CHEMICAL PROCESSES IN RENEWABLE ENERGY SYSTEMS

VIVEK UTGIKAR

Foreword by Professor **Man Mohan Sharma,** Former Director, Institute of Chemical Technology

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Chemical Processes in Renewable Energy Systems

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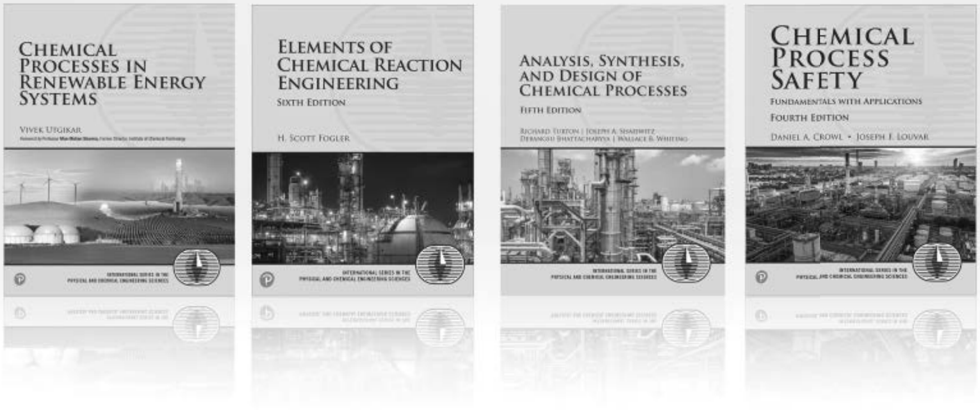

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This book is dedicated to all my teachers who have inspired me to explore, learn, and educate.

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FOREWORD

The Industrial Revolution marks a key milestone in the history of humankind. Humans worked out how to convert thermal energy into mechanical energy to drive the machines that would replace the muscle power of humans and animals. Societies embarked upon an unprecedented expansion in every aspect of their life, and this expansion shows no signs of abatement anytime soon. The key to unlocking these developments was and continues to be the human inventiveness in exploiting fossil resources created over thousands of millennia.

These activities have coincided with a significant change in earth's environment. The scientific community is in near-consensus about climate change and its linkage to fossil fuel usage. Under this scenario, a transition away from the fossil fuels is *sine qua non* for countering climate change, considered by many to be an existential threat to humankind. The full potential of nuclear energy has yet to be realized, and the high cost and time of installation, particularly due to safety measures, has proved to be a great barrier. This has left renewable energy as the sole candidate to replace fossil energy to quench the energy thirst of the world.

Renewable energy has a dual nature: it is conceptually very easy to understand but is technologically very challenging. Principles underlying wind power, solar thermal and photovoltaic, or geothermal energy are easily grasped by any individual. However, technological challenges in their implementation are highly complex due to the dilute nature of the energy sources. The high-entropy sources require considerable manipulations to provide energy and power on larger scales that are needed by modern industrial societies.

It is in this context that the author has presented the energy transformations of renewable energy sources. Converting the primary resources into energy carriers that operate the machine of the industry is, simply put, a nontrivial exercise that is continually evolving and requires imagination and creativity. As an example, development in composite materials has resulted in a substantial increase in the size of blades and consequently, the power generated by a wind turbine. Similarly, exciting advances in solar photovoltaics include the development of the next generation of solar cells, including dye-sensitized cells. Concomitant with energy generation, opportunities exist for obtaining value-added products through valorization of lignin in biomass energy systems and potable water from coupled desalination units increasing the competitiveness of renewable energy systems. Devising solutions for the success of this enterprise requires educating a new generation of engineers who are well-versed in the science and technology of renewable energy processes.

This book presents the fundamental principles governing these transformations and their applications, which will enable a reader to acquire the skill set necessary to function in the renewable energy arena. The discussion of hybrid energy systems and the techno-economic aspects brings an additional value to the book. The book takes readers on a fascinating journey, rewarding them with a broader perspective as well as deeper insights into key facets and concepts of renewable energy.

—Professor Man Mohan Sharma
Former Director, Institute of Chemical Technology
Mumbai, India
April 2021

PREFACE

The most famous and dramatic articulation of the principle of population growth outstripping resources was made toward the end of the 18th century by Reverend Thomas Malthus, a British political economist. Rev. Malthus was, of course, talking about food resources, postulating that populations have a geometric growth pattern and are bound to run out of food resources that grow only arithmetically, ultimately leading to a disaster involving mass starvation and deaths. This hypothesis was a major influence for many governments of the time in formulating their policies that were not necessarily beneficial to their populations.

In the intervening period since Rev. Malthus propounded his theory, the human population has increased by leaps and bounds, and despite occasional, localized episodes of famine and starvation, the dire prediction of a widespread Malthusian catastrophe has never materialized. Much of the success in averting this catastrophe is due to human ingenuity in harnessing new forms of energy, which is truly the master resource that enables the creation and exploitation of other resources. Development of these—primarily fossil energy resources—and the Industrial Revolution fueled by these resources have enabled populations the world over to thrive, grow, and enjoy an unparalleled standard of living compared to agrarian societies of the past.

Accelerated exploitation of fossil resources has reignited the question of resource limitations, and the 20th century saw an emergence of neo-Malthusianism that seeks to apply Malthusian concepts to all resources, including energy resources. Notwithstanding the successes in the prediction of exhaustion of localized fossil resources, global exhaustion of these resources remains questionable. However, climate change concerns portend an inevitable phase-out of fossil fuels and their displacement by renewable primary energy sources that by their very nature are untouched by any Malthusian constraints.

A sustainable energy future requires a substantial growth in renewable energy systems to replace the current energy mix. These systems provide a solution to the problem of growing carbon emissions and consequent climate change that threatens human civilization in its present form. Development of these renewable energy systems requires engineers and other technical professionals to be knowledgeable in harnessing the primary energy resources and converting those to energy carriers that can be integrated with the current energy infrastructure.

This book has grown out of the need to have a text that would provide the necessary theoretical foundation and exposure to practical systems to educate these technical professionals. The motivation was to create a book that will serve engineering students and practitioners engaged in the energy field. Despite the considerable literature regarding the technologies employed in the renewable energy field, a comprehensive text that presents the fundamental engineering principles and their applications in renewable energy technologies is currently not available. This text seeks to fill this unique niche and will be invaluable in preparing renewable energy professionals for responding to the current and future challenges in the sustainable growth of renewable energy technology.

Chapter 1, Introduction to Energy Systems, presents an overview of the energy systems and the status and limitations/challenges faced by the current energy mix leading to the vision of a renewable energy future. Various primary renewable sources are described in Chapter 2, Renewable Energy Sources, along with the nature of operations and processes involved in the energy transformations to electricity and other energy carriers. Chapter 3, Transformations and Chemical Processes in Solar Energy Systems, focuses specifically on the transformations of solar energy, while transformations of biomass energy are discussed in Chapter 4, Transformations and Chemical Processes in Biomass Energy Systems. Transformations of geothermal and other primary energy sources that are mainly mechanical (hydro, wind, and ocean) are presented in Chapter 5, Transformations and Chemical Processes in Mechanical, Geothermal, and Ocean Energy Systems.

Energy systems of the future will almost certainly be hybrid, featuring a combination of primary energy sources *and* a provision for energy storage. These hybrid energy systems are discussed in Chapter 6, Hybrid Energy Systems, with an emphasis on the different energy storage alternatives. Finally, principles of techno-economic analysis of renewable energy systems are presented in Chapter 7, Techno-Economic Analysis of Renewable Energy Systems, to provide the reader with an understanding of the factors that inform the energy policy.

The field of renewable energy can be visualized as a vast canvas with continually evolving scenery due to the rapid technological developments taking place in its every aspect. A particular challenge in the writing of this book, as it will be for any book on renewable energy, was to capture the latest scenery while maintaining the relevance for future development. The approach in this book in dealing with this challenge has involved focusing on the fundamental scientific and technological principles and explaining/analyzing the transformations in the context of these underlying principles. Every attempt has been made to incorporate the latest developments by consulting the state-of-the-art literature. Sufficient references are provided for the reader to explore any particular topic in greater detail. It is expected that this approach will serve readers well in their efforts to stay up to date with the most recent developments in the renewable energy field.

For a student, this book is a comprehensive introduction to the field of renewable energy, not only in terms of technical principles but also policy perspectives. For an instructor, it provides a framework for teaching the fundamentals and essential elements while offering flexibility to delve deeper into specific topics. And for the practitioners, it serves as a refresher and ready reference for dealing with the technological and socio-economic challenges they are facing in the implementation of a particular renewable energy system.

Human societies are marching inexorably towards a renewable energy future. It is my sincere hope that this book contributes to these efforts and helps accelerate, howsoever slightly it may be, the transition to renewable energy systems.

—Vivek P. Utgikar
Moscow, Idaho, United States
May 2021

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Dr. Vivek Utgikar is a professor of chemical engineering in the Department of Chemical and Biological Engineering at the University of Idaho. He has also served as the director of the Nuclear Engineering program and the associate dean of Research and Graduate Education for the College of Engineering at the University of Idaho. Dr. Utgikar has an extensive teaching portfolio that includes a broad range of fundamental and advanced engineering courses such as transport phenomena, kinetics, thermodynamics, energy storage, electrochemical engineering, hydrogen, and spent nuclear fuel disposition/management. His research interests include advanced energy systems, nuclear fuel cycle, modeling of multiphase systems, and bioremediation. He was a National Research Council associate at the National Risk Management Research Laboratory of the US Environmental Protection Agency in Cincinnati, Ohio, prior to joining the University of Idaho. Dr. Utgikar is a registered professional engineer with process development, design, and engineering experience in the chemical industry and holds a PhD in chemical engineering from the University of Cincinnati. His other degrees include bachelor's and master's degrees in chemical engineering from Mumbai University, India.

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CHAPTER 2

Renewable Energy Sources

As mentioned in Chapter 1, Introduction to Energy Systems, renewable energy systems (RESs) harness the energy that is being continuously supplied by the sun, transforming it into useful energy carriers to serve the needs of humankind.[1] As an ultimate energy source, the sun is infinite and inexhaustible for all practical purposes; any fraction of primary energy converted to the energy carriers is continuously replenished, giving the energy system its renewable character.

Energy supplied by the sun is in the form of electromagnetic radiation, which can be converted directly into energy carriers—heat and electricity—in one of the configurations of the RESs. The solar radiation also sets in motion several natural processes that convert its intrinsic energy into other forms of energy. The end results of these processes include the creation of wind patterns, water cycle, biomass growth, and many others. Solar energy is converted into different forms of energy, such as mechanical energy and chemical energy, during these processes. Further conversion of these forms of energy is accomplished through other alternate configurations of RESs, yielding the energy carriers that drive the service technologies to satisfy the societal demand, as shown earlier in Figure 1.2. This chapter discusses the nature of primary energy sources (solar energy and other forms of energy arising from natural processes). An overview of the chemical separations and processes in the transformation of energy sources to carriers is also presented.

2.1 Primary Renewable Energy Sources

The well-known principle of the *conservation of energy*[2] is a fundamental concept in physical sciences, which states that energy can neither be created nor destroyed, with only its form getting altered in any transformational process.

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[1] It should be noted that the ultimate source of all energy utilized on the earth, including the fossil and nuclear sources, is the sun. However, these sources are one-time creations (on the geologic time scale) and lack the renewability feature.

[2] *Conservation of mass* is a distinct principle; however, mass–energy equivalence has been established by the Special Theory of Relativity that led to the much-celebrated Einstein equation $E = mc^2$. This allows for the inclusion of nuclear (or atomic) energy in the consideration of conservation of energy, wherein mass is not conserved.

The equivalence of all forms of energy is restricted to only the total content of all energy streams involved in the transformation, not to the nature or, more importantly, the utility of the energy streams involved in the transformation. The service technologies shown in Figure 1.2 typically require energy in the form of electricity, heat, or chemical energy, while the primary energy sources are rarely in these forms. The different energy sources can be classified in several different ways; however, at a fundamental level, they can be categorized into either potential energy—energy associated with the position of a body or its constituent bonds—or kinetic energy—energy associated with the motion. Potential energy is categorized into chemical energy, gravitational energy, nuclear energy, and mechanical energy, whereas kinetic energy includes radiant energy, thermal energy, motion, electricity, and so on [1]. Classical thermodynamics approaches the categorization of different energy types slightly differently, from macroscopic and microscopic perspectives. *Macroscopic* forms of energy are those forms that are defined with respect to an external reference frame, whereas the *microscopic* forms of energy are those that are based on molecular configuration of matter and microscopic, internal modes of motion [2]. Potential and kinetic energies in this classification are based on the location of a body in a potential field and the bulk motion of the body with respect to an external reference frame, respectively. These two forms of energy are referred to as the *mechanical* energy forms. Other forms of energy are based on motion and potential internal to the body, for example, molecular rotation and bonds, and are referred to as the *internal energy* forms. Chemical energy, under this classification, is a form of internal energy. This macroscopic/microscopic energy approach is used in discussing the various primary energy forms.

The most important primary renewable energy forms are solar energy, wind energy, hydropower energy, biomass energy, and geothermal energy. The first four of these energy forms are continuously replenished directly or indirectly by solar radiation. Geothermal energy arises out of the decay of radioactive isotopes in the earth. These radioisotopes are not being replenished continuously, and strictly speaking, geothermal energy lacks the renewability feature of these other energy forms. However, the geothermal energy reservoir is sufficiently large to satisfy energy demands for several million years according to some estimates, and for all practical purposes, infinite in nature [3]. The hydropower and wind energy forms can be categorized as mechanical energy forms, with hydropower energy having the characteristics of potential energy, and wind energy having the characteristics of kinetic energy. The other three forms are different manifestations of internal energy forms: chemical energy (biomass energy), radiant energy (solar energy), and thermal energy (geothermal energy). Figure 2.1 summarizes this categorization of the renewable energy sources. Each of these forms is discussed below in detail.

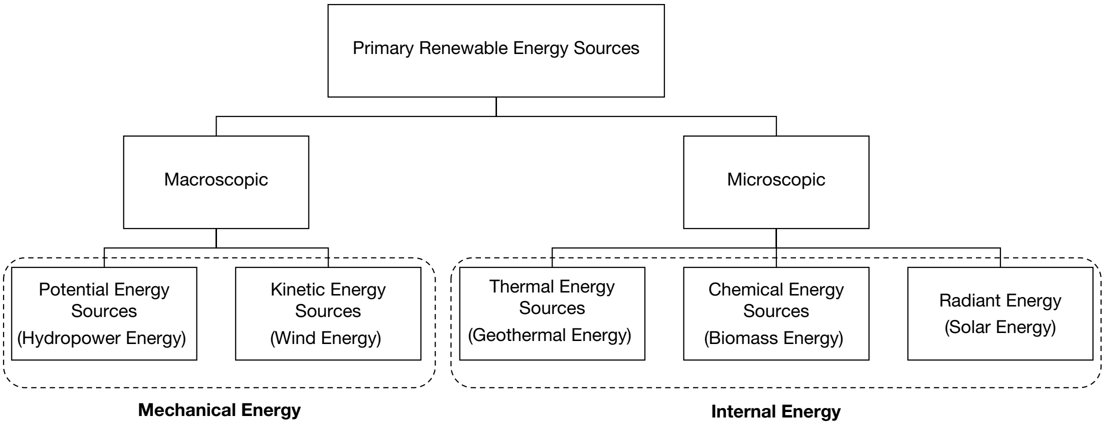

Figure 2.1 Categorization of primary renewable energy sources.

2.1.1 Solar Energy

The earth receives solar energy primarily in the form of electromagnetic radiation, which in itself is the product of nuclear fusion reactions, primarily hydrogen fusion to helium, occurring in the sun [4]. The surface temperature of the sun is approximately 6000 K, and the sun emits electromagnetic radiation that is characteristic of a black body at this temperature. Figure 2.2 shows the solar irradiance, which is the power per unit area per unit wavelength as a function of the wavelength of the radiation.

As can be seen from the curve, the peak irradiance occurs approximately at a wavelength of 0.5 μm. The area under the irradiance curve between any two wavelengths is equal to the power radiated per unit area by the sun by the electromagnetic radiation between those two wavelengths. The total area under the curve is the total solar irradiance, that is, the radiation flux from the sun. The value of the total solar irradiance at the top of the earth's atmosphere, also called the solar constant, is ~1360 W/m^2 [5]. This incident solar radiation interacts with the constituents of the earth's atmosphere with fractions of it getting absorbed in the atmosphere and reflected back into space, as well undergoing scattering before reaching the earth's surface. The earth, in turn, also emits radiation back into space, albeit at a much higher wavelength.[3] Overall, the incident solar energy is nearly balanced by the energy emitted by the earth, allowing a stable thermal

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[3] The peak wavelength (λ_{max}) at which maximum power is emitted by a body is related to its temperature (T) by Wien's law, which states that $\lambda_{max}T \approx 3 \times 10^{-3}$ m·K. The peak wavelength for the earth is 10 μm, well into the infrared region.

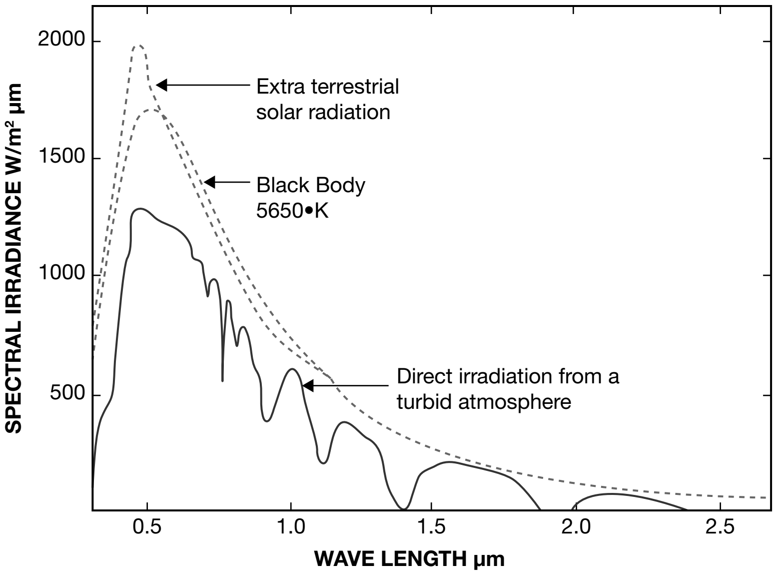

Figure 2.2 Solar spectral irradiance.

Source: Sen, Z., "Solar Energy in Progress and Future Research Trends," *Progress in Energy and Combustion Science*, Vol. 30, 2004, pp. 367–416.

equilibrium to exist that maintains temperature suitable for life [4]. Figure 2.3 depicts this energy balance for the radiant energy [6].

The majority, nearly 55%, of the solar energy reaching the earth's surface is in the infrared region, 40% of the energy is in the visible region, and 5% in the ultraviolet region [7]. The earth receives nearly 4 million EJ (~1.1 billion TWh) of solar energy every year, at a rate so large that the amount received in 1 hour exceeds the annual worldwide primary energy consumption [8].

2.1.2 Geothermal Energy

Geothermal energy, as can be inferred from the term, refers to the heat present in the interior of the earth, and is the result of radioactive decay of elements including the heat generated during the formation of earth (primordial heat), as well as ongoing decay of long-lived radioisotopes, such as ^{40}K, ^{232}Th, ^{235}U, and ^{238}U [9]. Figure 2.4 is a schematic of the earth's interior, showing relative thicknesses of different parts of the earth including the crust, the mantle, and the inner and outer cores.

The inner core of the earth, ~2400 km in diameter, is extremely hot, with a temperature approaching that of the surface of the sun (6000 K).

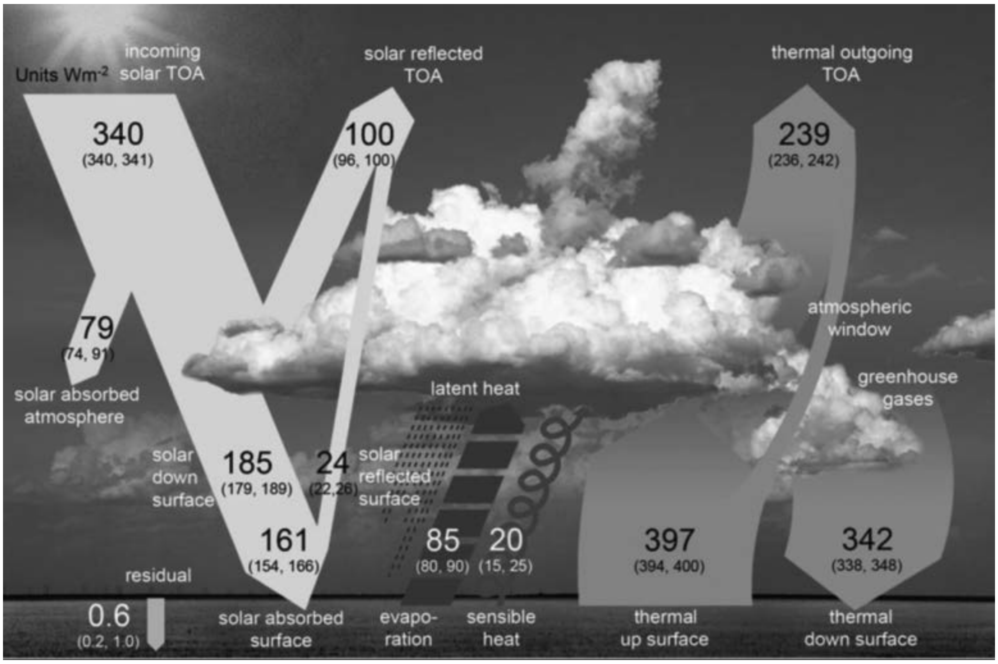

Figure 2.3 Radiation energy balance.[4]

Source: Wild, M., et al., "The Global Energy Balance from a Surface Perspective," *Climate Dynamics*, Vol. 40, 2013, pp. 3107–3134.

The inner core is surrounded by a ~2400-km-thick outer core of hot molten rock—magma. A mantle layer consisting of ultrabasic and igneous rocks and a thickness of ~2900 km surrounds the outer core. The outermost layer is the crust, which has negligible thickness (<70 km) compared to the earth's radius of approximately 6400 km [9, 10]. The temperature at the outer core mantle boundary is ~4200 K, while that in the upper mantle near the mantle crust boundary can be as low as 500 K. This radial variation in the temperature results in the establishment of significant temperature gradients within the earth's interior, giving rise to both conductive and convective heat fluxes toward the earth's surface. The average heat flux of earth is quite low (~80 mW/m^2); however, the total available energy is significantly large. By some estimates, globally, the geothermal energy has the potential to generate

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[4] The incident radiation flux is shown to be 340 W/m^2 in the figure, rather than the solar constant of 1360 W/m^2 stated earlier. The lower value is for the radiation reaching the surface of the earth based on the total surface area of earth ($4\pi r^2$), considering it to be a sphere of radius r. The solar constant is based on the projected area of the earth, which is simply πr^2.

Figure 2.4 Earth's interior structure.
Source: Adapted from a National Energy Education Development Project graphic (public domain). https://www.eia.gov/energyexplained/geothermal/.

12,000 TWh of electricity annually, again exceeding the worldwide primary energy demand. If the geothermal energy is utilized directly without conversion to electricity, then the resource is even larger, at 600,000 EJ or ~170 million TWh per year [11].

Geothermal energy from the earth's interior is transmitted to the surface through the mantle at various rates depending on the thermal conductivity of the geological formation and the temperature gradient, which is commonly taken as 30°C/km and may range from 10°C/km to 100°C/km [9, 11]. The interior of the earth is hardly uniform, though, and is characterized by widespread prevalence of geofluids—both aqueous and organic in nature, as well as in liquid and vapor states. These geothermal fluids also facilitate the transmission of the geothermal energy by convection. This heterogeneity leads to different configurations of geothermal energy sources [9, 11, 12]:

- Hydrothermal—hot water or steam at moderate depths (100–4500 m)
- Geopressed—hot water aquifers containing dissolved methane under high pressure at depths of 3–6 km
- Hot dry rock—abnormally hot geologic formations with little or no water
- Magma—molten rock at temperatures of 700°C–1200°C

Of the four types, the hydrothermal source is the only type that can be exploited economically with the prevalent technology. The hydrothermal sources are, as stated earlier, either liquid dominated (characterized by the presence of hot water) or vapor dominated (characterized by the presence of steam, i.e., water vapor). They can also be classified as high-temperature (>180°C), intermediate-temperature (100–180°C), and low-temperature (<100°C) systems. These resources can be harvested for electrical power generation, direct heat utilization, or combined heat and power applications [12].

The enormity of the total energy content of the earth in comparison to the primary energy demand makes geothermal energy practically inexhaustible, earning it its renewable characteristics. However, geothermal energy resources in the interior of earth are heterogeneous in the extreme, and geothermal energy fields are neither contiguous nor uniformly distributed across the earth. It is indeed possible to exhaust a geothermal energy reservoir, if energy is extracted out of it at a higher rate than the rate at which it is replenished by the processes occurring in the core. Proper reservoir management is indispensable for maintaining the presence of fluids in the hydrothermal fields and extraction at sustainable rates for ensuring long-term operation of the geothermal power plant [9].

2.1.3 Biomass Energy

Photosynthesis is the most fundamental process that plants perform to harness solar energy. It is *the* essential process without which no life will exist on earth. From the energy perspective, it can also be viewed as the process converting solar energy into chemical energy using carbon dioxide and water as the basic raw materials. This chemical energy is stored in the form of biomass and biochemical energy. Historically, as mentioned in Chapter 1, Introduction to Energy Systems, biomass has served as the energy source for all civilizations. Even today, populations in less developed countries continue to rely upon firewood as the primary energy source for cooking and heating applications [11].

Such traditional use of biomass through direct combustion is inefficient and unsustainable, contributes significantly to air pollution and carbon emissions, and affects human health adversely. Biomass-based RESs of the future are aimed at sustainable utilization of biomass through its conversion into chemicals that drive the modern, advanced service technologies. The biomass utilized for these conversions is cultivated and harvested specifically for energy applications. Different types of biomass serve as the energy source for these modern systems, the main ones being [11, 13]:

- Agriculture and forest residues: examples of agricultural residues include corn stover, wheat straw, and rice straw; forest products and residues include hardwoods and softwoods grown in forests as well as the residue left after natural processes and harvesting of products.

- Organic waste streams, including food and yard wastes, manure, and human sewage: examples of such streams include waste edible oils, residue from food processing plants, discarded leftover food, grass clippings from lawn, manure from large dairies and other animal farms, and municipal sewage.
- Crops—either food crops used as fuel or energy crops grown specifically for use as fuel or conversion to chemicals: food crops such as sugar beets and sugarcane, corn and potato, soybean and sunflower, and so on can be easily converted into energy chemicals.[5] Such diversion of food crops can cause significant disruption in the food supply chain and have disastrous consequences for a large fraction of global human population, and the future trend is to cultivate annual and perennial plant species such as switchgrass, miscanthus, bermudagrass, and microalgae.

Biomass is renewable and sustainable, and has the versatility to yield multiple energy carriers—electricity, heat, and chemicals, unlike the other renewable energy sources that are limited mostly to producing electricity. Geothermal and solar energy are exceptions in their ability to provide heat, but do not have the ability to yield chemicals. Biomass has theoretical potential to provide 30,000–80,000 TWh/year, with the low solar energy conversion efficiency (1%) of photosynthesis, and large area requirement limiting its growth [11].

2.1.4 Hydropower Energy

Solar energy is the driver for the water cycle consisting of evaporation, condensation, precipitation, and collection of water in bodies of water on earth, as shown in Figure 2.5.

The flow of water under gravitational flow is harnessed to generate the electricity in the hydropower plants. Hydropower plants can be run-of-river (RoR) plants that utilize the natural flow of water in the river and channels. These plants are subject to significant seasonal and periodic variations depending upon the precipitation and runoff. The uncertainty associated with the RoR plants is avoided in the storage (reservoir) type of hydropower plants, where a dam is constructed to create large reservoirs to store water at an elevation—transforming the solar energy into potential energy in the gravitational force field [12]. The water is released to a lower elevation through turbines to generate electricity, as shown in Figure 2.6.

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[5] Diversion of sugarcane in Brazil and corn in the United States to produce ethanol for use as motor vehicle fuel are two of the most prominent examples of repurposing food crops for energy applications.

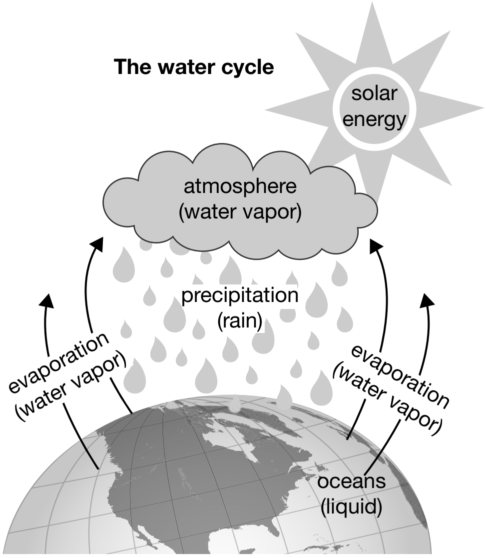

Figure 2.5 Water cycle on earth.
Source: Adapted from a National Energy Education Development Project graphic (public domain). https://www.eia.gov/energyexplained/hydropower/.

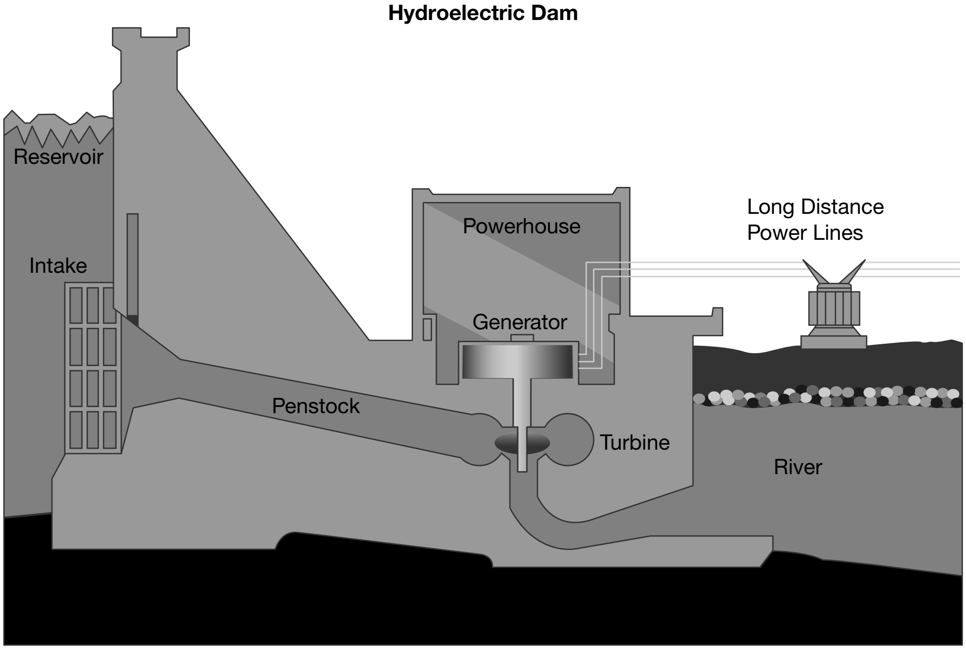

Figure 2.6 Reservoir hydropower plant.
Source: Tennessee Valley Authority (public domain). https://www.eia.gov/energyexplained/hydropower/.

Pumped storage hydropower plants are a special case of hydropower plants that utilize two reservoirs located at different elevations. These plants are not energy sources but energy storage devices associated with another power plant. Electricity generated by the power plant is used to pump water from the reservoir at the lower elevation to the one at the higher elevation at the times when the generation exceeds the consumer demand. The water stored in the upper reservoir is released through the turbines to augment the electricity generated in the main power plant when demand exceeds its capacity. Energy storage is described in greater detail in Chapter 6, Hybrid Energy Systems.

The inventory of water in the water cycle is estimated to be approximately 0.6 million km^3. This volume is evaporated annually due to the solar energy incident on earth and is returned to it through precipitation. The amount precipitating on land is slightly less than 20% of this volume, at 112,000 km^3. Slightly more than one-third of this volume ends up as runoff, with the balance getting absorbed by vegetation and land [11]. All of this volume, ~50,000 km^3, in theory, can be harnessed to generate hydropower. The total theoretical potential for global hydropower generation, estimated from the runoff volumes and the altitudes at the corresponding locations, ranges from 44,000 to 128,000 TWh/year [11, 14]. Of course, technical limitation makes it impossible to exploit all of the precipitation runoff. Economic considerations further limit the exploitable resources, even when it is technically feasible to construct a hydropower plant. The economic potential for global hydropower production is considerably less than the theoretical potential at 8000–15,000 TWh/year [11, 14].

2.1.5 Wind Energy

Another effect of solar insolation is the heating of the earth's surface. Earth's surface being nonuniform, land and water coverage being the most elementary divisions, different regions heat up at different rates, leading to significant variations in temperatures across the globe. Tropical regions have a net gain of heat causing them to have higher temperature, while the polar regions are subject to a net loss and are considerably cooler [11]. This temperature difference, in turn, leads to density and pressure differences across locations, resulting in convective wind currents. Coastal regions experience daily wind cycles as air over the land heats up faster than that over the water, setting off winds from water to land, as shown in Figure 2.7 [15]. The wind direction is reversed in the night as the air mass cools down faster creating higher pressure over the land.

In addition to solar insolation, earth's rotation contributes to establishment of circulatory patterns in the atmosphere. These patterns are further superimposed by local wind patterns arising out of local natural topographical

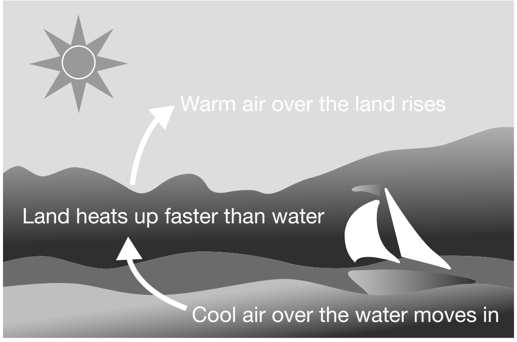

Figure 2.7 Daily wind cycle.
Source: Adapted from National Energy Education Development Project (public domain). https://www.eia.gov/energyexplained/wind/.

features that lead to uneven heating. Anthropogenic structures may also interfere and influence these patterns [11].

Wind energy systems harness the kinetic energy of these circulatory patterns. Historically, wind energy was harnessed in direct applications such as sailboats for transportation and windmills for grinding flour or pumping water [16]. Wind power systems, wherein the kinetic energy of wind is first transferred to the kinetic energy of a wind turbine and then converted into electricity, are a relatively recent phenomenon [12]. Wind energy systems (henceforth referring to wind power systems, i.e., where electricity generation is taking place) have seen significant growth over the past two decades, with the global installed capacity approaching 500 GW [16]. These systems produced in excess of 1100 TWh of electricity in 2017 (https://www.eia.gov/energyexplained/wind/history-of-wind-power.php).

Although nearly every location on earth experiences wind patterns, practical technological constraints limit the exploitation of wind energy resources to those locations where the wind power density exceeds 400–500 W/m^2. The global theoretical wind energy potential, on this basis, is approximately 500,000 TWh/year, exceeding the primary energy requirements. Advances in the wind energy technology can increase this potential even further. However, technical and economic limitations suggest that the actual realizable potential may be closer to 20,000 TWh annually [11].

In addition to the above five forms of energy sources that dominate the current renewable energy landscape, there exists another renewable energy source—marine energy—that can satisfy the primary energy demands for the foreseeable future and beyond. Marine (or ocean) energy actually consists of several different energy forms [11, 12, 17]:

- Tidal current energy—kinetic energy of oceans arising from rotation of the earth in the gravitational field of the sun and the moon

- Tidal barrage energy—potential energy exploiting the change in sea level during high and low tides by creating dams/barrages for the seawater
- Wave energy—which captures the kinetic energy of the wind
- Ocean thermal energy—based on the temperature differences between warmer surface waters and deep cooler waters
- Salinity gradient energy—chemical energy based on the salinity differences between the freshwater that is discharged into oceans and the saline seawater

The theoretical potential of marine energy is in excess of 2 million TWh/year, with the ocean thermal energy exceeding the other types by at least two orders of magnitude [11]. However, all these technologies, except for tidal barrages, are in developmental stages. The current contribution of marine energy to renewable energy is negligible and not expected to rise significantly for the foreseeable future.

As can be gleaned from the above discussion, the renewable energy sources possess theoretical and technical potential to satisfy the entire primary energy demands of the global population. However, these primary sources need to be transformed into appropriate secondary energy sources—the energy currencies—in order to operate the service technologies. These transformations are discussed in the following section.

2.2 Transformations of Primary Renewable Energy Sources

Almost all of the service technologies operate using one of the three energy currencies—electricity, heat, and chemical—with electricity dominating the vast majority of applications. Consequently, any discussion of RES transformations is dominated by conversion of the renewable energy forms into electricity. However, it should be recognized that some of the renewable energy sources have the ability to provide other forms of energy currencies as well, and these transformations are discussed in this section as well, in addition to electricity (or power) generation. Electricity is the only energy currency that can be obtained from mechanical energy forms, that is, hydropower energy and wind energy. Solar and geothermal energies can yield both electricity and heat, whereas biomass energy can additionally yield chemicals as well. The electricity generated from the renewable sources can be converted further into heat or used to produce chemicals (hydrogen, for example); however, these secondary transformations are external in scope and not discussed in this book. It should also be noted that synthesizing chemicals using renewable electricity requires external input of raw materials, except in the case of biomass resource. Transformations of the mechanical energy forms are discussed first, followed by those of geothermal, solar, and biomass energy.

2.2.1 Transformations of Mechanical Energy Sources

Nearly 99% of the power generated worldwide involves conversion of mechanical energy, specifically kinetic energy, into electrical energy. This conversion is based on Faraday's law of electromagnetic induction that provides the fundamental explanation of how the movement of a magnet induces electrical current in a conductor placed in its field [18]. Modern electricity generators operate on this principle and consist of an electromagnet rotor surrounded by a stator wound up in conducting wires. The rotor is driven by a turbine that captures the kinetic energy of the motive fluid inducing the current in conductor on the stator. The motive fluid is steam in thermal power stations, for example, those driven by fossil or nuclear energy. Fossil fuel, usually natural gas based combined cycle power plants also utilize a *gas turbine* driven by the hot combustion gases to generate electricity via a Brayton power cycle. Additional electricity generation is accomplished in a *steam turbine* operating a Rankine power cycle[6] with the steam generated through heat transferred from the combustion gases exiting the gas turbine [2].

The two mechanical forms of renewable energy—hydropower energy and wind energy—are converted to electricity using the same principle. As mentioned in the previous section, water stored in the reservoir type of hydropower plants possesses potential energy due to the force of gravity. This potential energy is converted into kinetic energy of the turbine as it is released through the penstock past the turbine located at a lower elevation, as shown in Figure 2.6. The turbine drives the rotor of the generator located in the powerhouse, generating the electricity. Figure 2.8 shows the schematic of a typical hydroelectric turbine. The RoR hydroelectric plants do not have a reservoir of stored water, and the kinetic energy of the flowing water is transferred directly to the turbine.

Wind turbines perform in the same manner as the turbines in the RoR hydropower plants; that is, they capture the kinetic energy of the wind and employ the same principle of electromagnetic induction to generate electricity. The power rating of a wind turbine depends upon the area swept by the blades of the turbine, and most large-scale wind turbines are of the horizontal axis

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[6] The theoretical basis for such power cycles is well-known and is available in most engineering thermodynamics textbooks.

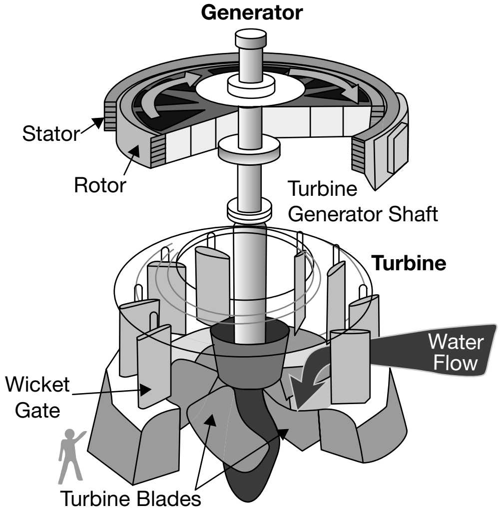

Figure 2.8 Schematic of a hydroelectric turbine and generator.

Source: U.S. Army Corps of Engineers, https://www.usgs.gov/special-topic/water-science-school/science/hydroelectric-power-how-it-works?qt-science_center_objects=0#qt-science_center_objects.

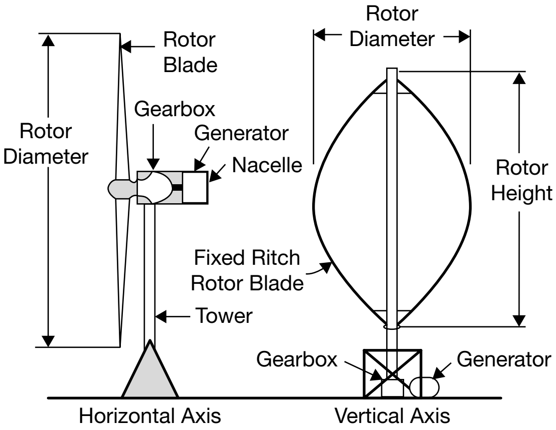

Figure 2.9 Horizontal and vertical axis wind turbines.

Source: U.S. Environmental Protection Agency, https://www.epa.gov/sites/production/files/2019-08/documents/wind_turbines_fact_sheet_p100il8k.pdf.

type, that is, the axis of rotation is parallel to the ground and the wind direction. A modern horizontal axis wind turbine (HAWT) in a commercial wind farm installation may have blades that are 50 m long and a power rating of up to 5 MW. The hub of the rotor may be located at a height of 100 meters above the ground to take advantage of the increased wind velocities compared to those near the surface of the earth [16]. Vertical axis wind turbines (VAWTs), where the axis of rotation is perpendicular to the ground, are less common and have smaller power ratings. These VAWTs may find niche applications in smaller residential settings and locations where wind patterns are not consistent or where larger installations are not permitted out of aesthetic or ecological considerations. Figure 2.9 shows a schematic of both horizontal axis and vertical axis turbines. The rotational speed of the blades in a wind turbine is typically 30–60 rpm, and the hub of the turbine contains a gearbox that steps it up to 1200–1500 rpm, which is within the range needed by the generator [19].

Unlike fixed windmills of the past, modern HAWTs contain sophisticated control systems to maintain the orientation of blades perpendicular to the wind to ensure uninterrupted power generation despite any changes in

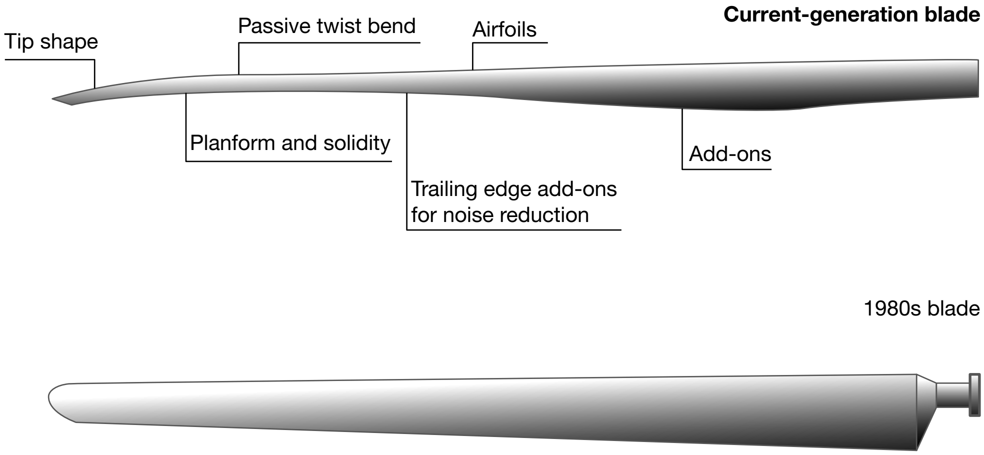

Figure 2.10 Evolution of wind turbine blades.
Source: Veers, P., et. al., "Grand Challenges in the Science of Wind Energy," *Science*, Vol. 366, 2019, eaau2027 (9 p).

the wind direction. The blades of the turbine have also evolved into longer, sleeker ones that are significantly quieter, despite their size, and have superior aerodynamic performance. Figure 2.10 shows the innovative transformations in blade design over the past four decades [16].

Wind energy installations can be located onshore or offshore, with offshore installations offering the advantages of the availability of a higher-quality wind resource and potential use of larger wind turbines while also avoiding utilizing large land areas that can be repurposed for other applications [12].

Hydropower energy, from reservoir-type plants, can be expected to generate electricity at a consistent rate; however, electricity generation from wind energy installations can be highly variable due to daily and seasonal variations. Possible solutions to improve the reliability and consistency of power generation from variable resources are presented in Chapter 6, Hybrid Energy Systems.

2.2.2 Transformations of Geothermal Energy

Geothermal energy has been utilized for several millennia by human beings, in direct heating applications, such as bathing, washing, and cooking. Direct utilization of geothermal energy in geothermal heat pumps, space heating, and bathing, accounts for 90% of such applications. Direct utilization of geothermal energy also includes industrial and agricultural applications, for example, for food dehydration, milk pasteurization, industrial process heat, and aquaculture pond heating [20]. Geothermal energy usage in direct applications increased by more than 400% over nearly two decades, rising from ~38 TWh in 1997 to ~164 TWh in 2015 [20, 21]. More than half of these applications involve geothermal heat pumps, wherein residential and commercial buildings are heated in winter and cooled in summer by circulating water in a closed loop between the building and subsurface with heat transfer areas provided in each location.

Compared to direct use, converting geothermal energy into electricity is a relatively recent phenomenon that started in the early 20th century. Wells drilled into geothermal reservoirs transport the geothermal fluids to the surface, where thermal energy is extracted from them via a power conversion cycle to generate electricity. Fluids present in the geothermal energy systems are primarily of two types: vapor-dominated systems consisting mainly of steam and liquid-dominated systems consisting of brine [22]. The vapor-dominated systems may typically contain some fraction of noncondensable gases as well. For vapors containing >15% noncondensables, a direct-intake, noncondensing cycle may be used for power generation, wherein the vapor is fed directly to a turbine and exhausted to the atmosphere without attempting to condense the steam [9]. Condensing systems are used for brine-dominated systems, as well as where the vapor consists mostly of dry or saturated steam. In a more general case, the geothermal fluid extracted via a production well consists of brine or a mixture of vapor and brine, and in these cases, single- or double-flash systems are used to generate additional steam from brine. The steam is fed to a turbine to generate the electricity via the Rankine cycle, and the condensate along with the concentrated brine is injected back into the geological formation via an injection well that is distinct from the production well [22]. The fluids present in geothermal energy reservoirs vary greatly with respect to their temperatures, and in some cases, the geothermal fluid may simply be hot water. In such cases, a low-boiling secondary fluid (ammonia or isobutene, for example) is vaporized by heat exchange with the geothermal fluid and used to operate an organic Rankine cycle or Kalina cycle for power generation. These types of plants are called binary-cycle plants. Figure 2.11 shows the conceptual schematics of the three different types of closed-loop geothermal power plants [23].

As mentioned earlier, temperatures of geothermal energy resources vary greatly, and this puts constraints on the type of technology that can be used to harness that energy, as well as the potential applications of the resource. Typically, for any geothermal energy source, a listing of potential applications is developed, arranged in the order of decreasing temperatures and corresponding technology used for those applications. This listing is called the

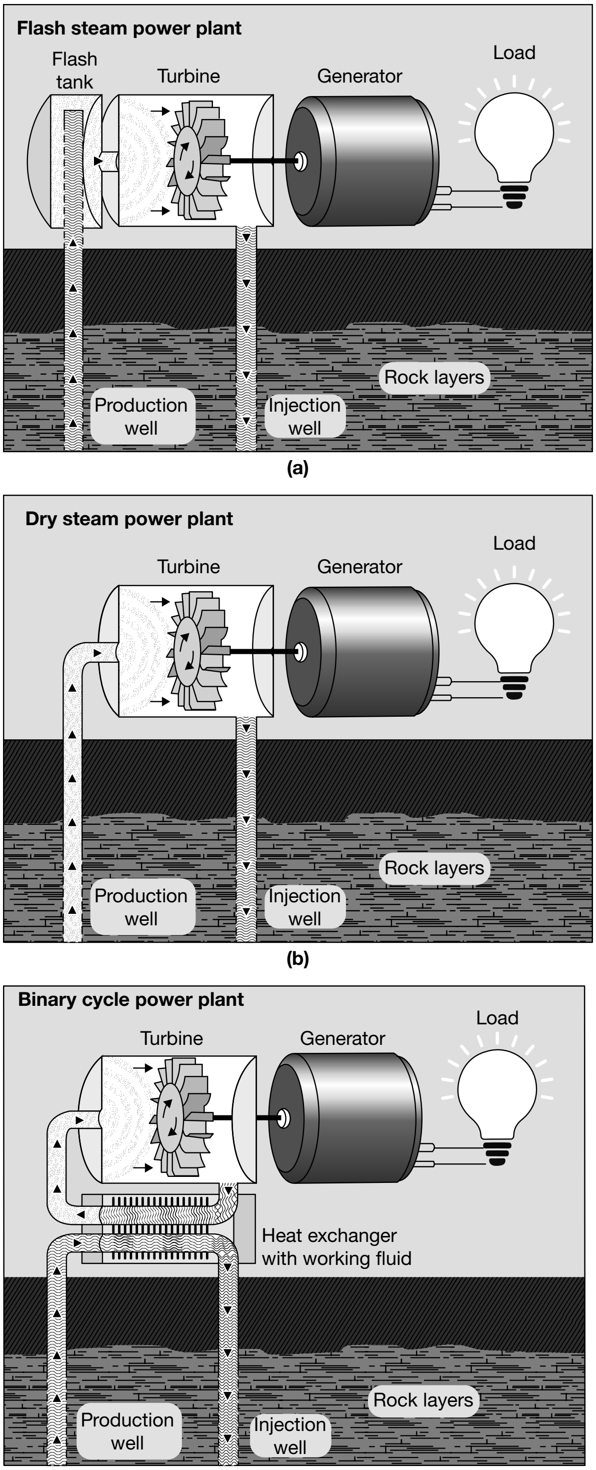

Figure 2.11 Types of geothermal power plants.

Source: U.S. Department of Energy, Energy Efficiency & Renewable Energy (public domain), https://www.eia.gov/energyexplained/geothermal/geothermal-power-plants.php.

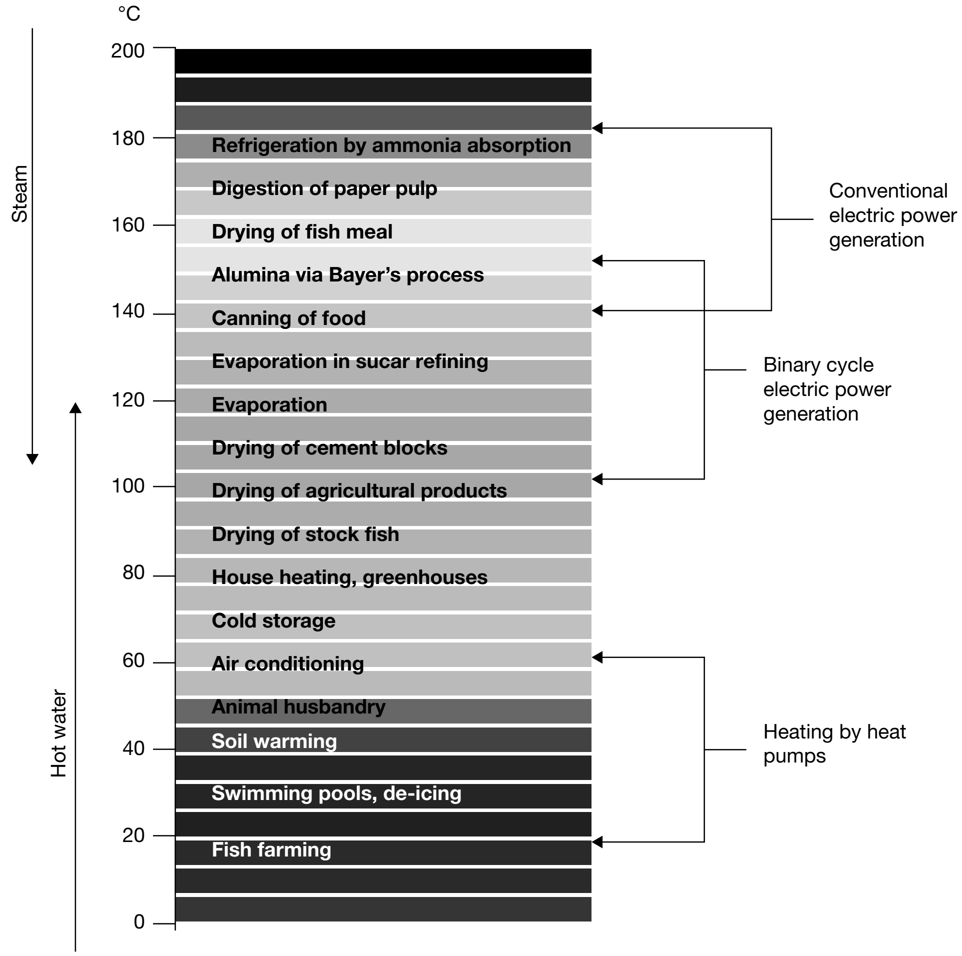

Figure 2.12 Example of a Lindal diagram.

Source: Moya, D., C. Aldas, and P. Kaparaju, "Geothermal Energy: Power Plant Technology and Direct Heat Applications," *Renewable and Sustainable Energy Reviews*, Vol. 94, 2018, pp. 889–901.

Lindal diagram,[7] which serves to identify, first the maximum temperature and the corresponding application that is feasible with the geothermal energy resource, and second, the potential to maximize the use of the resource through developing a heat exchange network to cascade through applications

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[7] Named in honor of Baldur Lindal, an engineer from Iceland who first presented such a diagram in 1973.

requiring progressively lower temperatures [24]. A sample Lindal diagram is shown in Figure 2.12.

As can be seen from the above figure, electricity generation via conventional power cycles is the first preference, provided high-temperature steam is available. Lower temperatures would drive the choice to binary power cycles, followed by direct thermal applications. The particular applications shown in Figure 2.12 are of relevance to a geothermal field in an agricultural/fisheries setting. The listing will be quite different for the geothermal field, which is in the proximity of a mine, as shown in reference 24. A situation-specific Lindal diagram needs to be developed to optimize the exploitation of any geothermal field.

2.2.3 Transformations of Solar Energy

The simplest utilization of solar energy is direct low-temperature applications, such as domestic water heating, solar cooking, space heating, and crop drying [21]. Energy management of buildings—heating, cooling, or ventilation—can be accomplished via an active or passive system utilizing solar thermal energy. As significant as these applications are, particularly from the environmental perspective of displacing polluting fuels used for domestic applications (cooking, heating, etc.) in developing economies, it is the conversion of solar energy into electrical energy that is of primary interest for large-scale systems and industrial applications.

Conversion of solar energy into electrical energy is effected in one of two ways: (1) Concentrated solar power (CSP) systems involve focusing solar radiation into a concentrated beam that transfers its thermal energy to a fluid, raising its temperature. This thermal energy conducted by the fluid is typically used to generate steam to drive a power cycle to generate electricity [25]; (2) photovoltaic (PV) systems involve direct conversion of solar energy using the photoelectric effect [26]. PV technology is one of the few exceptions in power generation systems wherein electricity is generated without any intermediate conversion to mechanical energy by using turbines [27].

Technologies for the conversion of solar energy—both CSP and PV systems—into electrical energy are discussed in detail in Chapter 3, Transformations and Chemical Processes in Solar Energy Systems.

2.2.4 Transformations of Biomass Energy

Biomass, particularly from agricultural/forest residues and products and organic waste streams, has been used historically for heating and cooking by direct combustion and continues to be used in this manner in many developing countries. As mentioned earlier, such use is unsustainable, causes

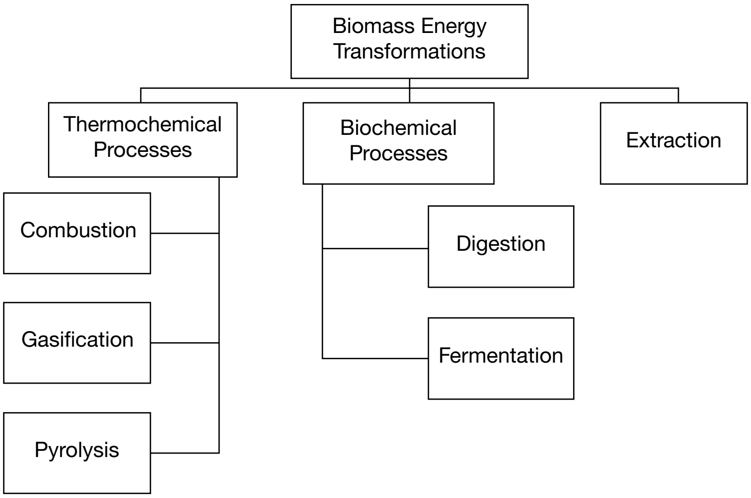

Figure 2.13 Biomass energy conversion processes.

environmental pollution, and has adverse health effects on human beings. Furthermore, this traditional burning of biomass hardly allows the energy content of the biomass to be used efficiently and effectively for more complex, value-added applications. Modern transformation technologies enable conversion of biomass to electricity and chemicals in addition to heat, expanding the utility of biomass energy to industrial processes, transportation applications, and consumer services.

Biomass energy is transformed into other forms of energy—electricity, thermal energy, and chemical energy—via a number of different processes. The two major types of conversion processes are thermochemical conversion processes and biochemical conversion processes. Figure 2.13 shows further details of specific processes that are categorized under these types [21]. Thermochemical processing includes direct combustion, pyrolysis, and gasification, while biochemical processing involves digestion or fermentation. Direct combustion of biomass can yield both electricity and heat, while gasification and pyrolysis can also yield other chemicals that can also be used as fuels. Electricity and chemicals can also be obtained through biochemical processing, while extraction processes can yield chemicals, typically biodiesels.

Transformations of biomass energy are described in detail in Chapter 4, Transformations and Chemical Processes in Biomass Energy Systems. Transformation of mechanical energy and other forms of energy are described in Chapter 5, Transformations and Chemical Processes in Mechanical, Geothermal, and Ocean Energy Systems.

2.3 Summary

Renewable energy sources differ in terms of the type of energy contained within them. Each of these sources—solar, wind, hydropower, geothermal, and biomass (as well as marine)—has the theoretical potential to satisfy most, if not all, primary energy requirements of society. Actual realizable technical and economic potential is, of course, considerably less than the theoretical potential for each energy form. Furthermore, the type of energy form constrains the transformations or conversions that can be accomplished with that energy. Macroscopic energy forms, such as wind and hydropower energy, are limited to conversion to electricity, whereas microscopic energy forms can additionally yield heat, and in case of biomass, chemicals as well. Technologies for the conversion of mechanical and thermal energies to electricity are well-established, and these technologies are applicable to the transformations of wind, hydropower, and geothermal energies. Transformation of solar energy into electrical energy can be accomplished through thermal systems, as well as photoelectric systems. Transformations of biomass energy into electricity, heat, and other forms of chemical energy are considerably more complex, and these transformations are discussed in the following two chapters.

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Problems

2.1 Using the resources mentioned in Chapter 1, obtain the latest estimate of the world primary energy consumption. How does this number compare to the primary energy available from various renewable resources?

2.2 What are the major differences between macroscopic and microscopic forms of energy? How will you classify the ocean energy resources?

2.3 What is solar constant? What is its numerical value? Why does it differ from the number (340 $\mathrm{W/m^2}$) shown in Figure 2.3?

2.4 What are the different types of geothermal energy resources?

2.5 What is the key difference between biomass energy and other renewable energy sources?

2.6 What are the two types of hydropower plants? Which of the two has the potential to generate electricity on a scale comparable to thermal power plants?

2.7 Conversion of primary energy sources into electricity involves several intermediate transformations into other energy forms. Describe for each primary source the sequential transformation steps and identify the intermediate energy forms in its conversion to electricity.

2.8 What is a Lindal diagram? Using the resources mentioned in Chapter 1, identify two geothermal reservoirs closest to your location. Develop a Lindal diagram for each reservoir.

INDEX

Note to reader: illustrations are indicated by italicized page numbers.