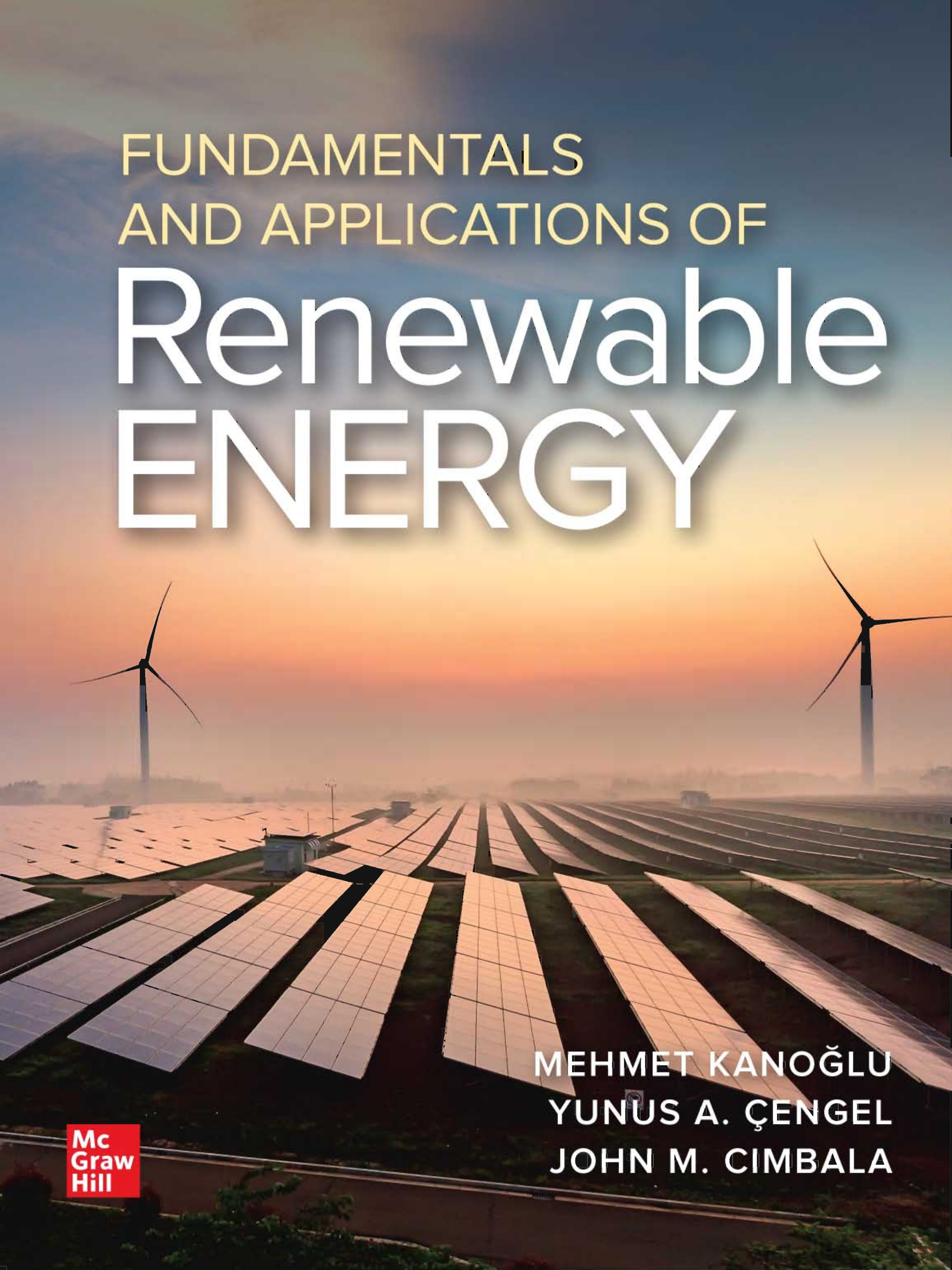

FUNDAMENTALS AND APPLICATIONS OF Renewable ENERGY

MEHMET KANOĞLU
YUNUS A. ÇENGEL
JOHN M. CIMBALA

Mc Graw Hill

Fundamentals and Applications of

Renewable Energy

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Dr. Kanoğlu has served as an instructor in certified energy manager training programs and as an expert for the United Nations Development Programme (UNDP) for renewable energy and energy efficiency projects. He instructed numerous training courses and gave lectures and presentations on renewable energy systems and energy efficiency. He has also served as advisor for state research funding organizations and industrial companies.

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Dr. Çengel is the recipient of several outstanding teacher awards, and he has received the ASEE Meriam/Wiley Distinguished Author Award for excellence in authorship in 1992 and again in 2000. Dr. Çengel is a registered professional engineer in the State of Nevada, and is a member of the American Society of Mechanical Engineers (ASME) and the American Society for Engineering Education (ASEE).

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Contents

Preface

BACKGROUND

The concern over the depletion of fossil fuels and pollutant and greenhouse emissions associated by their combustion can be tackled by essentially two methods: (1) using renewable energy sources to replace fossil fuels; (2) implementing energy efficiency practices in all aspects of energy production, distribution, and consumption so that less fuel is used while obtaining the same useful output. Energy efficiency can only reduce fossil fuel use while renewable energy can directly replace fossil fuels. The main renewable energy sources include solar, wind, hydropower, geothermal, and biomass. Wave and tidal energies are also renewable sources but they are currently not economical and the technologies are still in the developmental stage.

ABOUT THE BOOK

The study of renewable energy typically involves many different sciences including thermodynamics, heat transfer, fluid mechanics, geophysics, and chemistry. In this textbook, the primary emphasis is on thermodynamics, heat transfer, and fluid mechanics aspects of renewable energy systems and applications. This book provides an overview of common systems and applications for renewable energy sources. Systems are described and their fundamental analyses are provided.

The importance of renewable energy is relatively well-understood and there are numerous books written on the subject. However, most of these books are concentrated on providing general information and practical guidance for practicing engineers and the public, and most books are not suitable as a textbook for classroom use. This book is primarily intended as a textbook for an upper level undergraduate textbook for all relevant engineering majors. It may also be used as a convenient reference book for engineers, researchers, policy makers, and anyone else interested in the subject. This book provides insight into both the scientific foundations and the engineering practice of renewable energy systems. The thermodynamics, heat transfer, fluid mechanics, and thermochemistry background needed for the study of renewable energy is readily provided and thus the need for prerequisite courses is greatly minimized. This allows the use of this book for a variety of engineering majors since not all students may have backgrounds related to all thermal science courses. The book features both technical and economic analyses of renewable systems. It contains numerous practical examples and end-of-chapter problems and concept questions as well as multiple-choice questions.

OVERVIEW OF TOPICS

The first chapter covers the general energy picture of the world, a brief introduction to renewable energy systems, and a discussion of various fossil fuels. Chapter 2 provides a comprehensive review of thermal-fluid sciences needed for studying renewable energy systems including thermodynamics, heat transfer, fluid mechanics, thermochemistry, power plants, and refrigeration systems. Chapter 3 is on fundamentals of solar energy and Chap. 4 is on solar energy systems and applications. Chapters 5, 6, 7, 8, and 9 cover wind, hydro, geothermal, biomass, and ocean (OTEC, wave, and tidal) energies, respectively. Hydrogen is introduced as an energy carrier and the principles of fuel cells are described in Chap. 10. Chapter 11 describes engineering economic analyses of renewable energy projects. Finally, environmental effects of energy are covered in Chap. 12.

KEY FEATURES

- A comprehensive review of thermodynamics, heat transfer, fluid mechanics, thermochemistry, power plants, and refrigeration systems
- Technical and economic analysis of renewable energy systems
- Rigorous descriptions and analyses of renewable energy systems and applications including concepts and formulations
- Approximately 75 worked-out example problems throughout the chapters
- Over 850 end-of-chapter problems including conceptual and multiple-choice questions

UNIT SYSTEM

In recognition of the fact that English units are still widely used in some industries, both SI and English units are used in this text, with a primary emphasis on SI. The material in this text can be covered using combined SI/English units or SI units alone, depending on the preference of the instructor. The property tables in the appendices are presented in both units.

ACKNOWLEDGMENTS

The authors would like to acknowledge with appreciation the numerous and valuable comments, suggestions, constructive criticisms, and praise from several students and colleagues. Special thanks go to Dr. Mehmet Fatih Orhan, Dr. Ceyhun Yilmaz, and Tuğberk Hakan Çetin for their help in the preparation and checking of the manuscript. We would like to express our appreciation to our family members for their continued patience, understanding, inspiration, and support throughout the preparation of this text.

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Yunus A. Çengel
John M. Cimbala

Fundamentals and Applications of

Renewable Energy

CHAPTER 1

Introduction to Renewable Energy

1-1 WHY RENEWABLE ENERGY?

To meet its energy needs, the world community currently depends heavily on fossil fuels that are nonrenewable and unfriendly to the environment. Table 1-1 presents total world delivered energy consumption based on end-use sector and fuel type. Breakdown of each fuel by sector and each sector by fuel is also provided. As shown in Fig. 1-1, more than half of the global energy is used by the industrial sector (54.6%), followed by the transportation sector with 25.6 percent, the residential sector with 12.7 percent, and the commercial sector with 7.1 percent (EIA, 2018). Energy use is expected to increase worldwide, driven mainly by industry, but this will mostly take place in developing countries with strong economic growth.

Total global energy supply in 2017 was 589 Quad Btu, which is equivalent to 5.6×10^{17} kJ. Fossil fuels accounted for 82.7 percent (27.1% coal, 33.4% oil, 22.2% natural gas) of this total energy production. Renewable energy (including hydroelectric power), which is environment-friendly and can be harvested indefinitely, was responsible for 12.7 percent of the total energy supply globally. Nuclear power supplied the remaining 4.6 percent of the total energy supply (Fig. 1-2) (EIA, 2018).

In 2015, total electricity generation in the world was 24,255 TWh (or 24.255×10^{12} kWh since 1 TWh = 1 billion kWh = 10^9 kWh). Fossil fuels accounted for 66.3 percent of total electricity generation in the world with 39.3 percent for coal, 22.9 percent for natural gas, and 4.1 percent for oil. Renewable energy (including hydroelectric power) and nuclear power were responsible for 23.1 percent and 10.6 percent of global electricity generation, respectively (Fig. 1-3). A total of 5603 TWh (or 5.603×10^{12} kWh) of renewable electricity was generated that year (IEA, 2017).

Total installed capacity of electricity in the United States in 2016 was 1074 GW, and the U.S. power plants generated 4077 TWh (4.077×10^{12} kWh) of electricity that year. Figure 1-4 shows the percentages of electricity generation in the United States by the fuel type and source. Approximately 83.9 percent of electricity was generated by coal, natural gas, and nuclear power plants. The remaining 16.1 percent was generated mostly by renewable sources including hydro (6.5%) and wind (5.5%). The remaining generation was due to biomass, solar, and geothermal (EIA, 2018).

A comparison of U.S. electricity production data to global electricity generation data shows that the share of renewable electricity in the United States is considerably less than that in the world. Therefore, great potential exists to increase the share of renewables in

TABLE 1-1 Total World Delivered Energy Consumption by End-Use Sector and Fuel in 2017 (EIA, 2018)

All values are in Quad Btu (quadrillion Btu). (1 quadrillion Btu = 1×10^{15} Btu = 0.95×10^{15} kJ)

Fuel	Total	Electricity	Residential	Commercial	Industrial	Transportation	All End-Use Sectors
Oil*	196.7	6.7	8.5	3.9	69.7	106.7	188.8
Natural gas	130.7	44.0	20.6	8.8	53.2	4.1	86.6
Coal	159.8	90.5	4.3	1.6	63.5	0.0	69.4
Nuclear	26.9	26.9	—	—	—	—	—
Electricity	—	—	21.0	16.8	35.1	1.6	74.5†
Renewables	74.9	55.5	1.3	0.2	17.9	—	19.4
Total	589.0	223.6†	55.7	31.3	239.4	112.4	438.8

*The values given for oil also include other nonpetroleum liquid fuels such as ethanol, biodiesel, coal-to-liquids, natural gas liquids, and liquid hydrogen.

†The difference between the total energy value of fuel consumption to produce electricity (223.6 Quad Btu) and the actual amount of electricity consumed by all end-use sectors (74.5 Quad Btu) is equal to the energy lost during the production of electricity, which is equal to 223.6 − 74.5 = 149.1 Quad Btu. As a result, the difference between the totals in the second and last column is also equal to 589.0 − 438.8 = 150.2 Quad Btu, which is very close to 149.1 Quad Btu.

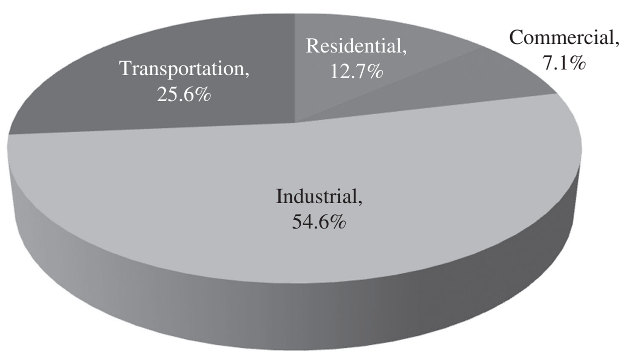

Figure 1-1 Percentages of global energy use by end-use sectors in 2017 (*EIA, 2018*).

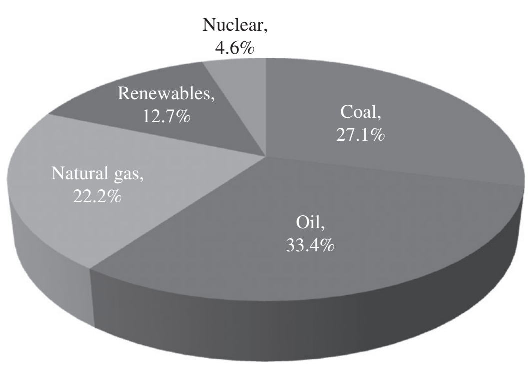

Figure 1-2 Percentages of total world primary energy supply by fuel in 2017 (*EIA, 2018*).

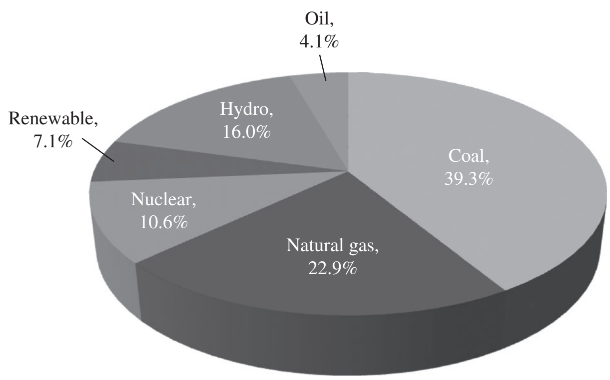

Figure 1-3 Percentages of global electricity generation by fuel type and source in 2015. Total electricity generation = 24,255 TWh (*IEA, 2017*).

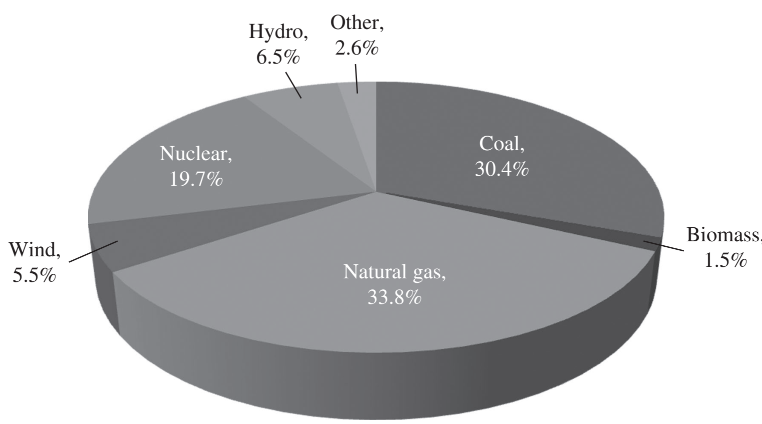

Figure 1-4 Percentages of electricity generation by fuel type and source in the United States in 2016 (*EIA, 2018*).

the U.S. energy mixture. In 2000, only nine percent of electricity came from renewables, and EIA (2018) projections indicate that the renewables will constitute 18 percent of electricity generation by 2040. Coal- and nuclear-based electricity generations are expected to decrease in the coming years, but natural gas electricity generation is expected to increase due to additional shale gas reserves.

Renewable electricity generation by source in the United States is given in Fig. 1-5. Total generation by renewables was about 640 billion kWh in 2017. This is projected to increase above 1600 billion kWh by the year 2050. Renewable electricity generation in 2017 is dominated by hydropower and wind, but solar electricity increased at the highest rate among all energy sources. Solar electricity is estimated to take the greatest share by the year 2050, followed by wind, hydropower, and geothermal. Other renewables represented in Fig. 1-5 are due mostly to biomass electricity production by the means of MSW/LFG (municipal solid waste/land fill gas) (EIA, 2018).

Renewables are currently the fastest-growing energy source in the world. Depletion and emission concerns over fossil fuel use and increasing government incentives can cause even higher growth in the use of renewables in the coming decades. The fastest-growing

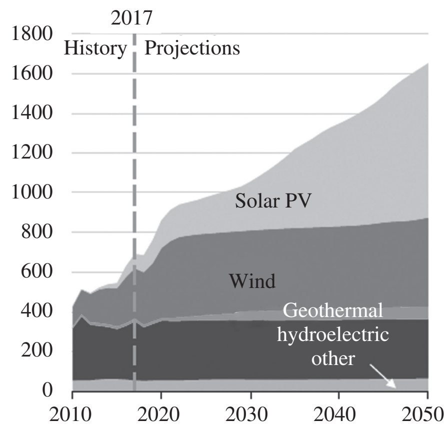

Figure 1-5 Renewable electricity generation by source in the United States, in billion kWh (*EIA, 2018*).

renewable sources are solar and wind. The installed wind capacity has increased from 18 GW in 2000 to 539 GW by the end of 2017. The solar power capacity has increased by 97 GW in 2017 bringing the global capacity to over 400 GW. The installed capacity of hydropower exceeds 1250 GW worldwide. Hydroelectric, geothermal, and wind power generation technologies are able to compete with fossil fuel–based electricity generation economically, but solar electricity generation is still expensive. However, steady decreases in solar electricity cost combined with increased government incentives are likely to help wider use of solar electricity in the coming years.

EXAMPLE 1-1 An Analysis of World Energy Consumption

In Table 1-1, the total energy consumption by different energy sources is given to be 589.0 Quad Btu while the total energy use by all end-use sectors is 438.8 Quad Btu. Explain the difference between these two values. Using the data in Table 1-1, calculate the total amount of energy lost during the production of electricity by all energy sources. Also, calculate the amount of electricity produced in kWh and the overall thermal efficiency of electricity production by all energy sources.

SOLUTION The difference between the total energy value of fuel consumption to produce electricity (223.6 Quad Btu, third column, last row) and the actual amount of electricity consumed by all end-use sectors (74.5 Quad Btu, last column, fifth row) is equal to the energy lost during the production and distribution of electricity, which is equal to

$$\text{Energy lost} = 223.6 - 74.5 = \mathbf{149.1\ Quad\ Btu}$$

The difference between the totals in the second and last column is equal to

$$\text{Energy lost} = 589.0 - 438.8 = 150.2 \text{ Quad Btu}$$

which is very close to the value of 149.1 Quad Btu.

The amount of electricity produced is expressed in kWh as

$$\text{Electricity produced} = (74.5\times10^{15}\ \text{Btu})\left(\frac{1\ \text{kJ}}{0.94782\ \text{Btu}}\right)\left(\frac{1\ \text{kWh}}{3600\ \text{kJ}}\right)$$

$$= 21.83\times10^{12}\ \text{kWh} = \mathbf{21.83\ trillion\ kWh}$$

The thermal efficiency of a power plant is defined as the power produced divided by the energy consumed. According to the data in Table 1-1, 223.6 Quad Btu of energy is consumed in all power plants worldwide, and 74.5 Quad Btu of electricity is produced. The overall thermal efficiency of producing electricity is then

$$\eta_{\text{th,overall}} = \frac{\text{Electricity produced}}{\text{Energy consumed}} = \frac{74.5 \times 10^{15}\ \text{Btu}}{223.6 \times 10^{15}\ \text{Btu}} = 0.333 = \mathbf{33.3\%}$$

That is, about 67 percent of energy is lost during the conversion of energy sources (coal, oil, natural gas, renewable) into electricity. ▲

EXAMPLE 1-2 Ton of Oil Equivalent (toe) Unit Ton of oil equivalent (toe) is an amount of energy unit commonly used to express large amounts of energy. It represents the amount of energy released by burning 1 ton (1000 kg) of crude oil. One toe is taken equal to 41.868 GJ, sometimes rounded to 42 GJ. The power plants in the United States generated 4.05×10^9 MWh of electricity in a year. According to the data in Table 1-1, 74.5 Quad Btu of electricity is produced. Express these values in the toe unit. Also, determine the percentage of global electricity generation that occurred in the United States.

SOLUTION Noting that 1 MWh = 1000 kWh, 1 kWh = 3600 kJ, 1 GJ = 1×10^6 kJ, and 1 toe = 41.868 GJ, we express electricity generation in the United States in toe, as follows:

$$\text{Electricity generation (in U.S.)} = (4.05 \times 10^9\ \text{MWh})\left(\frac{1000\ \text{kWh}}{1\ \text{MWh}}\right)\left(\frac{3600\ \text{kJ}}{1\ \text{kWh}}\right)\left(\frac{1\ \text{GJ}}{1 \times 10^6\ \text{kJ}}\right)\left(\frac{1\ \text{toe}}{41.868\ \text{GJ}}\right)$$
$$= \mathbf{3.48 \times 10^8\ toe}$$

Noting that 1 Quad = 1×10^{15} Btu and 1 toe = 41.868 GJ, we express global electricity generation in toe, as follows:

$$\text{Electricity generation (world)} = (74.5\ \text{Quad})\left(\frac{1 \times 10^{15}\ \text{Btu}}{1\ \text{Quad}}\right)\left(\frac{1.055\ \text{kJ}}{1\ \text{Btu}}\right)\left(\frac{1\ \text{GJ}}{1 \times 10^6\ \text{kJ}}\right)\left(\frac{1\ \text{toe}}{41.868\ \text{GJ}}\right)$$
$$= \mathbf{1.88 \times 10^9\ toe}$$

The percentage of global electricity generation that occurred in the United States is determined to be

$$\text{Percent generation in U.S.} = \frac{\text{Electricity generation (U.S.)}}{\text{Electricity generation (world)}} = \frac{3.48 \times 10^8\ \text{toe}}{1.88 \times 10^9\ \text{toe}} = 0.185 = \mathbf{18.5\%}$$

That is, 348 million toe of electricity is generated in the United States and 1.88 billion toe of electricity is generated in the world. The U.S. electricity generation represents 18.5 percent of global generation. Note that toe unit is not normally used to express the amount of electricity. Instead some multiples of kWh such as MWh, GWh, and TWh are used. ▲

Consequences of Fossil Fuel Combustion

Fossil fuels have been powering industrial development and the amenities of modern life since the 1700s, but this has not been without undesirable side effects. Pollutants emitted during the combustion of fossil fuels are responsible for smog, acid rain, and numerous other adverse effects on the environment. Environmental pollution has reached such high levels that it has become a serious threat to vegetation, wildlife, and human health. Air pollution has been the cause of numerous health problems including asthma and cancer. But this fossil fuel–based economy is not sustainable since the estimated life of known reserves is limited. Therefore, the switch to renewable energy sources is inevitable.

Carbon dioxide (CO_2) is the primary greenhouse gas that contributes to global warming. Global climate change is widely regarded as due to the excessive use of fossil fuels such as coal, petroleum products, and natural gas in electric power generation, transportation, buildings, and manufacturing, and it has been a concern in recent decades. The concentration of CO_2 in the atmosphere as of 2019 is about 410 ppm (or 0.41%). This is 20 percent higher than the level a century ago. Various scientific reports indicate that the earth has already warmed about 0.5°C during the last century, and it is estimated that the earth's temperature will rise another 2°C by the year 2100. A rise of this magnitude is feared to cause severe changes in weather patterns with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, variations in water supply, changes in the ecosystem due to the inability of some animal and plant species to adjust to the changes, increases in epidemic diseases due to the warmer temperatures, and adverse side effects on human health and socioeconomic conditions in some areas.

The combustion of fossil fuels produces the following undesirable emissions (Fig. 1-6):

- CO_2, primary greenhouse gas: contributes to global warming
- Nitrogen oxides (NO_x) and hydrocarbons (HC): cause smog
- Carbon monoxide (CO): toxic
- Sulfur dioxide (SO_2): causes acid rain
- Particulate matter (PM): causes adverse health effects

Notice from this emissions list that CO_2 is different from the other emissions in that CO_2 is a greenhouse gas and a natural product of fossil fuel combustion while other emissions are harmful air pollutants.

The concern over the depletion of fossil fuels and pollutant and greenhouse emissions associated with their combustion can be tackled by essentially two methods:

1. Using renewable energy sources such as solar, wind, hydroelectric, biomass, and geothermal to replace fossil fuels.
2. Implementing energy efficiency practices in all aspects of energy production, distribution, and consumption so that less fuel is used while obtaining the same useful output.

Energy efficiency is to reduce energy use to the minimum level, but to do so without reducing the standard of living, production quality, and profitability. Energy efficiency is an expression for the most effective use of energy resources, and it results in energy conservation. Energy efficiency can only *reduce* fossil fuel use while renewable energy can directly *replace* it.

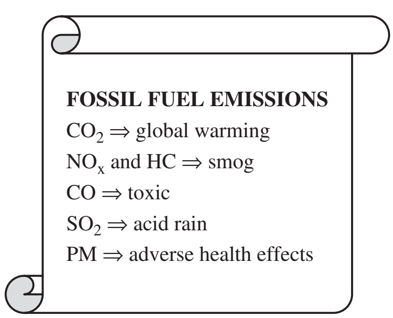

Figure 1-6 Effects of undesirable emissions from the combustion of fossil fuels.

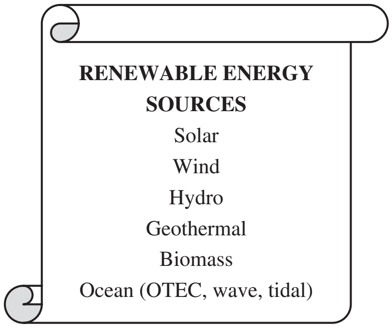

Figure 1-7 The switch from fossil fuels to renewable energy sources is inevitable.

Renewable Energy Sources

The main renewable energy sources include solar, wind, hydro, biomass, and geothermal (Fig. 1-7). Energy sources from the ocean, including ocean thermal energy conversion (OTEC), wave, and tidal, are also renewable sources, but they are currently not economical and the technologies are still in the experimental and developmental stage.

An energy source is called *renewable* if it can be renewed and sustained without any depletion and any significant effect on the environment. It is also called an *alternative*, *sustainable*, or *green* energy source (Fig. 1-8). Fossil fuels such as coal, oil, and natural gas, on the other hand, are not renewable, and they are depleted by use. They also emit harmful pollutants and greenhouse gases.

The best-known renewable source is *solar energy*. Although solar energy is sufficient to meet the entire energy needs of the world, currently it is not used as extensively as fossil fuels because of the *low concentration* of solar energy on earth and the *relatively high*

Figure 1-8 Renewable energies such as solar water collectors are called *green energy* since they emit no pollutants or greenhouse gases.

capital cost of harnessing it. The conversion of kinetic energy of wind into electricity via wind turbines represents *wind energy*, and it is one of the fastest-growing renewables as wind turbines are being installed all over the world. The collection of river water in large dams at some elevation and then directing the collected water into a hydraulic turbine is the common method of converting water energy into electricity. *Hydro* or *water energy* represents the greatest amount of renewable electricity production, and it supplies most of the electricity needs of some countries.

Geothermal energy refers to the heat of the earth. High-temperature underground geothermal fluid found in some locations is extracted, and the energy of the geothermal fluid is converted to electricity or heat. Geothermal energy conversion is one of the most mature renewable energy technologies. Geothermal energy is mostly used for electricity generation and district heating. Organic renewable energy is referred to as *biomass*, and a variety of sources (agriculture, forest, residues, crops, etc.) can be used to produce biomass energy. Biomass is becoming more popular with the help of the variety of available sources.

Wave and tidal energies are renewable energy sources, and they are usually considered as part of ocean energy since they are available mostly in oceans. Thermal energy of oceans due to absorption of solar energy by ocean surfaces is also considered as part of ocean energy, and this energy can be utilized using the OTEC system. Wave and tidal energies are mechanical forms of ocean energy since they represent potential and kinetic energies of ocean water.

Hydrogen is an energy carrier that can be used to store renewable electricity. It is still a developing technology, and many research activities are under way to make it viable. *Fuel cells* convert chemical energy of fuels (e.g., hydrogen) into electricity directly without a highly irreversible combustion process, and it is more efficient than combustion-based conversion to electricity.

All renewable energy sources can be used to produce useful energy in the form of electricity and some renewables can also produce thermal energy for heating and cooling applications. Wind and water energies are converted to electricity only while solar, biomass, and geothermal can be converted to both electricity and thermal energy (i.e., heat).

Electric cars (and other electricity-driven equipment) are often touted as "zero-emission" vehicles, and their widespread use is seen by some as the ultimate solution to the air pollution problem. It should be remembered, however, that the electricity used by the electric cars is generated somewhere else mostly by burning fossil fuels. Therefore, each time an electric car consumes 1 kWh of electricity, it bears the responsibility for the pollutants emitted as 1 kWh of electricity (plus the conversion and transmission losses generated elsewhere). The electric cars can be claimed to be zero-emission vehicles only when the electricity they consume is generated by emission-free renewable resources such as hydroelectric, solar, wind, and geothermal energy. Therefore, the use of renewable energy should be encouraged worldwide, with incentives, as necessary, to make the earth a better place to live.

We should point out that what we call *renewable energy* is usually nothing more than the manifestation of solar energy in different forms. Such energy sources include wind energy, hydroelectric power, ocean thermal energy, ocean wave energy, and wood. For example, no hydroelectric power plant can generate electricity year after year unless the water evaporates by absorbing solar energy and comes back as rainfall to replenish the water source (Fig. 1-9).

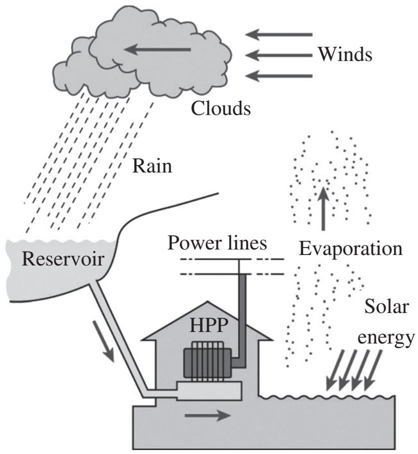

Figure 1-9 The cycle that water undergoes in a hydroelectric power plant (HPP).

1-2 FOSSIL FUELS AND NUCLEAR ENERGY

The main energy sources include coal, oil, natural gas, nuclear energy, and renewable energy (Fig. 1-10). Among these, coal, oil, and natural gas are fossil fuels. Fossil fuels are responsible for more than 90 percent of global combustion-related CO_2 emissions with 37 gigatons (37,000 million tons) in 2017. The shares of fossil fuels to the global CO_2 emissions are 45 percent for coal, 35 percent for oil, and 20 percent for natural gas (IEA, 2017). Here, we provide a short review of fossil fuels.

Coal

Coal is made of mostly carbon, and it also contains hydrogen, oxygen, nitrogen, sulfur, and ash (noncombustibles). The heating value of carbon is 32,800 kJ/kg. The percentages of carbon and other components vary depending on the production site. Energy content per unit mass (i.e., heating value) and sulfur content are among the important characteristics of coal. High energy content allows extraction of more heat from coal, making the fuel more valuable. Low sulfur content is crucial to meet emission limits of sulfur compounds. Coal is used mostly for electricity production in steam power plants. It is also used for space heating, water heating, and steam generation.

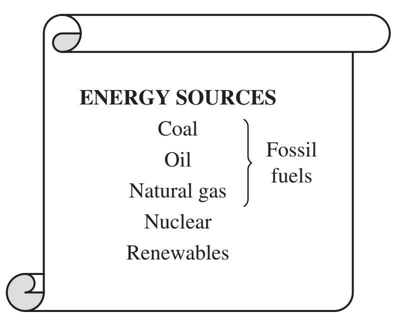

Figure 1-10 Main energy sources.

There are four common types of coal with the following general characteristics.

Bituminous coal: It is also known as *soft coal*. It has high energy content but unfortunately also has high sulfur content. A representative composition (referred to in the industry as an "assay") of this coal by mass is 67 percent carbon, 5 percent hydrogen, 8.7 percent oxygen, 1.5 percent nitrogen, 1.5 percent sulfur, 9.8 percent ash, and 6.7 percent moisture. The higher heating value for this particular composition of coal is 28,400 kJ/kg. Bituminous coal is primarily used for electricity generation in power plants.

Subbituminous coal: It has lower energy content due to lower fractions of carbon and hydrogen but also lower-sulfur content compared to bituminous coal. A representative composition of this coal by mass is 48.2 percent carbon, 3.3 percent hydrogen, 11.9 percent oxygen, 0.7 percent nitrogen, 0.4 percent sulfur, 5.3 percent ash, and 30.2 percent moisture. The higher heating value for this particular composition of coal is 19,400 kJ/kg. Subbituminous coal is primarily used for electricity generation and heating applications.

Anthracite coal: It is also known as *hard coal*. It is far less common compared to bituminous and subbituminous coals. It is used mainly for residential and industrial heating applications. Few coal-fired plants burn it. It contains 80 to 95 percent carbon with low sulfur and nitrogen content. The ash content is between 10 and 20 percent and the moisture content is 5 to 15 percent. Its heating value is typically higher than 26,000 kJ/kg.

Lignite: It is also known as *brown coal*. It is the lowest-quality coal with low energy content and high sulfur and moisture fraction. The carbon content is only 25 to 35 percent with a low heating value of less than 15,000 kJ/kg. The moisture and ash content can be as high as 75 and 20 percent, respectively. It is used mainly for electricity generation.

In the combustion of coal, hydrogen and sulfur burn first and carbon burns last. As a result, nearly all of the sulfur burns into SO_2 and nearly all of the hydrogen burns into H_2O by the following reactions:

$$S + O_2 \rightarrow SO_2$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

Carbon burns according to the following reactions:

$$C + \tfrac{1}{2}O_2 \rightarrow CO$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$

If some CO cannot find sufficient oxygen to burn with by the time combustion is completed, some CO is found in the combustion products. This represents a very undesirable emission as well as the waste of fuel as CO has energy content (the heating value of CO is 10,100 kJ/kg). This can happen even in the presence of stoichiometric or excess oxygen due to incomplete mixing and a short time for the combustion process.

Combustion of coal also causes pollutant emissions of unburned carbon particles, CO, unburned HC, SO_2, ash, and NO_x. The amount of CO_2 emission depends on the percentage of carbon in coal and the degree of completion of the combustion of carbon. Coal is considered to be the most polluting fossil fuel compared to liquid and gaseous fuels as well as being the largest contributor to global CO_2 emissions with about 40 percent.

EXAMPLE 1-3 Heating Value of Coal The assay of particular coal from Illinois is as follows by mass: 67.40 percent carbon (C), 5.31 percent hydrogen (H_2), 15.11 percent oxygen (O_2), 1.44 percent nitrogen (N_2), 2.36 percent sulfur (S), and 8.38 percent ash (noncombustibles). What are the higher and lower heating values of this coal? The heating value of sulfur is 9160 kJ/kg.

SOLUTION The combustible constituents in the coal are carbon C, hydrogen H_2, and sulfur S. The heating value of sulfur is given to be 9160 kJ/kg. The higher and lower heating values of hydrogen are 141,800 kJ/kg and 120,000 kJ/kg, respectively, and the heating value of carbon is 32,800 kJ/kg (Table A-7 in Appendix). Note that if the combustion of a fuel does not yield any water in the combustion of gases, the higher and lower heating values are equivalent for that fuel.

Using their mass fractions (mf), the higher heating value of this particular coal is determined as

$$\begin{aligned}\mathrm{HHV} &= \mathrm{mf_C} \times \mathrm{HHV_C} + \mathrm{mf_{H2}} \times \mathrm{HHV_{H2}} + \mathrm{mf_S} \times \mathrm{HHV_S} \\ &= (0.674)(32{,}800\ \mathrm{kJ/kg}) + (0.0531)(141{,}800\ \mathrm{kJ/kg}) + (0.0236)(9160\ \mathrm{kJ/kg}) \\ &= \mathbf{29{,}850\ kJ/kg}\end{aligned}$$

Similarly, the lower heating value of the coal is

$$\begin{aligned}\mathrm{LHV} &= \mathrm{mf_C} \times \mathrm{LHV_C} + \mathrm{mf_{H2}} \times \mathrm{LHV_{H2}} + \mathrm{mf_S} \times \mathrm{LHV_S} \\ &= (0.674)(32{,}800\ \mathrm{kJ/kg}) + (0.0531)(120{,}000\ \mathrm{kJ/kg}) + (0.0236)(9160\ \mathrm{kJ/kg}) \\ &= \mathbf{28{,}695\ kJ/kg}\end{aligned}$$

The difference between the higher and lower heating values is about 4 percent. ▲

Oil

Oil or petroleum is a mixture of a large number of HC with different compositions. Crude oil has 83 to 87 percent carbon and 11 to 14 percent hydrogen with small amounts of other components such as sulfur, nitrogen, oxygen, ash, and moisture. End products such as gasoline, light diesel fuel, jet fuel, LPG (liquefied petroleum gas), natural gas, and heavy diesel fuel (fuel oil) are obtained by distillation and cracking in oil refinery plants (Fig. 1-11). Nonpetroleum liquid fuels may include ethanol, biodiesel, coal-to-liquids, natural gas liquids, and liquid hydrogen.

Gasoline and light diesel fuel are used in automobiles and can be approximated by C_8H_{15} and $C_{12}H_{22}$, respectively. Diesel fuel also includes some sulfur, but the regulations in the United States and European Union already reduced the sulfur limit from about 300 to 50 and then to 10 ppm (parts per million). The higher heating values of gasoline and light diesel fuel are 47,300 and 46,100 kJ/kg, respectively.

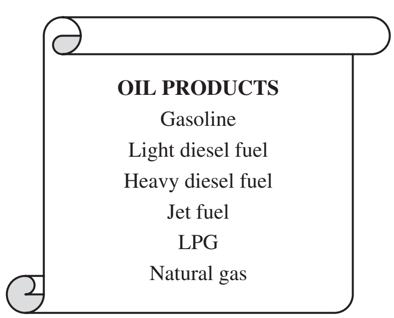

Figure 1-11 Main petroleum fuel products.

Oil is less commonly used for electricity generation compared to coal and natural gas. There are two groups of oil used in power plants and industrial heating applications:

Distillate oils: These are higher-quality oils that are highly refined. They contain much less sulfur compared to residual oils. A typical composition of distillate oils is 87.2 percent carbon, 12.5 percent hydrogen, and 0.3 percent sulfur. The higher heating value for this composition is 45,200 kJ/kg.

Residual oils: These oils undergo less refining. They are thicker with higher molecular mass, higher level of impurities, and higher sulfur content. A typical composition is 85.6 percent carbon, 9.7 percent hydrogen, 2.3 percent sulfur, 1.2 percent nitrogen, 0.8 percent oxygen, 0.1 percent ash, and 0.3 percent moisture. The higher heating value for this composition is 42,500 kJ/kg.

Natural Gas

Natural gas is mostly methane (CH_4) where its percentage varies between 60 and 98 percent. It also contains small amounts of ethane, propane, butane, nitrogen, oxygen, helium, CO_2, and other gases. It exists as a gas under atmospheric conditions and is stored as a gas under high pressure (15 to 25 MPa). It is mostly transported in gas phase by pipelines in and between cities and countries. When pipeline transportation is not feasible, it is first liquefied to about −160°C using advanced refrigeration technologies before being carried in large insulated tanks in marine ships. Natural gas is used in boilers for space heating, hot water and steam generation, industrial furnaces, power plants for electricity production, and internal combustion engines.

The higher and lower heating values of methane are 55,530 kJ/kg and 50,050 kJ/kg, respectively. The heating value of natural gas depends mainly on the fraction of methane. The higher is the methane fraction, the higher is the heating value. Natural gas is commonly approximated as methane without much sacrifice in accuracy. The heating value of natural gas is usually expressed in kJ/m^3 unit, and the higher heating value ranges from 33,000 to 42,000 kJ/m^3, depending on the resource. The lower heating value of natural gas is about 90 percent of its higher heating value. A comparison of higher heating values for various fuels is shown in Fig. 1-12.

Compared to coal and oil, natural gas is a cleaner fuel as it emits less pollutant emissions. Air quality in certain cities has improved dramatically when natural gas pipelines reached

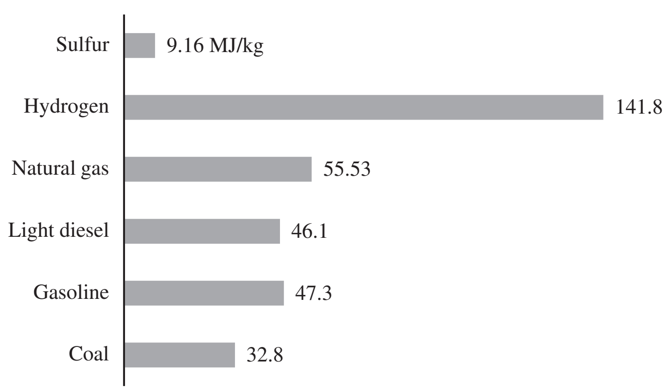

Figure 1-12 Higher heating values of various fuels, in MJ/kg. Coal is roughly approximated as carbon and natural gas as methane.

the city and heating systems running on coal were replaced by their natural gas counterparts. Usage of natural gas in public transportation (buses and taxis) is used as a measure to improve air quality in cities.

About 40 percent of the supply of natural gas is used by the industrial sector, while 33 percent is used for electricity generation in power plants (EIA, 2018). Residential and commercial applications account for the remaining use of natural gas. The supply of natural gas has recently risen substantially in the United States, Canada, and China. This is mostly due to exploitation of shale gas, which was made possible by horizontal drilling and hydraulic fracturing technologies.

EXAMPLE 1-4 Higher Heating Value of Methane in Different Units

The lower heating value of methane (CH_4) is 50,050 kJ/kg. Determine its higher heating value in kJ/kg, m^3/kg, and therm/lbm units. The enthalpy of vaporization of water at 25°C is h_{fg} = 2442 kJ/kg. Assume natural gas is at 1 atm and 25°C.

SOLUTION The molar masses of CH_4 and H_2O are 16 and 18 kg/kmol, respectively. When 1 kmol of methane (CH_4) is burned with theoretical air, 2 kmol of water (H_2O) is formed. Then the mass of water formed when 1 kg of methane is burned is determined from

$$m_{\mathrm{H2O}} = \frac{N_{\mathrm{H2O}} M_{\mathrm{H2O}}}{N_{\mathrm{CH4}} M_{\mathrm{CH4}}} = \frac{(2\ \text{kmol})(18\ \text{kg/kmol})}{(1\ \text{kmol})(16\ \text{kg/kmol})} = 2.25\ \text{kg H}_2\text{O/kg CH}_4$$

The amount of heat released as 2.25 kg water is condensed is

$$Q_{\text{latent}} = m_{\mathrm{H2O}} h_{fg} = (2.25\ \text{kg H}_2\text{O/kg CH}_4)(2442\ \text{kJ/kg H}_2\text{O}) = 5495\ \text{kJ/kg CH}_4$$

Then the higher heating value of methane becomes

$$\text{HHV} = \text{LHV} + Q_{\text{latent}} = 50{,}050\ \text{kJ/kg} + 5495\ \text{kJ/kg} = \mathbf{55{,}545\ kJ/kg}$$

The gas constant of methane is R = 0.5182 kPa·m^3/kg·K (Table A-1) and 1 atm = 101 kPa. The density of methane is determined from the ideal gas relation as

$$\rho = \frac{P}{RT} = \frac{101\ \text{kPa}}{(0.5182\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(25+273\ \text{K})} = 0.6540\ \text{kg/m}^3$$

The higher heating value of methane in kg/m^3 unit is

$$\text{HHV} = (55{,}545\ \text{kJ/kg})(0.6540\ \text{kg/m}^3) = \mathbf{36{,}330\ kJ/m^3}$$

Noting that 1 therm = 100,000 Btu = 105,500 kJ and 1 lbm = 0.4536 kg, the higher heating value of methane in therm/lbm unit is

$$\text{HHV} = (55{,}545\ \text{kJ/kg})\left(\frac{1\ \text{therm}}{105{,}500\ \text{kJ}}\right)\left(\frac{0.4536\ \text{kg}}{1\ \text{lbm}}\right) = \mathbf{0.2388\ therm/lbm}$$ ▲

Nuclear Energy

The tremendous amount of energy associated with the strong bonds within the nucleus of the atom is called *nuclear energy*. The most widely known fission reaction involves splitting the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants, to power nuclear submarines, aircraft carriers, and even spacecraft, and as a component of nuclear bombs.