in sizes of about 100 kW to about 2 MW (Katofsky, 2008). In the simple example shown in Figure 1.10, the wave rises into a chamber. The rising water forces the air out of the chamber. The moving air spins a turbine that can turn a generator. When the wave goes down, air flows through the turbine and back into the chamber through doors that are normally closed.

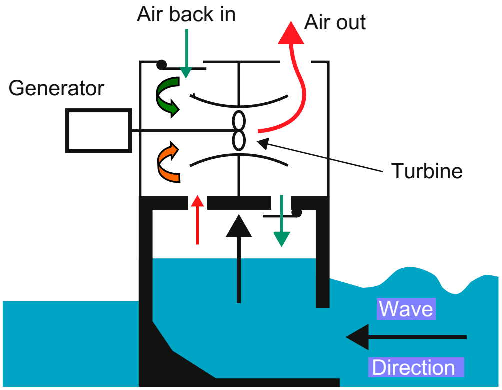

FIGURE 1.10

Principle of operation of a wave energy converter.

This is only one type of wave energy system. Others actually use the up-and-down motion of the wave to power a piston that moves up and down inside a cylinder. That piston can also turn a generator. Most wave energy systems are very small and are applied mainly to power a warning buoy or small lighthouses.

Although a massive potential exists, wave power generation is not currently a widely employed commercial technology. The first attempts to use this power date back to 1890. Only quite recently, in 2008, the first experimental wave farm was opened in Portugal, at the Aguçadoura Wave Park.

Waves are generated by wind blowing over the surface of the seawater. When the waves propagate at a slower speed than the wind speed, at the boundary of the two media an energy transfer exists from the wind to the waves. The wave height is determined by wind speed, the depth, and topography of the seafloor and by the duration of time the wind is blowing. Generally, the larger the waves the more powerful they are whereas the wave power depends also on the water density and wave speed and wavelength. It should be noted that a matching practical limit exists and variations in time or distance will not produce larger waves and thus when this limit is reached, the waves are fully developed.

One of the first applications of wave power was constructed around 1910 by Bochaux-Praceique, used to power his house at Royan, a small seaside city near Bordeaux in France. This was the first oscillating water column-type WEC. Subsequently, the research on wave energy carried out by Yoshio Masuda in the 1940s was very important as he tested various concepts of wave energy devices at sea to power navigation lights.

The interest in wave energy was renewed in the 1970s, motivated by the first oil crisis. At this time a number of researchers re-investigated the potential of generating useful energy from ocean waves and some important inventions were produced, like the Salter's or Edinburgh Duck developed by Stephen Salters in 1974. This unit attained a remarkable efficiency of 81% as the Duck's curved cam-like body can stop 90% of wave motion and convert 90% of that energy to useful electricity. More recently, the interest in wave energy as a renewable energy system has grown due to climate change issues.

Wave power devices are mainly classified according to the method used to capture the wave energy (point absorber or buoy, oscillating water column, tapered channels, oscillating flaps), location (shoreline, nearshore and offshore), and the power delivery system (elastomeric hose pump, pump to shore, hydroelectric turbine, hydraulic ram, and air turbine). Parabolic or tapered channel reflectors are used to amplify the height of the wave and create a head of water, which can be used to drive a conventional low-head hydro turbine (Sorensen, 2009b). Another design uses a flap that oscillates because of the action of the moving waves like a pendulum and this motion can be converted into electricity using hydraulic rams (Sorensen, 2009b). Once this energy is captured and converted into electricity, power must be transported to the point of use or connected to the grid. Some of the important applications of WECs are the following:

- *Protean WEC*. When deployed this system sits on the ocean surface and converts the relative movement between the static ocean floor and the floating buoy into energy.
- *Pelamis WEC*. This consists of a series of semi-submerged cylindrical sections linked by hinged joints. As waves pass along the length of the converter the sections move relative to one another and the wave-induced motion of the sections is resisted by hydraulic cylinders, which pump

high-pressure oil through hydraulic motors. Finally, the hydraulic motors drive the electrical generator to produce electricity.

- *Wave Dragon energy converter.* In the Wave Dragon large wing reflectors focus the waves up a ramp into an offshore reservoir. The water returns to the ocean by the force of gravity via hydroelectric generators.

Although wave energy conversion is still in the early development stage and a realistic picture of costs is impossible to be made, initial estimates give values of about €0.06–€0.12 per kWh (Sorensen, 2009b).

Tidal energy

Another form of ocean energy system is called *tidal energy*. This is a form of hydropower system that converts the energy of tides into electricity. When tides come into the shore, they can be trapped in reservoirs behind dams. Then when the tide drops, the water behind the dam can be allowed to flow, just like in a regular hydroelectric power plant. Tidal technologies can also employ underwater turbines or propellers driven by the flowing water. Such technologies can be deployed in streams and rivers as well.

Tidal energy has been used since about the eleventh century, when small dams were built along ocean estuaries and small streams. The tidal water behind these dams was used to turn water wheels to mill grains. Tidal barrage systems are in commercial operation in a few locations, but their further development is questionable because of their environmental impact in blocking off large estuaries (Katofsky, 2008).

Tidal energy works well when there is a large increase in tides. An increase of at least 5 m between low tide and high tide is needed. There are only a few places on earth where this tide change occurs.

Some power plants are already operating using this idea. One plant, the La Rance Station, in France, makes enough energy from tides (240 MW) to power 240,000 homes. It began making electricity in 1966. It produces about one-fifth of a regular nuclear or coal-fired power plant. It generates more than 10 times the power of the next largest tidal station in the world, the 17 MW Canadian Annapolis station.

Although tidal power is not widely adopted yet, it has the potential to supply large quantities of electricity in the near future. The greatest advantage of these systems compared with other renewable energy systems is that tides are more predictable than wind energy and solar power. Despite this, the costs involved are still relatively high and there is a limited availability of sites with high tidal potential. Many recent technological achievements in system and turbine designs, however, with the adoption of new axial and cross-flow turbines, give promise for a much lower cost of electricity produced.

Tidal forces are created because of the periodic variations in gravitational attraction exerted by celestial bodies, and they create motions or currents in the oceans of the earth. The intensity of this motion depends mainly on the earth rotation, the position of the moon and sun relative to the earth, and the local topography of the seafloor and coastline. The greatest effect is due to the orbital characteristics of the earth–moon system, and to a lesser extent in the earth–sun system. Because the earth's tides and currents are due to the rotation of the earth and the gravitational interaction with the moon and sun, this form of energy resource is renewable and practically inexhaustible. Other currents are caused by geothermal gradients.

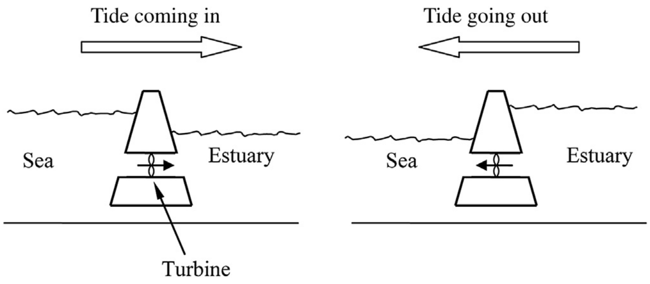

FIGURE 1.11

Principle of operation of tidal barrage.

The conversion of tidal currents is similar to the conversion of kinetic energy from the wind. Therefore, many of the proposed designs to harness this potential have resemblances to the wind turbines. As the water density is much bigger than that of air much higher energy densities are present, which leads to lower exploitable current velocities and smaller diameter turbines.

A tidal generator converts the energy of tides and currents into useful electricity. As can be understood, the greater the tidal variation and the higher the tidal current velocities, the greater is the potential of a site for electricity generation. Tidal power can be classified into three generating methods:

- *Tidal stream generator*. Tidal stream generators use the kinetic energy of moving water to power turbines, similar to the way wind turbines use wind.
- *Tidal barrage*. Tidal barrages use the potential energy created because of the difference in hydrostatic height between high and low tides. Barrages are in fact dams constructed across the opening of a tidal estuary (see Figure 1.11).
- *Dynamic tidal power*. Dynamic tidal power is not applied yet. In principle it is a technology that could convert the kinetic energy in tidal flows or currents into useful electricity. Systems can be built into the sea or ocean, without enclosing an area. For this purpose wind-type turbines can be used underwater.

A horizontal axis turbine comprises a propeller with two or more blades. The turbine can be mounted on a tower fixed to the seafloor, which is more suitable for shallow waters, or can be deployed below a floating support, for deep waters. To increase the efficiency of a horizontal axis turbine, the water flow around the turbine can be controlled with a shroud. These designs however are large underwater constructions and to avoid problems, sites of major shipping lanes and local fisheries must be avoided (Sorensen, 2009b).

Ocean thermal energy conversion

OTEC systems use the temperature difference of surface and deep water to make energy. This idea is not new but actually dates back to 1881, when a French engineer by the name of Jacques D'Arsonval first thought of OTEC. Ocean water gets colder the deeper you go from the surface, and at a great depth the ocean gets very cold. It is warmer on the surface because sunlight warms the water.

Power plants can be built that use this difference in temperature to make energy. A difference of at least 21 °C is needed between the warmer surface water and the colder deep ocean water. Using this type of energy source, an OTEC system is being demonstrated in Hawaii.

OTEC relies on the principle of thermodynamics that a source of heat and a source of cold can be used to drive a heat engine. It is well known from the laws of thermodynamics that a heat engine gives greater efficiency and power when a large temperature difference exists. In the oceans the temperature difference between surface and deep water is quite low in the order of 20–25 °C. So the main technical challenge of OTEC is to generate significant amounts of power efficiently from small temperature difference. The greatest temperature differences can be found in the tropics, and these offer the greatest possibilities for OTEC. Tropical oceans have surface water temperatures between 24 °C and 33 °C, whereas the temperature 500 m below the surface temperature drops between 9 °C and 5 °C (Sorensen, 2009b). Maps of the word showing the magnitude of the resource are presented by Rajagopalan and Nihous (2013). A temperature difference of about 20 °C gives a thermodynamic efficiency of 6.7% but when pumping energy is considered, this drops to about 3% as OTEC cycles must compensate with several cubic meters per second seawater flow rates per MW of net electricity produced. For example to generate 1 MW of electricity an OTEC plant requires 4 m^3/s of warm seawater and 2 m^3/s of cold seawater. To supply a 100 MW plant a pipe 11 m in diameter would be required (Sorensen, 2009b). These systems have the potential to offer great amounts of energy although a variation of 1 °C in the seawater thermal resource corresponds to a change in net power output of 15% (Rajagopalan and Nihous, 2013). OTEC plants, however, can operate continuously providing a base load supply of electrical power.

The first operational OTEC system was built in Cuba in 1930 and generated 22 kW. The most commonly used heat cycle for OTEC is the Rankine employing a low-pressure turbine and systems can be either closed cycle or open cycle. The former cycles use volatile working fluids (refrigerants) such as ammonia or R-134a, whereas open-cycle engines use vapor produced from the seawater. Useful by-products of OTEC system are the supply of large quantities of cold water, which can be used for air-conditioning or refrigeration and freshwater distilled from the sea, which can be used as a freshwater supply. Additionally the fertile deep ocean water can feed various biological processes. A schematic diagram of possible applications of OTEC is shown in Figure 1.12.

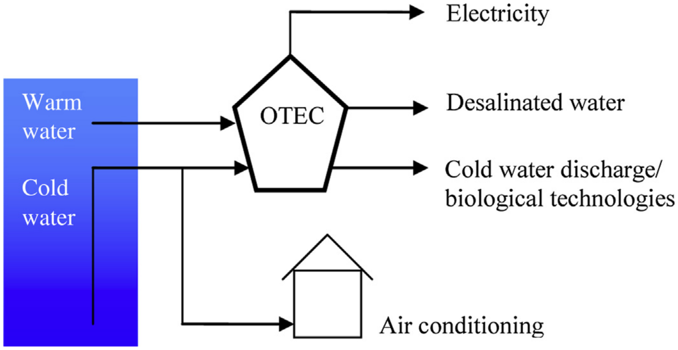

FIGURE 1.12

OTEC applications.

Three types of thermodynamic cycles can be used for OTEC; open, closed, and hybrid. One of the main problems is to pump the cold seawater from the deep ocean to the surface. This can be achieved by ordinary pumping and desalination. In the latter, desalinating seawater at the ocean floor lowers its density and this is the driving force to raise it to the surface. An alternative to high-cost pipes, which bring cold water to the surface, is to pump a vaporized low-boiling-point fluid into the required depth, which reduces pumping volume with consequent lowering of the costs. In any case OTEC plants require a long large diameter intake pipe, which is usually 1 km or more in length, to bring cold water to the surface.

Open-cycle OTEC uses warm surface water to produce electricity directly by pumping it in a low-pressure container, which causes its boiling. The expanding steam thus produced drives a low-pressure turbine/generator set. The steam produced in this way is pure freshwater, which is finally condensed by exposing it to cold temperatures from deep ocean water. This method produces also desalinated freshwater, which is an added advantage.

Closed-cycle systems use a fluid with low boiling point, such as ammonia or other refrigerants, expanding in a turbine so as to generate electricity. To achieve this, warm surface seawater is pumped through a heat exchanger to vaporize the volatile fluid. Cold water, which is pumped through a different heat exchanger, condenses the vapor, which is then recirculated through the system.

A hybrid cycle, as its name implies, combines the characteristics of both closed- and open-cycle systems. In these systems, warm seawater is fed in a vacuum chamber where it is flash evaporated, as in the open-cycle process. The steam thus produced vaporizes the working fluid, which is usually ammonia, of a closed-cycle loop on the other side of the evaporator. The vaporized working fluid then drives a turbine/generator unit while the steam condensed within the heat exchanger is used to produce desalinated water.

OTEC has the potential to produce large quantities of electrical power. For this purpose a number of systems have been proposed generally falling into three categories; land based, shelf based, and floating.

Land-based or near-shore facilities offer a number of advantages over those located in water; they do not require sophisticated mooring and lengthy power cables and compared with the open-ocean systems they require simple maintenance. These systems can be installed in sheltered areas to protect them from storms and the weather. Additionally, all products such as electricity, desalinated water, and cold water can be transmitted easily to the grid and water network.

Shelf-based OTEC plants can be mounted on a shelf at depths up to about 100 m to avoid the turbulent wave zone and to be closer to the cold water resource. This type of plant can be fixed to the sea bottom, similar to the way used for offshore oil rigs. Because of the conditions encountered by operating an OTEC plant in deeper water and open ocean, the expenditure involved is bigger compared with land-based systems. There are also problems associated with the difficulties related to the delivery of the produced electricity and freshwater. In fact, depending on the distance of the plant from the shore, power delivery can require long underwater cables, which makes shelf-mounted plants less attractive.

As their name implies, floating OTEC plants are located off-shore on special platforms and although they can be used for large power systems, they present a number of difficulties, for example related to the fixing of the platform with cables to the seabed and the power delivery. For the latter the problems are similar to those presented by the shelf-mounted system, whereas cables attached to floating platforms are more prone to damage, especially during heavy storms.

Exercise

Perform a review of the current status of energy consumption, by sector and type of fuel, and the current status of the use of renewables in your country. It is highly recommended that you use data from the statistical service of your country and the Internet. Suggest various measures to increase the contribution of renewables.

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