Chapter 2

Modern energy conversion technologies

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2.1 Introduction

One of the central challenges for mankind is to transform the present energy structure into a sustainable one. Energy-conversion methods and energy-conversion efficiency play a crucial part to accomplish this goal. The sole purpose of energy conversion is to convert the inoperative form of energy available in nature into useful forms, such as work. Developments in energy-conversion processes and devices like the steam engine or nuclear power throughout time mark breakthroughs of eras in the history of human civilization. Over the centuries, a range of systems and technologies has been developed for efficient conversion of energy wherein fossil fuel energy conversion was the main motive; in contrast, current energy-conversion technologies cover renewable energies.

2.2 Fossil fuel energy conversion

Energy in fossil fuels (oil, gas, and coal), originally captured from the sun through photosynthesis, is nonrenewable in nature. Fossil fuels are all hydrocarbons and upon burning, carbon dioxide (CO_2) and water (H_2O) molecules are formed with the release of a huge amount of heat. This heat is utilized to produce rotation (in turbines) or translation (in heat engines), which is finally converted into electrical energy through generators. The major fossil fuel conversion technologies are briefly discussed in the subsequent sections.

2.2.1 Internal combustion engines

The internal combustion (IC) engine is a class of heat engine wherein the chemical energy of fuel is transformed into shaft work. It is so named because

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combustion occurs inside a combustion chamber that is an integral part of the working fluid flow circuit. The two basic components of an IC engine are a stationary cylinder and a motile piston, the piston being pushed down by growing combustion gases inside the cylinder, which in succession revolves the crankshaft and by way of a gear system in the power train drives the vehicle.

Combustion in IC engines may be intermittent or continuous. IC engines with intermittent combustion are spark ignition (SI) gasoline and compression ignition (CI) diesel engines. Most are four-stroke engines including four distinctive processes, viz., intake, compression (and combustion), power, and exhaust stroke. The distinction between SI and CI engine consists in the method of igniting the fuel. In an SI engine, the fuel is first blended with air and then drafted into the cylinder during the intake process, while in a CI engine, only air is inducted into the engine and compressed, after which diesel fuel is injected into the hot compressed air at a suitable measured rate resulting in ignition (Heywood, 2018).

IC engines with continuous combustion include gas turbines, jet engines, and most rocket engines. Although typically IC engines are fed with fossil fuels, the use of alternative fuels like biodiesel in CI engines and bioethanol or methanol in SI engines is growing day by day. Recently, hydrogen as a fuel for IC engine has also been in the experimental application stage.

2.2.2 Steam turbines

A steam turbine is the single prime technology that has been employed globally in base load power plants to provide continuous electricity supply throughout the year. About 85% of all electricity in the USA in 2014 was generated by steam turbines, and the global scenario is almost identical (Manushin, 2011). Steam turbine units with as high as a 1500 MW capacity are commercially available, whereas most gas turbine units do not exceed 750 MW capacity, which is why most base load plants comprise steam turbines.

In steam turbines (Fig. 2.1), heated and compressed steam (generated by a boiler or from natural origin like geothermal wells) is allowed to expand in the turbine blade cascades, through which potential energy is transformed into kinetic energy and drives a shaft (BLAIR, 2017). Steam turbines work on the Rankine cycle comprising four processes, viz., an isentropic compression of saturated liquid (i.e., pumping water from condenser to boiler), heat addition at constant pressure (to produce steam inside the boiler), isentropic expansion of the steam (through the turbine), and constant pressure heat rejection from the steam (in the condenser to obtain saturated liquid). Hence, a steam turbine power plant consists of the major components, viz., boiler (steam generator), turbine, condenser, and feed pump along with some auxiliary systems: lube oil system, steam condensate system, etc. (STP, 2019).

Steam turbines offer better thermal efficiencies than reciprocating engines and gas turbines and offer greater reliability when sustained high power output

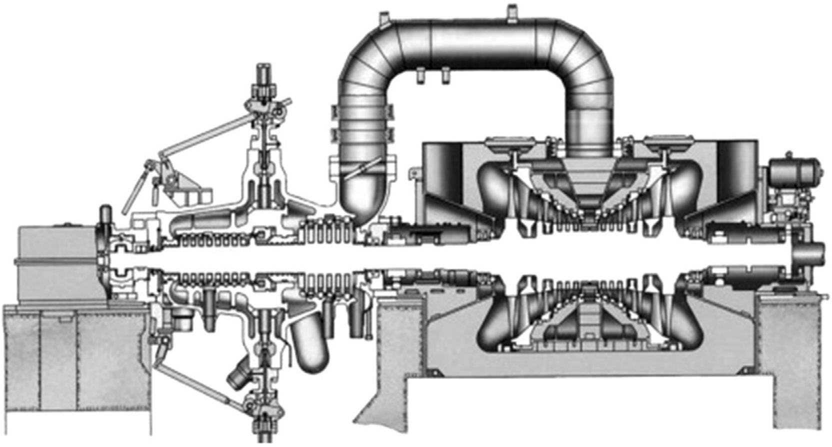

FIGURE 2.1 Steam turbine cutaway view Breeze, P. (2014). Power Generation Technologies, 2nd Edition, Imprint: Newnes, Elsevier.

is required. However, longer start-up time and efficiency drop at part-load operation are some of the few shortcomings of this device.

2.2.3 Gas turbines

Gas turbines (Fig. 2.2) convert the potential energy of heated and compressed gas into kinetic energy as a result of its expansion in several stages of turbine blading that eventually rotate the turbine shaft to realize mechanical work. This continuous combustion IC engine work on the Joule-Brayton cycle (J-B)

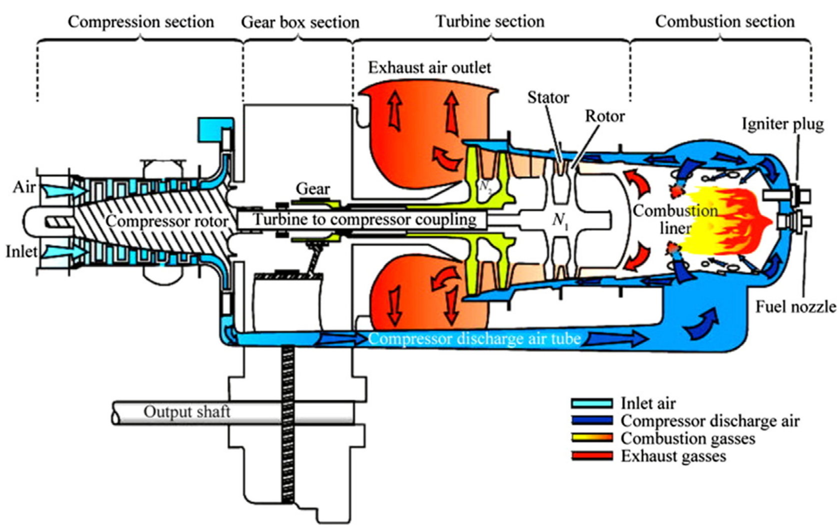

FIGURE 2.2 Gas turbine. *From Nkoi, B., Pilidis, P., & Nikolaidis, T. (2013). Performance assessment of simple and modified cycle turboshaft gas turbines. Propulsion and Power Research, 2(2), 96–106.*

(also known as the Brayton cycle) and comprises a compressor, a combustor or burner, and a turbine. Although air is the standard working fluid for the J-B cycle, inert gases or their mixtures or the combustion products of fossil fuels are also frequently used based on the application (STP, 2019). In fact, gas turbines offer the good advantage of fuel flexibility with the capability of adopting almost any flammable gas or light distillate petroleum products.

Gas turbines are primarily employed in large-scale power generation in solitary setup or in a cogenerating installation along with steam turbine power plants. Apart from power generation, gas turbines are the most widely employed propulsion systems in modern aircraft. In the aviation sector, different designs of gas turbines (popularly called engine) are available such as turbofan engine, turboprop engine, turbojet engine, etc.

2.2.4 Combined-cycle power plants

Combined-cycle power plants (Fig. 2.3) are compound gas turbine−steam turbine systems wherein the extreme hot exhaust from a gas turbine is employed to run a boiler, and the steam thus produced is fed into a steam turbine to generate power. These plants can deliver high power output at efficiencies as high as 50%−60% with low emissions and produce 50% more electricity than a simple-cycle plant consuming the same amount of fuel (Ramireddy, 2012). Combined cycle power plants may be either single-shaft, wherein both of the gas turbine and steam turbine are connected to the same generator in a tandem arrangement, or multishaft, with each gas turbine and steam turbine driving a separate generator.

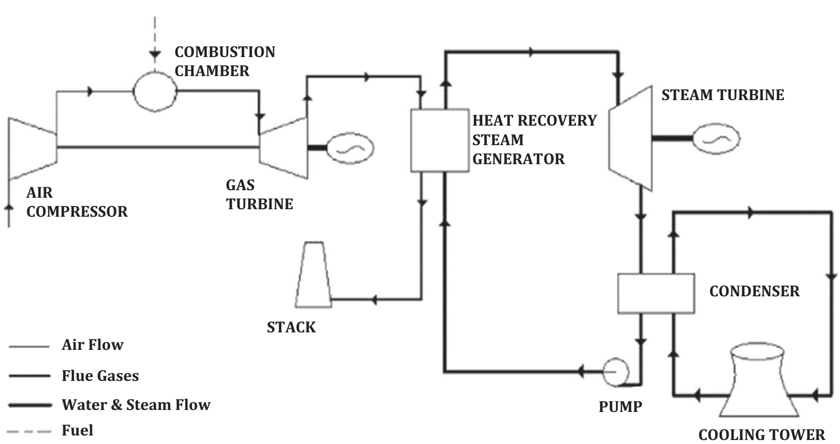

FIGURE 2.3 Schematic of combined-cycle power generation. *Dev, N., Kachhwaha, S. S., & Attri, R. (2014). Development of reliability index for combined cycle power plant using graph theoretic approach. Ain Shams Engineering Journal, 5(1), 193−203.*

2.2.5 Advanced combustion technologies

2.2.5.1 Clean coal technology

Coal is the world's most plenteous and widely disseminated fossil fuel source and fulfills about 27% of global primary energy needs. Almost 70% of world steel production and 38% of global electricity generation is dependent on coal feedstock (USC, 2019). However, it is the dirtiest of all fossil fuels, and emissions from its combustion contribute to global warming, create acid rain, and pollute water. It has been estimated that every year more than 14 billion tonnes of CO_2 are emitted from coal burning (USC, 2019).

Clean coal technology, as shown in Fig. 2.4, is a combination of technologies developed in attempts to diminish the negative environmental impact of coal energy generation. "Clean coal" connotes supercritical coal-fired plants without carbon capture and storage (CCS), since CO_2 emissions are less than for conventional plants (IEA, 2008). Coal cleaning removes primarily pyritic sulfur along with other impurities such as Pb, As, Hg, Ni, Sb, Se, and Cr and thereby improves the heating value of the coal.

2.2.5.2 Pulverized coal combustion

Coal-based power plants with conventional stoke firing suffer from some shortcomings such as the inability to handle load fluctuations due to limited combustion capacity, difficulties in removing large quantities of ash, and interference of the formed ash in the combustion process. Pulverized coal combustion systems offer a viable solution to all these problems, wherein coal is reduced to a fine powder in grinding mills and projected into the combustion chamber through a hot primary air current. To ensure complete combustion, supplementary air (known as secondary air) is delivered separately to the combustion chamber. Globally, almost 97% of the coal power plants with sizes up to 1000 MW are run by pulverized coal. The efficiency of the pulverized fuel firing system mostly depends on the size of the powder, and average net efficiencies reach up to 35% (Nicol, 2013). Pulverized coal technology is classified (Table 2.1) based on the operating temperature and pressure, wherein

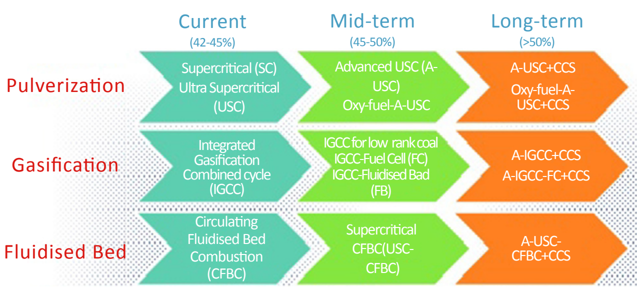

FIGURE 2.4 Clean coal technologies (Zhu, 2017).

TABLE 2.1 Classification of pulverized coal combustion plant with steam parameters, efficiency, etc. (Cocco, Reddy Karri, & Knowlton, 2014).

Technology	Super heating point	Efficiency (%)	Coal consumption (gm/kWh)
Subcritical	≤540°C <22.1 MPa	<35	≥380
Supercritical	540°C–580°C 22.1–25 MPa	35–40	380–340
Ultrasupercritical	580°C –620°C 22–25 MPa	40–45	340–320
Advanced ultrasupercritical	700°C–725°C 25–35 MPa	45–52	320–290

subcritical plants operate below the critical point of water, and the supercritical, ultrasupercritical, and advanced ultrasupercritical (AUSC) work beyond the critical point. The efficiency of these technologies increases (from <35% for subcritical to 52% for AUSC) with their operating temperatures and pressures.

2.2.5.3 Fluidized bed combustion

Fluidized bed combustion (FBC) is a specialized combustion process wherein solid particulates are suspended in upward jets of air in order to achieve more effective chemical reaction and heat transfer. This advanced technology is being used in the cracking of hydrocarbons, gasification of coal, roasting of ore, calcination of limestone, combustion of waste, etc. (NNFCC, 2009). One of the major benefits of FBC is that it facilitates the combustion of many unconventional fuels that would not be otherwise possible. In addition, it allows very low emission of NOx and SO_2.

2.2.5.4 Gasification technology

Gasification is the transformation of carbonaceous materials (either organic or fossil fuel) into CO, H_2, and CO_2 by means of reacting the materials with a regulated volume of oxygen and/or steam at high temperatures (>700°C) without burning them up. The resulting gas, which itself is a fuel, is called syngas or producer gas (Tucker, 2018). Gasifier technology is compliant with a wide range of fuels such as coals, petroleum coke, etc. and can also be employed in combined-cycle power plants—e.g., integrated gasification combined-cycle plants.

2.2.5.5 Carbon capture and storage

CCS is a cluster of technologies including accumulating, transporting, and then containing the carbon dioxide in order that it does not break out into the atmosphere and add to climate change. There are three key techniques in CCS: (1) converting coal into a clean-burning gas, (2) cleaning the power plant of exhaust gas using chemicals, and (3) burning the coal with pure oxygen of high concentration resulting in almost pure CO_2 exhaust. After trapping CO_2, it is liquefied, transported, and buried either in suitable geological formations, deep underground saline aquifers, or abandoned oil fields. Referring to the last option, CO_2 is sometimes pumped into oil fields to force out the residual pockets of oil (known as enhanced oil recovery) that would otherwise be tough to extract (Tanaka & Hasanuzzaman, 2018; Walker, 1980).

2.3 State-of-the-art energy conversion technologies

2.3.1 Stirling engine

The Stirling engine (Fig. 2.5) is a closed-cycle regenerative heat engine with permanently sealed gas, wherein the heat source is generated external to the engine. The engine is designed such that the gas is compressed in the cooler part and expanded in the hotter part ensuing a net conversion of heat into work (Andersson et al., 2015). Although air is the traditional working fluid for Stirling engines, hydrogen and helium are also employed for improved performance due to their better thermal properties.

Combustion occurs continuously in Stirling engines, which ensures clean burning. Moreover, the efficiency of this engine is not susceptible to the fuel

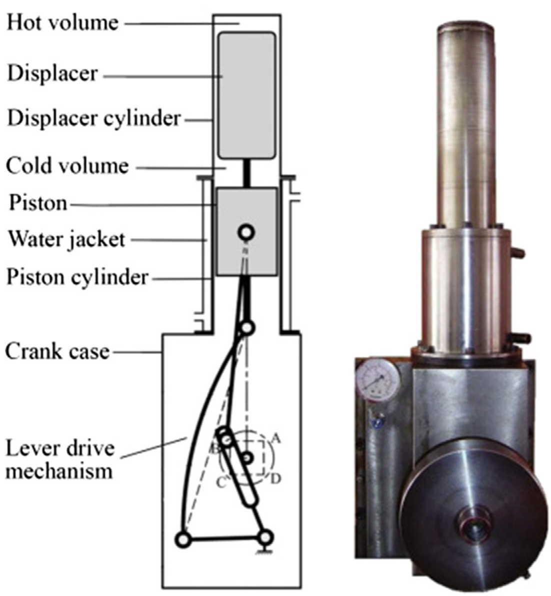

FIGURE 2.5 Stirling engine schematic *(Source: Wang, K., Sanders, S. R., Dubey, S., Choo, F. H., & Duan, F., 2016).*

type or quality. That is why the Stirling engine is more effectual than SI 2engines for hybrid electric automotive applications. In addition, the Stirling engine is attuned with both conventional and renewable energy sources, making it a future solution to fossil fuel depletion and climate change problems.

2.3.2 Nuclear power

Nuclear power has been the most concentrated and high-quality energy available to date. The energy contained in 1 kilogram of uranium, if it were all released, would produce energy equivalent to that produced from firing 3000 tonnes of coal. A nuclear reactor discharges nuclear energy as heat that is employed to generate steam; the steam is fed to a conventional steam turbine to generate electricity (DEC. Duke Energy Corporation, 2013). Although most nuclear power plants employ nuclear fission (splitting an atom into two), nuclear fusion (combining atoms into one) has good potential to be a benign way to produce power (Juan, Douglas, David, Paul, & Darla, 2012).

Different types of nuclear reactors have been developed to facilitate controlled release of nuclear energy, and many are still under development. Some major reactor technologies are pressurized water reactor, boiling water reactor, pressurized heavy water reactor, gas-cooled reactor, light water-cooled graphite-moderated reactor, fast breeder reactor, high-temperature gas-cooled reactor, and very-high-temperature reactor (EPA. U.S. Environmental Protection Agency, 2015).

Nuclear power plants are designed to run unceasingly, and it has been observed that nuclear plants run at their full capacity more than 90% of the time without any maintenance, making it the most reliable energy source. However, the problem with these power plants is the radioactive waste they produce in the course of power generation. It has been estimated that the USA alone produces 2000 metric tonnes of radioactive waste every year (Un-Noor, Padmanaban, Mihet-Popa, Mollah, Hossain, 2017).

2.3.3 Fuel cells

Fuel cells are electrochemical cells that produce electricity directly by extracting the chemical energy of a fuel and an oxidant eluding the wasteful multistep processes of heat engines, thereby enhancing efficiency and reducing emissions. Fuel cells operate silently without vibration and hence are suitable for onsite usage. Due to the simplicity of their construction and operation, fuel cells are apposite for distributed and portable power generation. Moreover, these devices can cope quickly with varying load conditions without compromising efficiency, which makes them suited for part-load operation. Above all, for the same quantity of energy-conversion, fuel cells produce less

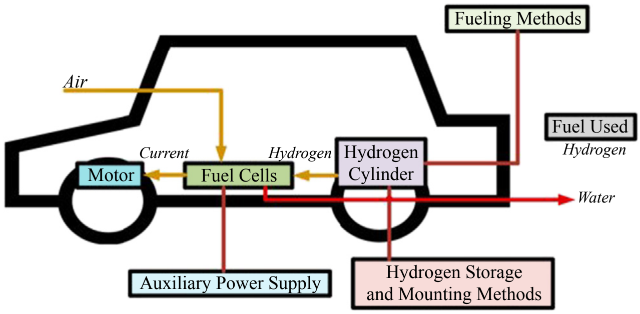

FIGURE 2.6 Basic components of a fuel cell electric vehicle (Williams, 2004).

emissions because of high conversion efficiency. Fuel cells are frequently used in space applications, zero-emission vehicles (Fig. 2.6), etc.

Currently, six major fuel cell technologies are at different stages of development and commercialization: alkaline, phosphoric acid, polymer electrolyte membrane, molten carbonate, solid oxide, and direct methanol fuel cells (Chang, 1982).

2.3.4 Thermionic power conversion

Thermionic energy conversion (TEC) is the direct generation of electricity by thermionic electron emission, wherein intensely hot electron vapor works as the working fluid in cycle (Baksht et al., 1978). When refractory metals like cesium or tungsten are heated to temperatures as high as 2000 K, electrons are vaporized from their surface (known as the emitter) to create a plasma and then cross the small interelectrode gap to a colder surface (known as the collector) at around 1000 K where they condense, creating a voltage that impels the current through the load and returns it to the emitter. TECs are high-current low-voltage devices, and depending on the emitter temperature, usually 25−50 A/cm^2 at a voltage of 1.0−2.0 V is achievable through this process. Like other cyclic heat engines, the maximum efficiency of thermionic generators is limited by Carnot's law and typically efficiencies of 5%−20% are practicable (Geller et al., 1996). The magnitude of current and voltage depends on electrode surface properties, and the rate of transport of electrons from emitter to collector is determined by plasma properties. Cesium vapor is employed in most converters because it can be easily ionized of all stable elements. Although TEC is a high-temperature device, research shows that at lower operating temperatures, significant enhancements in converter performance are possible if oxygen is added to the cesium vapor (Ramalingam & Young, 1993).

The TEC can produce power in the range of 5 kWe to 5 MWe, and electrical power in this range can work for telecommunication satellites, navigation, propulsion, and terrestrial exploration missions (Leighton et al., 2015).

2.3.5 Thermoelectric generators

Thermoelectric generators (TEGs) refer to any class of solid-state device that either converts heat directly into electricity (by the Seebeck effect) or transforms electrical energy into thermal energy (by the Peltier effect) (Goldsmid, 2017). To generate electricity, thermoelectric objects should possess both good electrical conductivity and low thermal conductivity. The main three semiconductors known to have both low thermal conductivity as well as high power factor are bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon germanium (SiGe). However, all three compounds are highly expensive (Teffah, Zhang, & Mou, 2018).

A thermoelectric module (Fig. 2.7) comprises two different thermoelectrics, with n-type and p-type semiconductor substances connected at their ends. As the two ends are maintained at different temperatures, DC electricity will generate in the circuit, the magnitude being directly proportional to the temperature difference. TEG modules are subjected to high thermal stresses and strains for extended periods of time, which also creates mechanical fatigue. Thus, selection of junctions and materials should ensure resistance to these harsh conditions.

The efficiency of a thermoelectric module is greatly dependent on its design. Usually thermoelectric materials should be arrayed thermally in parallel but electrically in series. Despite the fact that they have no moving parts, thus eliminating friction losses, TEGs are still less efficient. However, TEGs can utilize the waste heat of conventional power plants to produce supplementary electrical power. Automotive thermoelectric generators are another practical application of this technology. Moreover, radioisotope thermoelectric generators are used in space probes.

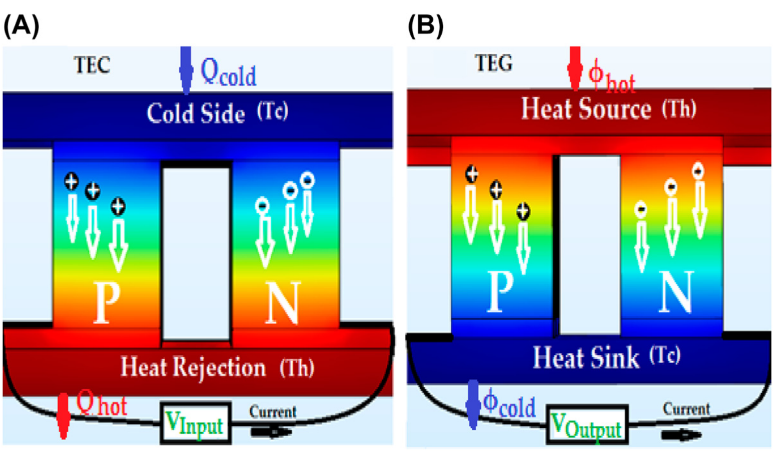

FIGURE 2.7 Thermoelectric generator (Messerle, 1995).

2.3.6 Magneto-hydrodynamic power generation

A magneto-hydrodynamic (MHD) generator, similar to a regular generator, generates electricity by means of revolving a conductor over a magnetic field, where instead of copper a hot conductive plasma is used as the moving conductor (Ajith Krishnan & Jinshah, 2013). In fact, MHD generators are one of the initiatives of scientists to eliminate mechanical systems working in between thermal and electrical energy conversion, with a view to reduce the loss associated with thermodynamic conversion. That is, MHD generators are employed to generate electricity directly from heat without any intermediate moving parts. An electrically conductive gas under high pressure is flown over a magnetic field (stemmed from the Hall effect), then the gas is expanded to run a turbine. Exclusion of moving parts in MHD generators facilitates running at higher temperatures (as high as 3000 K) than conventional heat engines, which could deliver efficiencies near 90% (Klinghoffer & Castaldi, 2013).

2.3.7 Waste-to-energy conversion

Waste-to-energy (WtE) is a specially designed energy generation facility that employs household waste as fuel. It has been estimated that from one tonne of municipal solid waste, 750 kWh of power and 22.68 kg of metal can successfully be recovered. WtE conversion facilitates reduce the volume of waste by almost 90% and save space in the landfill. One hundred cubic yards of waste can be burnt to only 10 cubic yards of ash with a significant amount of electricity supply, equivalent to 13,000 kWh. Currently, the best technology for WtE conversion is incineration in combined heat and power (CHP) plants, wherein solid waste volume can be decreased ninefold (Overend, Milne, & Mudge, 2012).

2.3.7.1 Thermochemical conversion

Incineration with mixed waste input is the most popular thermochemical conversion technology applied through CHP plants.

Cocombustion of solid waste with a supplementary fuel (usually coal or biomass) helps to regulate thermal properties.

Refuse-derived fuel technology can be employed for energy production either by monocombustion or cocombustion with municipal solid waste or coal (Angelidaki, Karakashev, Batstone, Plugge, & Stams, 2011).

Thermal gasification transforms carbonaceous materials into energy-rich gases, which can be a worthy alternative to burning out the wastes.

2.3.7.2 Biochemical conversion

Several methods for biodecomposition of wastes into energy-rich fuels are as follows:

Bioethanol is manufactured by chemical treatment of some organic wastes through hydrolysis (via enzymatic treatment), fermentation (using microorganisms), and distillation (Angenent, Karim, Al-Dahhan, Wrenn, & Domíguez-Espinosa, 2004).

Dark fermentation and photofermentation are practices to mend organic materials into hydrogen without light or under light in turn through the activity of different bacteria. These technologies are applied mainly for wastewater treatment (Zaman, 2009).

Biogas is the raw methane gas (unfiltered and unpurified) from anaerobic digestion processes (Angenent et al., 2004).

Landfill gas is a mixture of gases (40%−60% methane) created by the action of microorganisms within landfill sites (Min, Cheng, & Logan, 2005).

Microbial fuel cells produce electricity by means of the conversion of the chemical energy content of organic substances by means of the catalytic reaction of microorganisms and bacteria (Hamad, Agll, Hamad, & Sheffield, 2014).

2.3.7.3 Chemical conversion (esterification)

Esterification is the process of producing ester through the reaction of an alcohol and an acid. Various biofuels can be obtained from wastes through esterification (IRENA, 2018).

2.4 Renewable energy conversion systems

Renewable energy still lacks a unanimous definition, with definitions split by type of energy sources included and in sustainability criterion adopted. The International Renewable Energy Agency has a statutory definition, ratified by 108 members (107 states and the European Union) as of February 2013 (IEA, 2002): "Renewable energy includes all forms of energy produced from renewable sources in a sustainable manner, including bioenergy, geothermal energy, hydropower, ocean energy, solar energy and wind energy."

The International Energy Agency (IEA) defines renewable energy resources as those "derived from natural processes and replenished at a faster rate than they are consumed." The IEA definition of renewable energy includes the following sources: "electricity and heat derived from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources."

2.4.1 Solar energy conversion systems

Basically, there are two types of solar energy-conversion systems—solar thermal energy-conversion systems and solar electrical or photovoltaic (PV) systems. In recent years, there have been developed hybrid photovoltaic thermal systems that provides both electricity and heat form the same module (Fayaz, Rahim, Hasanuzzaman, Nasrin, Rivai, 2019a, Fayaz, Rahim, Hasanuzzaman, Rivai, Nasrin 2019b; Gary Cook, 1995).

2.4.1.1 Solar photovoltaics

PV or solar cells are semiconductor devices that produce electricity when exposed to sunlight through photovoltaic effect. Although PV modules (electrically connected PV cells) constitute the heart of a PV power system, a number of other components are required to conduct, control, convert, distribute, and store the energy produced by the PV array (an assembly of electrically connected PV modules). Depending on the functional and operational requirements, the DC—AC power inverter, battery bank, battery controller, and auxiliary energy sources are integrated with PV modules (or arrays). In addition, overcurrent, surge protection, disconnect devices, and other power processing equipment, known as the balance of system, are also included in a PV power system (Fig. 2.8) (SPS, 2019).

Primarily crystalline silicon (c-Si) cells (both mono- and multicrystalline) are used in PV panels, though recently the use of amorphous silicon (a-Si) cells has been growing steadily. The most favorable feature of a-Si is that only 1% of the material (silicon) is required to produce an a-Si cell as compared to that required to produce a c-Si cell of the same size. Apart from silicon cells, nowadays thin-film (cadmium telluride; copper-indium diselenide; copper-indium-gallium disulphide, and CIGS) are becoming commercially worthwhile due to their lower production costs. Recently, organic solar cells such as dye-sensitized solar cells are becoming popular.

2.4.1.2 Solar thermal technologies

Low-temperature solar thermal systems includes unglazed flat-plate solar collectors and evacuated tube collectors and are employed in temperature requirements not exceeding 180°C. These collectors employ the "greenhouse

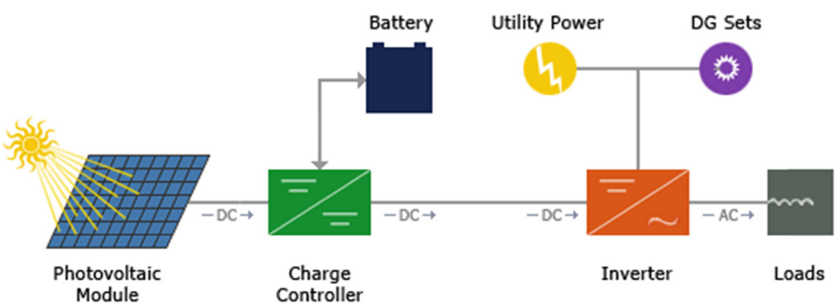

FIGURE 2.8 Solar PV power system (John & Duffie, 2006).

effect" to arrest the high-energy short-wavelength incident radiation to transform into long wave and gradually heat up an absorber plate. Applications include water and space heating, swimming pool heating, etc. (Fayaz et al., 2019a, 2019b; IRENA, 2013; Nahar, Hasanuzzaman, Rahim, & Parvin, 2019).

Concentrating solar power systems focus incident sunrays along a line or to a point. Line focus collectors track the sun along a line in a single axis and raise temperatures from 100 to 550°C. On the other hand, point focus collectors concentrate incident sun rays at a point receiver, creating temperatures as high as 800°C or more (Heimsath, Platzer, Heß, Krüger, & Eck, 2009; Islam, Hasanuzzaman, & Rahim, 2015; Kumar, Hasanuzzaman, & Rahim, 2019) shows different concentrating technologies with their temperature ranges and applications.

2.4.2 Bioenergy technologies

Bioenergy is the energy derived from materials of biological origin that is not fossilized. Raw woody biomass and animal wastes meet the world's major share of primary energy need; however, these can be metamorphosed into various gaseous or liquid fuels.

2.4.2.1 Biomass for power and heat

Thermochemical (combustion, pyrolysis, gasification, and liquefaction) or biochemical (digestion and fermentation) gasification of cellulosic biomasses such as wood chips, pellets or wood powder, or agricultural wastes like straw or husks transform these things into a flammable gas (Anna Schnürer, 2010).

2.4.2.2 Biogas

Biogas is a blend of gases produced by the decomposition of organic matter in the absence of oxygen. It is used for heating or cooking, running IC engines, or as synthetic gas to yield higher-quality fuels or chemicals. To produce biogas, biomass is first heated in lack of air to break down the solid mass into gas, the gas is then cleaned, and lastly filtered to remove unwanted chemicals. Anaerobic digestion, a form of fermentation, is another way to transform organic matter into biogas. Anaerobic biogas, which is comparable to landfill gas, comprises 60% methane and 40% carbon dioxide (Uriarte, 2010). Biogas is used in power generation systems such as combined-cycle power plants.

2.4.2.3 Biofuels

Liquid biofuels cover pure plant oil (also called straight vegetable oil), biodiesel, and bioethanol (Omidvarborna, Kumar, & Kim, 2014). Ethanol is principally produced from sugar, maize, and other starch-rich crops. Biodiesels are vegetable oil- or animal fat-based diesel replacements comprising long-chain alkyl esters, usually produced by reacting lipid with alcohols

(Ackermann, 2005). Biodiesel can be used in regular diesel engines in pure form or may be blended with petro diesel in any proportion; thus 100% pure biodiesel is denoted B100, 20% biodiesel blended with 80% petro diesel is denoted B20, and so on. On the other hand, bioethanol is ethyl alcohol (C_2H_5OH) produced from the fermentation of glucose, sucrose, etc. from plant sources (sugarcane, corn, sugar beet, etc.) by engaging microorganisms like yeasts or bacteria.

2.4.3 Wind energy conversion systems

Wind energy is the kinetic energy of blowing air as it flows due to atmospheric pressure gradients, and wind turbines are the contrivance to convert this kinetic energy into electricity. Wind power that could be harvested is proportional to the rotor diameter and cube of the wind speed; hence, as wind speed is doubled, wind power potential upsurges by eight times. There are two basic configurations of wind turbines, namely vertical axis wind turbines and horizontal axis wind turbines (HAWTs); a vast majority of installations are HAWTs with either two or three vanes. Large turbines are grouped together to form a wind power plant, which feeds power to the electrical transmission system (TSSWT, 2012).

2.4.4 Ocean or marine energy technology

The waves and tides of the oceans involve enormous energy potential that can be harvested for practical applications. Moreover, temperature difference between cold deep waters and hot surface waters and the salinity gradient at river mouths can also be encountered for power generation (Ruud Kempener, 2014). The established and potential marine energy technologies are as follows.

2.4.4.1 Ocean thermal energy conversion

Solar energy reserved as thermal energy in the upper layers of the oceans constitute an enormous renewable source estimated to be as high as 10^{13} W (SERI, 1989). Ocean thermal energy-conversion (OTEC) technology harnesses energy by using the temperature gradient between the warmer ocean surface water and the cooler deep water (Hamedi & Sadeghzadeh, 2017). It has been observed that even a temperature difference of 20°C can provide operative energy (Barstow, Mollison, & Cruz, 2008).

OTEC plants are of three types: open (Claude) cycle, closed (Anderson) cycle, and hybrid cycle. Claude cycle makes use of the tropical ocean's warm surface water as a heat transfer fluid (HTF) wherein warm water is allowed to expand rapidly in a partially evacuated chamber causing a phase change to steam, and as the steam continues to expand it drives a low pressure steam turbine. At the turbine exit, by using cold seawater, the vapor is condensed to freshwater containing no salt, which can be a source of drinking water for nearby townships. A 1-MW OTEC can produce around 4500 m^3 of freshwater per day, adequate to provide for a 20,000 populace. The Anderson cycle employs ammonia, propane, or Freon as the working HTF, which is confined in an entirely closed system including the turbine. Hot surface water is employed to vaporize the fluid through a heat exchanger, and the vapor produced thereby is expanded over the vanes of a turbine which in turn drives a generator. At the turbine exit, the vapor is condensed with cool deep ocean-water and pumped back to the evaporator. In hybrid cycles, instead of discharging the hot water of a closed-cycle OTEC to the ocean, it is fed to an open-cycle OTEC system to augment power output.

2.4.4.2 Wave energy

Wave energy is a blend of both kinetic and gravitational potential energy of ocean waves created as a result of the wind blowing over the surface. Wave resources are extremely variable, as availability is strongly dependent on wave height, and during storms wave power can reach highs of 200 kW/m, but are insecure for maneuvering. The average yearly incident wave power at the northeastern Pacific and Atlantic is about 50 kW/m, while near Cape Horn in South America this figure may reach as high as 100 kW/m (Goswami & Kreith, 2017).

Electricity can be generated by harnessing wave energy by means of an oscillating water column that comprises an air compartment in contact with the ocean; as the water column oscillates, it makes the air to flow in and out, thereby turning a turbine. Well turbines with symmetrical airfoil blades counterbalanced by flywheels (to transform the oscillation motion due to waves into linear motion) are used to deliver power.

2.4.4.3 Tidal power

Tides contain huge amounts of potential energy that can generate power during the gravity-driven inflow or outflow (or both) of seawater through a turbo-generator (Dye, 2012). A dam is erected to isolate the tidal basin from the sea and create a difference in water level between them. During high tide, water flows from the sea into the basin through the turbine and generates power; on the other hand, during low tide, as water flows out from tidal basin to the sea it rotates the turbine in opposite direction and produces power, too.

2.4.5 Geothermal power generation

Geothermal energy is heat energy generated and stored in the Earth's crust and originates from the radioactive decay of materials in the original formation of the planet (DiPippo, 2012). While the global average geothermal gradient is 30°C/km, the regional gradient can exceed 90°C/km, which is adequate for power generation, and this high-temperature energy is available only in a few places. Geothermal energy can be ranked as high temperature (>180°C), intermediate temperature (101 to 180°C,) and low temperature (30 to 100°C) energy.

There are four categories of geothermal power plants: dry steam plants, flash power plants, binary geothermal plants, and flash/binary combined cycle. Dry steam noncondensing cycle is the basic and inexpensive way to generate electricity, wherein steam from the geothermal well is flown over a turbine and spent to the atmosphere. However, the most common type of geothermal plant is the flash steam power plant, which mainly addresses water-dominated reservoirs with temperatures greater than 180°C. The hot water is pumped up to the surface until its pressure drops and water starts boiling, creating a two-phase mixture of water and steam. Thus, steam is separated from the water, going to the turbine, with the cooled water piped back to source. Binary-cycle power plants use the heat of the hot geothermal fluid (74−177°C) to boil a working fluid (typically an organic compound of low boiling point), the geothermal fluid and the working fluid are confined to separate closed loop fluids to generate steam through a heat exchanger and then run a turbine. Apart from the above configurations, there are binary-cycle plants, which have three configurations, viz., brine bottoming binary, spent steam bottoming binary, and hybrid system (WorldAtlas, 2019). Although geothermal power provides about 0.4% of global power generation, the growth rate is stable. With 22 power plants with a combined installed capacity of 1.52 GW, the Geysers Complex, in the Mayacamas Mountains, San Francisco, California, USA, is the biggest geothermal field in the world (Breeze, 2018).

2.4.6 Hydropower generation

Hydroelectric power (briefly called hydropower) is derived from water in motion. Water stored at a higher level is allowed to flow down through conducting lines and flow over the vanes of a turbine installed downstream of the flow; as the water turns the turbine, it runs the generator to generate electricity. In order to generate a reliable supply of water with significant potential energy, dams are essential; the dam creates a head from which water flows through a pipe (called penstock) from the headwater reservoir through the turbine to the tailwater reservoir. Apart from conventional hydro dams, electricity can be produced from run-of-the-river by harnessing the kinetic energy in rivers or streams, pumped-storage reservoirs, etc. In addition, microhydropower and picohydropower plants are attracting substantial attention from researchers (IHA, 2018). Depending on the head available, hydroelectric power plants employ mainly three categories of water turbines: a Pelton wheel for very high heads (>1500 m), Francis turbines for medium head (∼750 m), and Kaplan turbines (<100 m).

In 2017, the installed capacity of world hydropower was 1267 GW with an estimated generation of 4185 TWh (AFP, 2015). The Three Gorges Dam over the river Yangtze in Hubei, China, is the world's largest hydropower plant with a generation capacity of 22.5 GW, while Itaipu in Brazil/Paraguay over the river Parana has a capacity of 14.0 GW (AFP, 2015).

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