PES University
Department of Mechanical Engineering
UE18ME101: Mechanical Engineering Sciences

Detailed Lesson Plan

Unit-1 : Energy Sources and Power Generation

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3 Power Plant Engineering and Sources of Energy

Chapter Objectives

In this chapter, you will learn about:

- Prime movers
- Thermal power plant
- Hydroelectric power plant
- Nuclear power plant
- Conventional and non-conventional sources of energy

3.1 INTRODUCTION

There are different forms of energy; all the energy cannot be used as a work. The convertibility of energy into work depends on its availability. In this chapter, we will discuss about the conversion of energy from one form to another and various sources of energy. The principles of operations of various types of power plant have been discussed such as thermal power plant, hydroelectric power plant, and nuclear power plant. Also the different sources of renewable and non-renewable form of energy have been introduced. The main application of power plant is to produce electrical power from other sources of energy such as coal, water, diesel, kerosene oil, gasoline, nuclear materials, tidal power, wind energy, geothermal energy, etc.

3.2 PRIME MOVERS

Prime mover is a primary source of power. All the machinery that provides power for performing various kinds of mechanical work is prime movers. It is a group of machines that transform various forms of energy such as thermal, electrical or pressure into mechanical energy. Engines, turbines, pumps, actuators, etc. are the examples of prime movers.

On the basis of direction of movement, prime movers may be classified as *reciprocating prime movers* and *rotating prime movers*. Steam engine, reciprocating pump, reciprocating compressors, internal combustion engines, mechanical actuators, etc. are the examples of reciprocating prime

movers and centrifugal pump, gas turbines, steam turbines, rotary compressors, etc. are the examples of rotating prime movers.

3.2.1 Historical Development of Prime Movers

- The revolution was begun when the technology of the steam engine was invented by James Watt.
- For power generation, three principal competitors are introduced in the field of production of mechanical power. They are the steam turbine plant, the diesel piston engine and the gasoline piston engine.
- Steam turbines became the most important prime mover for power generation in the 19th century.
- Because of this, new bulky and expensive steam generating equipment, the boiler, and the nuclear reactor, were introduced. They are intended to produce steam as an intermediate working fluid.
- Later many other power generation systems were introduced. The example of such types of power generators is diesel plant. In many locations these machines started replacing bulky power plants for power generation.
- Gasoline engines were used in the early days for aircraft propulsion. A device named the gas turbine was also introduced during that time, and it supplanted the use of superchargers based on piston engines.
- The main development of the gas turbine started only after the Second World War. They were based on shaft power technology and were called turboprops. After some time the development of turbo-jet engines for aircraft usage started, and these are based on mass airflow rather than shaft output.

3.3 POWER PLANT ENGINEERING

Power plant engineering is a branch of engineering which deals with conversion of various forms of energy into electrical energy. In this text we will discuss about thermal power, hydroelectric power, nuclear power, and non-conventional sources of energy. In thermal power plant, coal, diesel, petrol, natural gas, and kerosene oil are used as fuel and chemical energy of these fuels is converted into mechanical energy and then mechanical energy into electrical energy. In hydroelectric power plant the potential energy of water is converted into mechanical energy as shaft power and then mechanical energy into electrical energy. Similarly, in the case of nuclear energy, nuclear power is used to generate the heat required to produce superheated steam and then the heat energy is converted into mechanical energy and the mechanical energy is converted into electrical energy.

3.3.1 Thermal Power Plant

Thermal power plant may be coal based or gas based. In coal-based power plant, coal is used as burning fuel and the heat energy is transferred to water to convert it into superheated steam. The heat energy of the steam is converted into shaft power through expansion of steam in steam turbine. The shaft of steam turbine is coupled with generator where electricity is generated. The exhaust steam from steam turbine is condensed into condenser using cooling water. Condenser works just like a heat exchanger where heat energy of steam is transferred to cooling water and steam is condensed in the form of water which is then pumped into boiler. The cooling water is re-circulated through cooling tower to release the heat. A self-explanatory diagram is shown in Figure 3.1. The detail working of boilers and steam turbines is discussed in Chapters 4 and 5, respectively.

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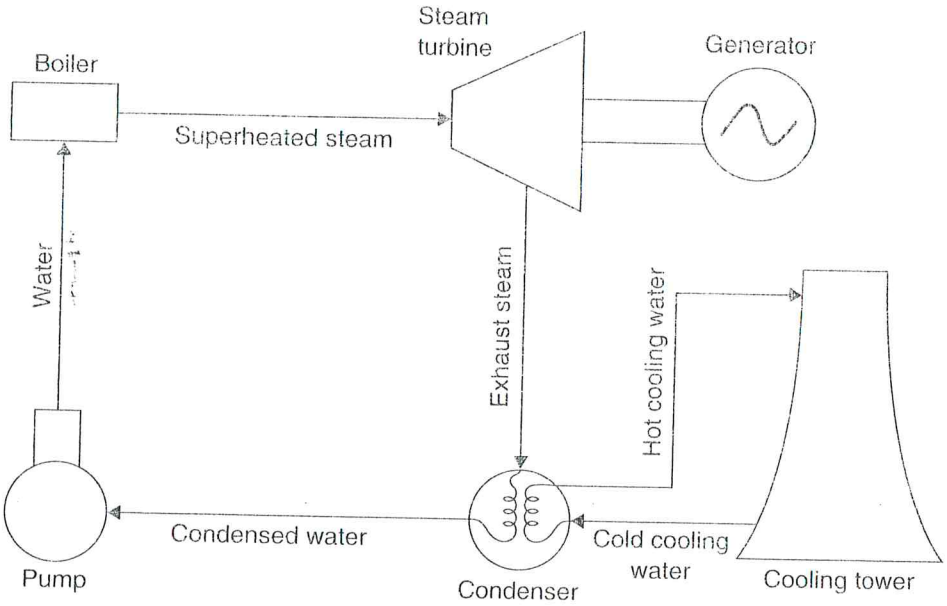

Figure 3.1 A Block Diagram of Steam Power Plant

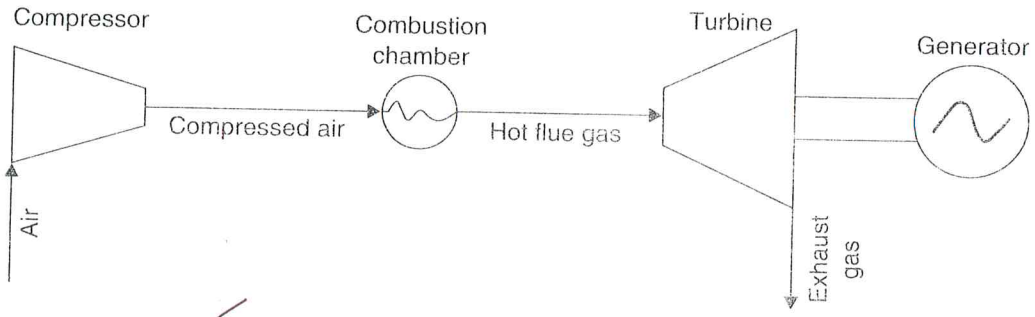

Figure 3.2 A Block Diagram of Gas Power Plant

In gas-based power plant or gas power plant, air is compressed to high pressure and heat energy is added to compressed air using combustion chamber by direct burning of fuel in compressed air or indirect heat transfer to compressed air. The high pressure and high temperature air is expanded in gas turbine which is coupled with generator generating electricity due to shaft rotation. The exhaust gas from turbine is released into atmosphere in the case of open cycle gas turbine and re-circulated to the compressor in the case of closed cycle gas turbine. The self-explanatory diagram of gas power plant is shown in Figure 3.2. The detail discussion about gas turbine and compressor is given in Chapters 5 and 10, respectively.

3.3.2 Hydroelectric Power Plant

The principle of electricity generation in the case of hydroelectric power plant is the same as in thermal power plant; only difference is that the shaft power to the turbine is provided by pressure and kinetic energy of water in the case of hydroelectric power plant and in thermal power plant the shaft power to the turbine is provided by heat energy of superheated steam or gas. As shown in Figure 3.3, the potential energy of water stored in a dam is used to rotate the turbine blades mounted on a shaft coupled with a generator. Different types of turbines may be used in hydroelectric power plant and

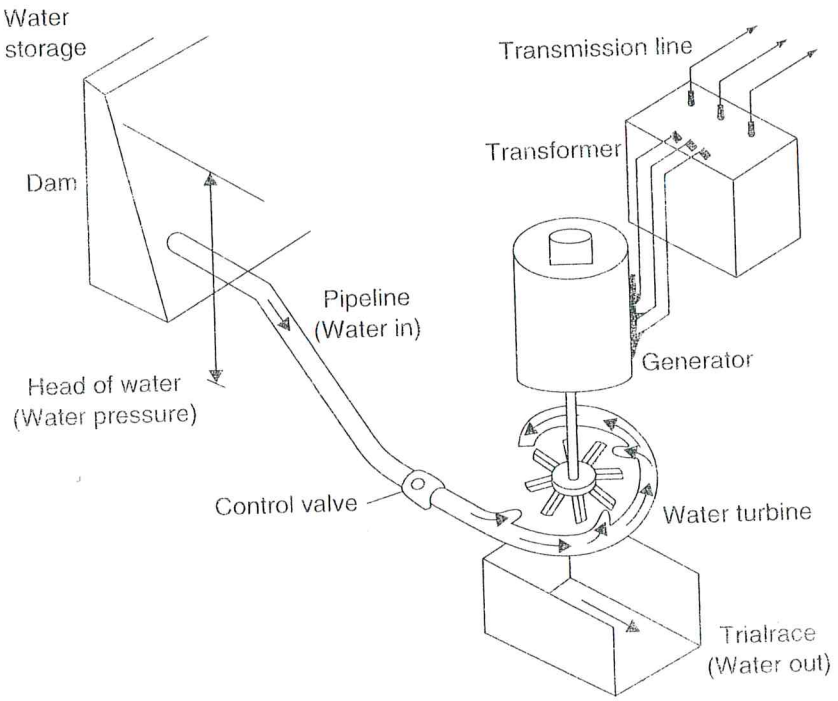

Figure 3.3 A Block Diagram of Hydroelectric Power Generation

it depends on availability of water heads. The applicability of different types of water turbine for various water heads and their specific speeds are discussed in detail in Chapter 9.

3.3.3 Nuclear Power Plant

In nuclear power plant, nuclear energy released from radioactive materials due to fission reaction is utilized to heat the water and convert it into superheated steam. Rest of the electricity generation process is similar to steam power plant as discussed in Section 1.3. The main problem is careful handling of radioactive fuel used in nuclear reactor. Radiations from nuclear fuel are very harmful and dangerous for human beings. Therefore, complete shielding of nuclear reactor is required. After useful life of nuclear fuel, disposal of nuclear waste is second major problem in nuclear power plant. The installation cost of nuclear power plant is very high but the operational cost and production cost per unit of electricity is very economical. A self-explanatory block diagram of nuclear power plant is shown in Figure 3.4.

Components of Nuclear Reactor

Fuel: ${}_{92}U^{235}$, ${}_{94}Pu^{239}$, ${}_{92}U^{233}$ are nuclear fuels used in nuclear reactor to release the heat energy. In uranium ore, ${}_{92}U^{235}$ is available only up to 0.7% and the remaining is ${}_{92}U^{238}$. The other two fuels ${}_{94}Pu^{239}$ and ${}_{92}U^{233}$ are formed in the reactor during the fission process of ${}_{92}U^{235}$. ${}_{90}Th^{232}$ is formed due to absorption of neutron by ${}_{92}U^{235}$ without fission. In homogeneous reactors, the fuel (uranium) and moderator (carbon) are mixed homogeneously and used in the form of rods or plates in the reactor. In heterogeneous reactors, fuel is used in the form of rod and moderator surrounds it. The fuel rod is clad with aluminium, stainless steel or zirconium to prevent from oxidation.

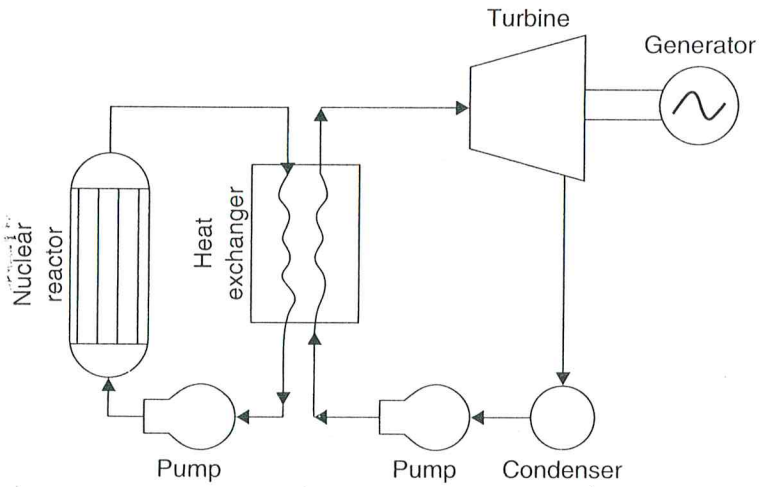

Figure 3.4 A Block Diagram for Nuclear Power Plant

Moderator: The moderator is a material which is used to reduce the kinetic energy of fast neutron (1 MeV or 13,200 km/s to 0.25 eV or 2,200 m/s) within fraction of second to maintain the fission chain reaction. H_2, D_2, N_2, C, heavy water and Be are some important moderators. The ordinary water is used as moderator only with enriched uranium (enrichment is a process to increase the amount of $_{92}U^{235}$) whereas graphite, heavy water, and beryllium can be used with natural uranium. The major characteristics of moderators are ability to slow down neutrons, resistant to corrosion, high melting point, high chemical stability, and non-absorbent of neutrons.

Control Rod: The function of control rod is to start the nuclear chain reaction when the reactor is started from cold, to maintain the chain reaction at steady state condition and to shut down the reactor automatically under emergency condition. The materials used for control rods must have very high absorbent capacity for neutrons. The common materials used for control rods are cadmium, boron or hafnium.

Shielding: Neutrons, gamma rays, and all other radiations are efficiently absorbed by the concrete and steel. The inner lining of the core is made of 50–60 cm thick steel plate and it is further thickened by few metres of concrete. The lining of steel plate absorbs these rays and becomes heated but prevent the adjacent wall of the reactor vessel from becoming heated. The thermal shield is cooled by circulating water.

Reactor Vessel: It consists of reactor core, reflector, and shield. It also provides the entrance and exit passage for directing the flow of the coolant. It should have withstanding capacity of more than 200 bar. At the top of the vessel a hole is provided to insert the control rods. The reactor core is generally placed at the bottom of the vessel.

Different Types of Nuclear Reactors

The nuclear reactors can be classified on the basis of neutron energy, fuel used, moderator used, and coolant used. On the basis of neutron energy, we can classify the nuclear reactor as fast reactor and thermal reactor; on the basis of fuel used, we can classify them as natural fuel reactor and enriched uranium reactor; on the basis of moderator, we can classify them as water moderated, heavy water moderated, graphite moderated, and beryllium moderated; on the basis of coolant, we can classify them as water cooled reactor and gas cooled reactor.

Pressurized Water Reactor (PWR): Fuel used in this reactor is enriched uranium (uranium oxide). Uranium oxide is highly resistant to irradiation damage and is very well adapted to minimize high burn-up. It is also highly resistant to corrosion by high pressure water in the event of break-up in the fuel cladding. The water becomes radioactive during passing from the reactor. Therefore, the entire primary circuit including steam generator must be shielded to protect the operating people. The radioactive coolant does not make the steam radioactive in the boiler.

Boiling Water Reactor (BWR): In this reactor, enriched uranium is used as fuel and water is used as coolant and moderator like PWR except the steam is generated in reactor itself.

Heavy Water Cooled and Moderated CANDU (Canadian Deuterium Uranium) Reactor: In this reactor, natural uranium is used as fuel and heavy water is used as coolant and moderator. The heavy water is passed through the pressure tubes in the reactor and heat exchanger in primary circuit in the same way as in PWR and the steam is raised in secondary circuit. Heat is transferred from heavy water to ordinary water in heat exchanger. The control of the reactor is achieved by level of moderator, i.e., heavy water in the reactor. Therefore, control rod is not required in this reactor.

Gas Cooled Reactor (GCR): The reactor is cooled by the gas and the heat carried away by the gas from the reactor is either used for generating steam in secondary circuit like PWR or it can be directly used in gas turbine.

Liquid Metal Cooled Reactor: The excellent heat transfer capacity of molten metals makes them attractive as reactor coolant. The liquid metal coolant is circulated through reactor at moderate pressure and high temperature (540°C). In this reactor, enriched uranium is used as fuel and graphite as moderator. The common metals which can be used as coolant may be sodium, potassium, etc. Sodium is most suitable coolant as it has low absorption, low melting point, high boiling point, high specific heat, high thermal conductivity, and considerably cheaper in cost.

Fast Breeder Reactor (FBR): In fast breeder reactor, enriched uranium or plutonium is kept in a casing without moderator. The casing is covered with a thick blanket of depleted fertile uranium. The ejected excess of neutrons are absorbed by the fertile blanket and it converts into fissile material. The heat produced in the reactor core is carried away by liquid metal. The major difficulty is to remove the large quantity of heat from the core as the power density is very high (430 kW) per litre of core volume which is 40 times greater than CANDU type reactor, 13 times greater than BWR and 20 times greater than gas cooled reactor.

3.4 SOURCES OF ENERGY

The sources of energy can be classified as renewable and non-renewable. Renewable form of energy can be regenerated and source of energy is infinite, e.g., solar energy, wind energy, tidal energy, and geothermal energy are renewable forms of energy. In contrast to renewable energy, non-renewable energy cannot be regenerated and its source is limited, e.g., coal, petroleum, fossil fuels, nuclear power, etc. are non-renewable forms of energy.

3.4.1 Renewable Energy

Renewable energy comes from the sources that can theoretically be renewed as quickly as they are consumed. If used at a sustainable rate, these sources will be available for consumption for

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thousands of years or longer. Unfortunately, some potentially renewable energy sources, such as biomass and geothermal, are being depleted in some areas because the usage rate exceeds the renewal rate.

Solar Energy: Solar energy is the ultimate source of energy available on the earth. Though only a small fraction of the solar energy reaches on the earth's surface, it is sufficient to meet the world's energy requirements. The process of directly converting solar energy to heat or electricity is considered as renewable energy source. Solar energy has been used to heat homes and water, and modern technology such as photovoltaic cells has provided a way to produce electricity from sunlight.

There are two basic forms of radiant solar energy use: passive and active. Passive solar energy systems are static and do not require the input of energy in the form of moving parts or pumping fluids to utilize the sun's energy. Buildings can be designed to capture and collect the sun's energy directly. A southern exposure greenhouse with glass windows and a concrete floor is an example of a passive solar heating system.

Active solar energy systems require the input of some energy to drive mechanical devices such as solar panel, which collect the energy and pump fluids used to store and distribute the energy. Solar panels are generally mounted on a south or west-facing roof. A solar panel usually consists of a glass-faced, sealed, insulated box with a black matte interior finish. Inside are coils full of a heat collecting medium such as water. The sun heats the water in the coils, which is pumped to coils in a heat transfer tank containing water. The water in the tank is heated and then either stored or pumped through the building to heat rooms or supply hot water to taps in the building.

Photovoltaic Cells: A group of cells are linked together to provide the required flow of current. The electricity can be used directly or stored in storage batteries. Because photovoltaic cells have no moving parts, they are clean, quiet, and durable. The recent development of inexpensive semiconductor materials has helped greatly to lower the cost to the point where solar electric panels can compete much well cost wise with traditionally produced electricity.

Hydroelectric Energy: Hydroelectric power is generated by converting the kinetic and/or pressure energy of water into shaft power (mechanical work) producing electricity with the help of generator. Hydroelectric power is generated with the help of dams across the rivers. A dam built across river creates a reservoir. The head of the water behind the dam is greater than that below the dam, representing stored potential energy. When water flows down through the penstock of the dam, the potential energy is converted into electricity driving the turbines coupled with generator.

Wind Power: Wind is the result of the sun's uneven heating of the atmosphere. Warm air expands and rises, and cool air contracts and sinks. This movement of the air is called wind. Wind has been used as an energy source for long time. It has been used to pump water, to power ships and to mill grains. Areas with constant and strong winds can be used by wind turbines to generate electricity. The major drawbacks of wind-powered generators are they require lots of open lands and a fairly constant wind supply. Windmills are also noisy, and some people consider them aesthetically unappealing and label them as visual pollution.

Biomass Energy: Biomass energy is the oldest source of energy used by human beings. It is the organic matter that composes the tissues of plants and animals. It can be burned for heating and cooking, and even generating electricity. The most common source of biomass energy is from the burning of wood, but energy can also be generated by burning animal manure, herbaceous plant material,

peat or converted biomass such as charcoal. Biomass can also be converted into a liquid biofuel such as ethanol or methanol. Biomass is a potentially renewable energy source. Unfortunately, trees that are cut for firewood are frequently not replanted.

The use of biomass as a fuel source has serious environmental effects. When harvested trees are not replanted, soil erosion can occur. The loss of trees results in increased amounts of carbon dioxide in the atmosphere and contributes to global warming.

Geothermal Energy: Geothermal energy uses heat from the earth's internal geological processes in order to produce electricity or provide heating. One source of geothermal energy is steam. Groundwater percolates down through cracks in the subsurface rocks until it reaches rocks heated by underlying magma, and the heat converts the water to steam. Sometimes this steam makes its way back to the surface in the form of a geyser or hot spring. Wells can be dug to tap the steam reservoir and bring it to the surface to drive generating turbines, and produce electricity. Hot water can be circulated to heat buildings. Regions near tectonic plate boundaries have the best potential for geothermal activity.

3.4.2 Non-renewable Energy

Over 85% of the energy used in the world is from non-renewable sources. Most of the developed nations are dependent on non-renewable energy sources such as fossil fuels (coal and oil) and nuclear power. These sources are called non-renewable because they cannot be renewed or regenerated quickly enough to keep pace with their use.

Coal: Coal is the most abundant fossil fuel in the world with an estimated reserve of one trillion metric tons. Coal is formed slowly over millions of years from the buried remains of ancient swamp plants. During the formation of coal, carbonaceous matter was first compressed into a spongy material called 'peat', which is about 90% water. As the peat became more deeply buried, the increased pressure and temperature turned it into coal.

Different types of coal resulted from differences in the pressure and temperature that prevailed during formation. The softest coal (about 50% carbon), which also has the lowest energy output, is called lignite. Lignite has the highest water content (about 50%) and relatively low amounts of smog-causing sulphur. With increasing temperature and pressure, lignite is transformed into bituminous coal (about 85% carbon and 3% water). Anthracite (almost 100% carbon) is the hardest coal and also produces the greatest energy when burned.

Oil: Crude oil or liquid petroleum is a fossil fuel that is refined into many different energy products (e.g., gasoline, diesel fuel, jet fuel, heating oil). Oil forms underground in rock such as shale, which is rich in organic materials. After the oil forms, it migrates upward into porous reservoir rock such as sandstone or limestone, where it can become trapped by an overlying impermeable cap rock. Wells are drilled into these oil reservoirs to remove the gas and oil. Over 70% of oil fields are found near tectonic plate boundaries, because the conditions there are conducive to oil formation.

Despite its limited supply, oil is a relatively inexpensive fuel source. It is a preferred fuel source over coal. An equivalent amount of oil produces more kilowatts of energy than coal. It also burns cleaner, producing about 50% less sulphur dioxide. Oil, however, does cause environmental problems. The burning of oil releases atmospheric pollutants such as sulphur dioxide, nitrogen oxide, carbon dioxide, and carbon monoxide. These gases are smog precursors that pollute the air and greenhouse gases that contribute to global warming. Another environmental issue associated with

the use of oil is the impact of oil drilling. Substantial oil reserves lie under the ocean. Oil spill accidents involving drilling platforms kill marine organisms and birds. Some reserves such as those in northern Alaska occur in wilderness areas. The building of roads, structures, and pipelines to support oil recovery operations can severely impact the wildlife in those natural areas.

Natural Gas: Natural gas production is often a by-product of oil recovery, as the two commonly share underground reservoirs. Natural gas is a mixture of gases, the most common being methane (CH_4). It also contains some ethane (C_2H_5), propane (C_3H_8), and butane (C_4H_{10}). Natural gas is usually not contaminated with sulphur and is therefore the cleanest burning fossil fuel. After recovery, propane and butane are removed from the natural gas and made into liquefied petroleum gas (LPG). LPG is shipped in special pressurized tanks as a fuel source for areas not directly served by natural gas pipelines (e.g., rural communities). The remaining natural gas is further refined to remove impurities and water vapour and then transported in pressurized pipelines.

Natural gas is highly flammable and is odourless. The characteristic smell associated with natural gas is actually that of minute quantities of a smelly sulphur compound which is added during refining to warn consumers of gas leaks. The use of natural gas is growing rapidly. Besides being a clean burning fuel source, natural gas is easy, and inexpensive to transport once pipelines are in place. In developed countries, natural gas is used primarily for heating, cooking, and powering vehicles. It is also used in a process for making ammonia fertilizer.

Nuclear Power: In most electric power plants, water is heated and converted into steam, which drives a turbine generator to produce electricity. Fossil-fuelled power plants produce heat by burning coal, oil or natural gas. In a nuclear power plant, the fission of uranium atoms in the reactor provides the heat to produce steam for generating electricity.

Several commercial reactor designs are currently used. The most widely used design consists of a heavy steel pressure vessel surrounding a reactor core. The reactor core contains the uranium fuel, which is formed into cylindrical ceramic pellets and sealed in long metal tubes called fuel rods. Thousands of fuel rods form the reactor core. Heat is produced in a nuclear reactor when neutrons strike uranium atoms, causing them to split in a continuous chain reaction. Control rods, which are made of a material such as boron that absorbs neutrons, are placed among the fuel assemblies.

When the neutron-absorbing control rods are pulled out of the core, more neutrons become available for fission and the chain reaction speeds up, producing more heat. When they are inserted into the core, fewer neutrons are available for fission, and the chain reaction slows or stops, reducing the heat generated. Heat is removed from the reactor core area by water flowing through it in a closed pressurized loop. The heat is transferred to a second water loop through a heat exchanger. The water also serves to slow down or 'moderate' the neutrons which are necessary for sustaining the fission reactions. The second loop is kept at a lower pressure, allowing the water to boil and create steam, which is used to power the turbine generator and produce electricity.

Nuclear fission does not produce atmospheric pollution or greenhouse gases and it proponents expected that nuclear energy would be cheaper and last longer than fossil fuels. Unfortunately, because of construction cost overruns, poor management and numerous regulations, nuclear power ended up being much more expensive than predicted. The nuclear accidents at Three Mile Island in Pennsylvania and the Chernobyl Nuclear Plant in the Ukraine, recently in 2011 nuclear radiation in Japan due to earthquake and tsunami raised concerns about the safety of nuclear power. Furthermore, the problem of safely disposing spent nuclear fuel remains unresolved. The United States has not built a new nuclear facility in over 20 years, but with continued energy crises across the country that situation may change.

SUMMARY

The chapter can be summarized as follows:

- The convertibility of energy into work depends on its availability.
- Thermodynamics is a branch of science and engineering that deals with interaction of energy mainly in the forms of heat and work.
- Thermodynamics is concerned with thermal behaviour of a matter and its interaction with other physical and chemical behaviour of the matter.
- Prime mover is a primary source of power. All the machinery that provides power for performing various kinds of mechanical work is prime movers.
- It is a group of machines that transform various forms of energy such as thermal, electrical or pressure into mechanical form.
- Engines, turbines, pumps, actuators, etc. are the examples of prime movers.
- Power plant engineering is a branch of engineering which deals with conversion of various forms of energy into electrical energy.
- Thermal power plant may be coal based or gas based.
- In coal-based power plant, coal is used as burning fuel and the heat energy is transferred to water to convert it into superheated steam.
- In gas-based power plant or gas power plant, air is compressed to high pressure and heat energy is added to compressed air using combustion chamber by direct burning of fuel in compressed air or indirect heat transfer to compressed air.
- The high pressure and high temperature air is expanded in gas turbine which is coupled with generator which generates electricity due to shaft rotation.
- The principle of electricity generation in the case of hydroelectric power plant is same as in thermal power plant only difference is that the shaft power to the turbine is provided by pressure and kinetic energy of water in place of steam in thermal power.
- In nuclear power plant, nuclear energy released from radioactive materials due to fission reaction is utilized to heat the water and convert it into superheated steam.
- ${}_{92}U^{235}$, ${}_{94}Pu^{239}$, ${}_{92}U^{233}$ are nuclear fuels used in nuclear reactor to release the heat energy.
- In uranium ore, ${}_{92}U^{235}$ is available only up to 0.7% and the remaining is ${}_{92}U^{238}$.
- The moderator is a material which is used to reduce the kinetic energy of fast neutron (1 MeV or 13,200 km/s to 0.25 eV or 2,200 m/s) within fraction of second to maintain the fission chain reaction.
- H_2, D_2, N_2, C, heavy water and Be are some important moderators.
- The function of control rod is to start the nuclear chain reaction when the reactor is started from cold, to maintain the chain reaction at steady state condition and to shut down the reactor automatically under emergency condition.
- The common materials used for control rods are cadmium, boron or hafnium.
- The nuclear reactors can be classified on the basis of neutron energy, fuel used, moderator used and coolant used.
- On the basis of neutron energy, we can classify the nuclear reactor as fast reactor and thermal reactor.
- On the basis of fuel used, we can classify them as natural fuel reactor and enriched uranium reactor.
- On the basis of moderator, we can classify them as water moderated, heavy water moderated, graphite moderated, and beryllium moderated.
- On the basis of coolant, we can classify them as water cooled reactor and gas cooled reactor.
- The sources of energy can be classified as renewable and non-renewable. Renewable form of energy can be regenerated and source of energy is infinite, e.g., solar energy, wind energy, tidal energy, geothermal energy are renewable forms of energy.
- In contrast to renewable energy, non-renewable energy cannot be regenerated and its source is limited, e.g., coal, petroleum, fossil fuels, nuclear power, etc. are non-renewable forms of energy.

MULTIPLE CHOICE QUESTIONS

1. The radiation in the sunlight that gives us feeling of hotness is
   (a) visible radiation (b) infrared
   (c) red (d) ultraviolet
2. Which of the following is not a source of biomass?
   (a) Gobar gas (b) Coal
   (c) Wood (d) Nuclear energy
3. Which of the following is not derived from sun?
   (a) Biomass (b) Fossil fuels
   (c) Nuclear energy (d) Geothermal energy
4. The substance producing a lot of heat on burning is called as
   (a) oxidizing agent (b) biogas
   (c) biomass (d) fuel
5. The fuel formed under the earth's surface by the decomposition of organic matter is called
   (a) organic fuel (b) biogas
   (c) fossil fuel (d) underground fuel
6. The main constituent of LPG is
   (a) methane (b) butane
   (c) hydrogen (d) propane
7. The main constituent of CNG is
   (a) methane (b) butane
   (c) hydrogen (d) propane
8. Which of the following is not a renewable source of energy?
   (a) The sun (b) Natural gas
   (c) Wind (d) Ocean tidal energy
9. Which of the following is not a combustible gas?
   (a) Oxygen (b) Hydrogen
   (c) Butane (d) Methane
10. A solar cell converts
    (a) heat energy into electrical energy
    (b) solar energy into electrical energy
    (c) heat energy into light energy
    (d) solar energy into light energy
11. The scientist who first carried out critical nuclea fission reaction is
    (a) Otto Hahn (b) Enrico Fermi
    (c) Hans Bethe (d) Einstein
12. The sources of energy of the sun is
    (a) nuclear fission
    (b) chemical reaction
    (c) nuclear fusion
    (d) photoelectric effect
13. The fuel used in the nuclear reactor is
    (a) cadmium (b) radium
    (c) uranium (d) thorium
14. In a hydroelectric power plant, which of the following is used to produce shaft power?
    (a) The pressure and kinetic energy of stored water
    (b) Heat energy of water
    (c) Heat energy of flue gas
    (d) Nuclear energy
15. In a thermal power plant, which of the following is used to produce shaft power?
    (a) The pressure and kinetic energy of stored water
    (b) Heat energy of water
    (c) Heat energy of flue gas
    (d) Nuclear energy
16. In a gas power plant, which of the following is used to produce shaft power?
    (a) The pressure and kinetic energy of stored water
    (b) Heat energy of water
    (c) Heat energy of flue gas
    (d) Nuclear energy

Answers

1. (b), 2. (d), 3. (c), 4, (d), 5. (c), 6. (b), 7. (a), 8. (b), 9.(a), 10. (b), 11. (b), 12. (c), 13. (c), 14, (a), 15. (b), 16. (c).

REVIEW QUESTIONS

1. Explain the concept of energy and transformation of one form to another.
2. What is a prime mover? Give some examples of reciprocating and rotating prime movers.
3. Explain the principle of working of thermal power plant.

12

4. Explain the principle of working of gas power plant.
5. Explain the principle of working of hydroelectric power plant.
6. Explain the principle of working of nuclear power plant.
7. Explain the terms used in nuclear power plant such as fuels, fissile materials, moderators, control rods, working fluids, shield, etc.
8. Explain the basis for classification of nuclear reactors.
9. Differentiate pressurized water reactor and boiling water reactor.
10. What do you mean by renewable and non-renewable sources of energy?
11. Write short notes on solar energy, wind power energy, biomass, and geothermal energy.
12. Write short notes on application of coal, oil, natural gas, and nuclear energy.

Objective-Type Questions

Each chapter contains a set of objective-type questions, totaling 210 questions in the book. This enables the user to obtain a clear comprehension of the subject matter and prepares him for competitive examinations. Answers to all these questions are provided in Appendix D at the end of the book.

Objective-type Questions

1. Energy storage means
   (a) sparing primary energy for future generations
   (b) storing secondary energy in an easily recoverable form

Objective-type Questions

1. Storage of biomass energy is
   (a) very difficult (b) inbuilt feature (c) expensive (d) impossible
2. Biogas is predominantly
   (a) hydrogen (b) carbon monoxide (c) carbon dioxide (d) methane
3. Heating value of producer gas is
   (a) 4–8 MJ/m³ (b) 14–18 MJ/m³ (c) 24–28 MJ/m³ (d) 34–38 MJ/m³
4. Fluidized bed gasifier produces
   (a) low tar and high particulate (b) high tar and low particulate
   (c) low conversion efficiency (d) low exit temperature

Review Questions

Each chapter contains a set of review questions, totaling 264 questions in the book, including many from examinations of selected universities. This enables the user to have an idea about university examinations. The answers are embedded in the text of the chapter.

Review Questions

1. How is per capita energy consumption related with standard of living?
2.
3.
4.
5.
6.

Review Questions

1. What percentage of the industrial heating need is of low-grade type?
2. For which type of heating is solar energy best suited?
3. What is the average range of solar radiation received on the earth's surface during a day?
4. Define concentration ratio of a solar collector.
5. What are the main advantages of a flat-plate solar collector?
6. Describe the flat-plate collector with the help of a suitable diagram.

(UPTU Lucknow 2003–04)

7. What is the approximate value of the concentration ratio obtained from a CPC collector?
8. Name three collectors requiring one-axis sun tracking.
9. What range of temperature can a paraboloidal dish collector may attain?
10. What range of CR is realizable from a central tower receiver collector?
11. Discuss the principle of a solar collector. How can collector coating be used to improve the performance of a collector?

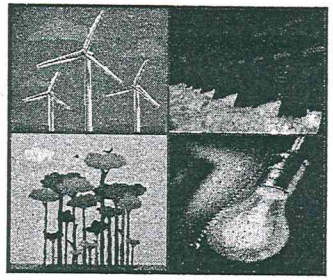
(UPTU Lucknow 2005–06)

Internet Resources

To effectively use the internet resources, a list of useful websites related to renewable and non-conventional energy resources is provided at the end of the book.

Internet sites for further reading:

1. http://mnes.nic.in/
2. http://www.hitzeindia.com/hitze/NCES.html
3. http://mapsofindia.com/maps/nonconventional/
4. http://www.retscreen.net
5. http://www.nmstar.org/sdenergy/
6. http://www.exideindustries.com/eil/energy/ncbhome.html
7. http://www.em-er.org/
8. http://www.freewebs.com/projectpromoter/
9. http://www.kalarugroup.com/english/scheme.html
10. http://www.worldenergy.org/
11. http://www.braincourse.com.creative.html
12. http://www.eia.doe.gov/
13. http://www.iaei.org/
14. http://www.nrel.gov/
15. http://www.iahe.org/
16. http://www.theregister.co.uk/
17. http://www.energy.ca.gov/
18. http://www.waterpower.hypermart.net/



Fundamentals of Energy—Science and Technology

Introduction

1

Any physical activity in this world, whether carried out by human beings or by nature, is caused due to flow of energy in one form or the other. Energy is required to do any kind of work. The word 'energy' itself is derived from the Greek word '*en–ergon*', which means 'in–work' or 'work content'. The work output depends on the energy input. The capability to do work depends on the amount of energy one can control and utilize. Energy is the most basic infrastructure input for economic growth and development of a country.

Before the industrial revolution that started around 200 years ago, people were essentially dependent on manual and animal labour. Human and animal energy requirements were met through food intake. Life was simple and unsophisticated, and the environment was relatively clean. Then in 1785, the invention of the steam engine by James Watt of Scotland brought the industrial revolution. It was the beginning of a mechanical age or the age of machines. The advent of the internal combustion engine in the late nineteenth century gave a further momentum to the trend. Gradually, the industrial revolution spread to the whole world. In 1888, Nickola Tesla invented the commercial induction motor. The introduction of electrical machines along with the commercial availability of electrical power started the new electrical age. All this led to an increase of energy requirement by leaps and bounds. Energy has been the lifeblood for continual progress of the human civilization. Thus, with developments in the human living standard, the energy consumption also accelerated.

ENERGY CONSUMPTION AND STANDARD OF LIVING

1.1 The energy consumption of a nation can be broadly divided into the following areas or sectors depending on energy-related activities. These can further be subdivided into subsectors:

- Domestic sector (houses and offices including commercial buildings)
- Transportation sector
- Agriculture sector
- Industry sector

Consumption of a large amount of energy in a country indicates increased activities in these sectors. This may imply better comforts at home due to use of various appliances, better transport facilities and more agricultural and industrial production. All this amounts to a better quality of life. Therefore, the per capita energy consumption of a country is an index of the standard of living or

prosperity (i.e. income) of the people of the country. In Table 1.1, the comparative data of the annual primary energy consumptions of some countries are given to emphasize this point.

Table 1.1 *Primary energy consumption of some countries (as in 2003)*

S.N.	Country	Total annual energy consumption (in exajoules, i.e., 10^{18} joules)	Per capita annual energy consumption (in gigajoules, i.e., 10^{9} joules)
1.	USA	99.6	327
2.	Japan	21.5	169
3.	France	12.1	189
4.	UK	9.9	164
5.	China	62.2	47
6.	India	23.8	21
Global average			70

At present (year 2005) the total annual energy consumption of the world is estimated as 500 exajoules. Out of which 26% energy is consumed by USA, which has about 5% of the world's population, while India which houses 17% of the world's population consumes only 3.3% of the total world energy. This mismatch reflects in the negative differential in the quality of life of the people in these countries. Electricity is considered a necessary requirement for economic and social development of a country. For the year 2007, the annual per capita electrical-energy consumption in USA was 12,133 kWh and that in India it was 702 kWh.

1.2 OIL CRISIS OF 1973

The year 1973 brought an end to the era of secure and cheap oil. In October of that year, OPEC (Organization of Petrol Exporting Countries, founded in 1960) put an embargo on oil production and started the oil-pricing control strategy. Oil prices shot up fourfold causing a severe energy crisis the world over. This resulted in spiraling price rise of various commercial energy sources, further leading to global inflation. Governments of all countries took this matter very seriously and for the first time, a need for developing alternative sources of energy was felt. Alternate energy sources were given serious consideration and huge funds were allocated for the development of these resources. Thus, the year 1973 is considered as the year of the first 'oil shock'. In the same decade, one more 'oil shock' jolted the world in 1979, which further focussed the attention on alternate energy sources. By the end of 1980, the price of crude oil stood at 19 times what it had been just ten years earlier.

1.3 CLASSIFICATION OF ENERGY RESOURCES

Energy resources can be classified in the following ways.

1. Based on Usability of Energy

(a) Primary Resources These are resources embodied in nature prior to undergoing any human made conversions or transformations. Examples of primary energy resources are coal, crude oil, sunlight, wind, running rivers, vegetation, uranium, etc. These resources are generally available in raw forms and are, therefore, known as raw energy resources. Generally, this form of energy cannot be used as such. These are located, explored, extracted, processed and are converted to a form as required by the consumer. Thus, some energy is spent in making the resource available to a user in a usable form. The energy yield ratio of an energy extraction process is defined as follows:

$$\text{Energy yield ratio} = \frac{\text{Energy received from raw energy source}}{\text{Energy spent to obtain raw energy source}}$$

Only resources for which the energy yield ratio is fairly high are considered worthy of exploration.

(b) Intermediate Resources These are obtained from primary energy by one or more steps of transformation and are used as vehicles of energy.

(c) Secondary Resources The form of energy which is finally supplied to a consumer for utilization is known as secondary or usable energy, e.g., electrical energy, thermal energy (in the form of steam or hot water), chemical energy (in the form of hydrogen or fossil fuels), etc.

Some forms of energy may be categorized both in intermediate as well as secondary resources, e.g., electricity and hydrogen.

2. Based on Traditional Use

(a) Conventional Energy resources which are being traditionally used for many decades and were in common use around the oil crisis of 1973, are called conventional energy resources, e.g., fossil fuels, nuclear and hydro resources.

(b) Non-conventional Energy resources which are considered for large-scale use after the oil crisis of 1973, are called non-conventional energy sources, e.g., solar, wind, biomass, etc.

3. Based on Long-term Availability

(a) Non-renewable Resources which are finite and do not get replenished after their consumption are called non-renewable, e.g., fossil fuels, uranium, etc.

(b) Renewable Resources which are renewed by nature again and again and their supply is not affected by the rate of their consumption are called renewable, e.g., solar, wind, biomass, ocean (thermal, tidal and wave), geothermal, hydro, etc.

4. *Based on Commercial Application*

(a) *Commercial Energy Resource* The secondary usable energy forms such as electricity, petrol, diesel, gas, etc., are essential for commercial activities and are categorized as commercial energy resources. The economy of a country depends on its ability to convert natural raw energy into commercial energy.

(b) *Non-commercial Energy* The energy derived from nature and used directly without passing through a commercial outlet is called a non-commercial resource, e.g., wood, animal dung cake, crop residue, etc.

5. *Based on Origin*

(a) Fossil fuels energy
(b) Nuclear energy
(c) Hydro energy
(d) Solar energy
(e) Wind energy
(f) Biomass energy
(g) Geothermal energy
(h) Tidal energy
(i) Ocean thermal energy
(j) Ocean wave energy

1.4 CONSUMPTION TREND OF PRIMARY ENERGY RESOURCES

The average percentage consumption trend of various primary energy resources of the world is indicated in Fig. 1.1, though the trend differs from country to country. Looking at this figure, the heavy dependence on fossil fuels stands out clearly. About 86% of the world's energy supply comes mainly from fossil fuels. The share of fossil fuels is more than 90% in India.

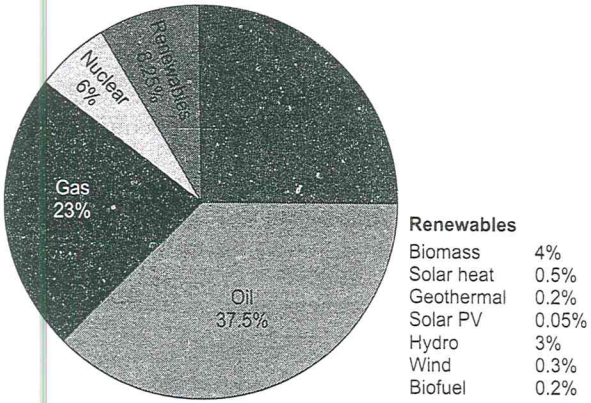


Fig. 1.1 *Percentage consumption of various primary energy resources (year 2005 data)*

1.5 IMPORTANCE OF NON-CONVENTIONAL ENERGY SOURCES

Concern for the environment due to ever-increasing use of fossil fuels and rapid depletion of natural resources have led to development of alternative sources of energy which are renewable and environment friendly. The following points may be mentioned in this connection:

1. The demand of energy is increasing by leaps and bounds due to rapid industrialization and population growth, and hence the conventional sources of energy will not be sufficient to meet the growing demand.
2. Conventional sources (except hydro) are non-renewable and are bound to finish up one day.
3. Conventional sources (fossil fuels, nuclear) also cause pollution, thereby their use degrades the environment.
4. Large hydro resources affect wildlife, cause deforestation and pose various social problems.
5. In addition to supplying energy, fossil fuels are also used extensively as feed stock materials for the manufacture of organic chemicals. As reserve deplete, the need for using fossil fuels exclusively for such purposes may become greater.

Due to these reasons it has become important to explore and develop non-conventional energy resources to reduce too much dependence on conventional resources. However, the present trend of developments of non-conventional sources indicate that these will serve as supplements rather than substitute for conventional sources for some more time to come.

Realising the importance of non-conventional energy sources, in March 1981, the government of India established a Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology, on the lines of the Space and Atomic Energy Commissions. In 1982, CASE was incorporated in the newly created Department of Non-Conventional Energy Sources (DNES) under the Ministry of Energy. Also, IREDA (Indian Renewable Energy Development Agency Ltd.) was established in 1987 to promote the development of non-conventional sources. The DNES was later converted to MNES (Ministry of Non-conventional Energy Sources) in 1992. In October 2006, the ministry was re-christened as the Ministry of New and Renewable Energy. India is the only country having a full-fledged ministry devoted to developing new and renewable energy sources.

1.6 ENERGY CHAIN

Generally, (but not always) we cannot use the energy available from primary energy sources directly. For example we cannot drive an electric motor from uranium or coal. The energy available from a primary energy source is known as raw energy. This energy undergoes various forms of transformations before

being utilized finally. The sequence of energy transformations between primary and secondary energy (usable energy) is known as energy chain or energy route.

Primary energy $\xrightarrow[\text{Processing}]{}$ Electrical energy $\xrightarrow[\text{Transmission}]{}$ Consumer

Primary energy $\xrightarrow[\text{Processing}]{}$ Secondary energy (fuel) $\xrightarrow[\text{Transported by rail / road / ocean / pipeline}]{}$ Consumer

At present about 30–40% of the world's energy supply is met through the electrical-energy route.

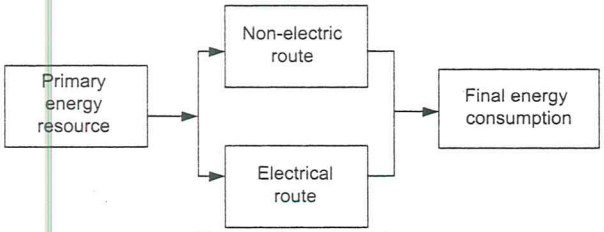


Fig. 1.2 *Energy routes*

1.7 COMMON FORMS OF ENERGY

1. ***Mechanical Energy*** Mechanical energy is required for movement of objects, changing the shape of the objects, and so on. It is used in transportation, agriculture, handling, processing, and other industrial processes.

2. ***Electrical Energy*** Electrical energy is considered to be the top-grade form of energy. It is used universally as a vehicle of energy. About 30–40% energy distribution in the world is met through electrical supply systems at present. It can be very conveniently and efficiently converted to other forms of energy.

3. ***Thermal Energy*** It is used to raise the temperature of an object during industrial processes. It can also be converted to mechanical energy with the help of heat engines. There are three grades of thermal energy:

(a) High Grade (500–1000°C and higher) Can be converted efficiently into mechanical energy.

(b) Medium Grade (150–500°C) Can be converted into mechanical energy with difficulty.

(c) Low Grade (80–150°C) Cannot be converted efficiently into mechanical energy and is used mostly for heating purposes.

4. ***Chemical Energy*** Fuels and organic matter contain chemical energy. Exothermic chemical reactions release heat energy. Also, chemical energy is directly converted into electrical energy in fuel cells, storage batteries, etc., and into thermal energy by combustion.

1.8 ADVANTAGES AND DISADVANTAGES OF CONVENTIONAL ENERGY SOURCES

Fossil fuels, nuclear and hydro resources are considered as conventional sources. Their use has the following advantages and disadvantages.

Advantages

1. *Cost* At present, these are cheaper than non-conventional sources. The approximate cost of electrical energy derived from different sources at present is given as:

Rs 1.90 per kWh from gas, Rs 1.65 per kWh from coal, Rs 3.0 per kWh from diesel, Re 1.0 per kWh from hydro resource, Rs 1.20 per kWh from nuclear resource. (US$ 1≅Rs 42.8 as in August 2008)

2. *Security* As storage is easy and convenient, by storing a certain quantity, the energy availability can be ensured for certain period.

3. *Convenience* These sources are very convenient to use as technology for their conversion and their use is universally available.

Disadvantages

1. Fossil fuels generate pollutants. Main pollutants generated in the use of these sources are CO, CO_2, NO_x, SO_x, particulate matter and heat. These pollutants degrade the environment, pose health hazards and cause various other problems. CO_2 is mainly responsible for global warming.
2. Coal is also a valuable petrochemical and is used as raw material for chemical, pharmaceutical and paint industries. From the long-term point of view, it is desirable to conserve coal for future needs.
3. Safety of nuclear plants is a controversial subject. The major problems with nuclear energy are the following:
   (a) The waste material generated in nuclear plants has radioactivity quotients of dangerous levels, it remains above the safe limit for a long period of time, and thus is a health hazard. Its safe disposal, which is essential to prevent radioactive pollution, is a challenging task. Also, the disposed radioactive waste is required to be guarded for a long period (till its radioactivity level comes down to a safe limit) lest it goes in wrong hands.
   (b) There is possibility of accidental leakage of radioactive material from reactor (as happened in Chernobyl, former USSR, in April 1986).
   (c) Uranium resource, for which the technology presently exists, has a limited availability.
   (d) Sophisticated technology is required for using nuclear resources. Only few countries posses the technology required to use nuclear energy.

Due to these serious disadvantages, Sweden has banned new nuclear plants since 1984 and has planned to dismantle the existing plants in a phased manner.

4. Hydroelectric plants are cleanest but large hydroreservoirs cause the following problems:

   (a) A large land area submerges into water leading to deforestation
   (b) Causes ecological disturbances such as earthquakes
   (c) Affects wildlife
   (d) Causes dislocation of a large population and their rehabilitation.

1.9 SALIENT FEATURES OF NON-CONVENTIONAL ENERGY SOURCES

Merits

1. Non-conventional sources are available in nature free of cost.
2. They produce no or very little pollution. Thus, by and large, they are environment friendly.
3. They are inexhaustible.
4. They have a low gestation period.

Demerits

1. In general, the energy is available in dilute form from these sources.
2. Though available freely in nature, the cost of harnessing energy from non-conventional sources is generally high.
3. Availability is uncertain; the energy flow depends on various natural phenomena beyond human control.
4. Difficulty in transporting such forms of energy.

1.10 ENVIRONMENTAL ASPECTS OF ENERGY

1.10.1 Trade-off Between Energy and Environment

Environment literally means surroundings. Air, soil and water are the main constituents of environment. Nature has originally provided them to human beings in clean form. However, with passage of time, their quality is continuously being degraded due to various manmade reasons. The chief among them are a number of activities involving energy generation and its utilization. During every energy conversion process, some energy is expelled by the energy conversion system into surroundings in the form of heat. Also, some pollutants may be produced as a by-product of this process. Both of these cause degradation of environment. Every step must be taken to conserve the environment. Therefore, while supplying the increased energy demand, efforts should be made to adopt measures to minimize the degradation of environment. The present trend is to have a trade-off between the two. The future seems to be in favour of developing

renewable and environment-friendly energy resources. To create public awareness about environment conservation, 5th June is observed as *World Environment Day*.

1.10.2 Ecology

Ecology deals with the relationship between living organisms (man, animal, plants and vegetation) and the environment. Normally, nature has self-cleaning capability and recycles (renews) its resources through various processes, thus maintaining a state of equilibrium. The water cycle, nitrogen cycle and carbon cycle are the well-known examples of this. However, when human interference exceeds natural limits, the ecological balance gets disturbed.

1.10.3 Greenhouse Effect

A greenhouse is an enclosure having transparent glass panes or sheets as shown in Fig. 1.3. It behaves differently for incoming visible (short wave) radiations and outgoing infrared (long wave) radiations. It is transparent for incoming solar radiation, allows entry of sunlight and becomes largely opaque for reflected infrared radiation from the earth's surface, thus preventing the exit of heat. Hence, it maintains a controlled warmer environment inside for growth of plants in places where the climate is very cold.

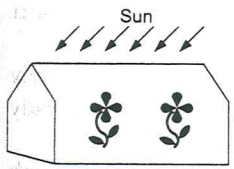


Fig. 1.3 *Greenhouse*

The CO_2 envelope present around the globe in the atmosphere behaves similar to a glass pane and forms a big global greenhouse. This tends to prevent the escape of heat from the earth, which leads to global warming. This phenomenon is known as **greenhouse effect**. At present (year 2008), its concentration in the atmosphere is 385 ppm (parts per million) by volume. It is due to this effect that the earth maintains an average surface temperature of 15°C that is hospitable to life. In the absence of this layer, the earth would be a frozen planet at about –25°C (the temperature of outer atmosphere). However, any further increase in the concentration of CO_2 from the present level will upset the temperature balance and would cause further warming of the globe, which may have disastrous consequences. Apart from CO_2, other harmful gases include methane, nitrous oxide, hydroflourocarbons, sulphur hexafloride and water vapour. All these gases are known as greenhouse gases. The CO_2 emission from developed countries accounts for 82% of the total greenhouse gas emission of the world.

1.10.4 Consequences of Global Warming

Global warming is caused mainly due to the emission of excessive CO_2 due to burning of fossil fuels in industry, burning of wood and also due to agricultural practices. This trend is leading to the melting of polar snowcaps, which accounts

for more than 90% of the world's ice. Melting of the polar snowcaps would, in turn, increase the level of oceans and would possibly redefine ocean boundaries inundating low-lying areas and smaller islands. During the last 100 years, the earth's temperature has increased about half a degree Celsius and sea levels have risen 6 to 8 inches (15 to 20 cm). Experts have predicted more frequent and severe heat waves, more intense tropical cyclones, change in rainfall patterns, melting of ice and glaciers at mountains, thus causing floods, followed by decline of water supplies and an increased incidence of vector-borne deceases like malaria.

The earth is already showing many signs of worldwide climate change.

- Average temperatures have climbed 1.4 degrees Fahrenheit (0.8 degree Celsius) around the world since 1880, much of this in recent decades, according to NASA's Goddard Institute for Space Studies.
- The rate of warming is increasing. The 20th century's last two decades were the hottest in 400 years and possibly the warmest for several millennia, according to a number of climate studies. And the United Nations' Intergovernmental Panel on Climate Change (IPCC) reports that 11 of the past 12 years are among the dozen warmest since 1850.
- The Arctic is feeling the most severe effects. Average temperatures in Alaska, western Canada, and eastern Russia have risen at twice the global average, according to the multinational Arctic Climate Impact Assessment report compiled between 2000 and 2004.
- Arctic ice is rapidly disappearing, and the region may have its first completely ice-free summer by 2013. Polar bears and indigenous cultures are already suffering from the sea-ice loss.
- Glaciers and mountain snows are rapidly melting—for example, Montana's Glacier National Park now has only 27 glaciers, versus 150 in 1910. In the northern hemisphere, thaws also come a week earlier in spring and freezes begin a week later in winter.
- Coral reefs, which are highly sensitive to small changes in water temperature, suffered the worst bleaching—or die-off in response to stress—ever recorded in 1998, with some areas seeing bleach rates of 70 per cent. Experts expect these sorts of events to increase in frequency and intensity in the next 50 years as sea temperatures rise.
- An upsurge in the amount of extreme weather events, such as wildfires, heat waves, and strong tropical storms, is also attributed in part by some experts to climate change.

1.10.5 Pollution

(a) Indoor Pollution Indoor pollution is mainly caused due to use of conventional *chulhas* in rural areas. About 5,00,000 children and women die from diseases caused due to indoor air pollution each year. This requires the need of improved household stoves to reduce indoor pollution.

LIBRARY

(b) Outdoor Pollution Outdoor pollution is mainly caused due to use of fossil fuels. Emissions from fossil fuel based plants degrade the environment and cause various other problems. Coal and oil are more pollutant than gas.

Remedy

1. Use of fossil fuels should be slowly curtailed. Less-polluting technologies should be employed for use instead of fossil fuels, i.e., gasified coal, which is less polluting, should be used in power plants.
2. Clean alternative fuels such as hydrogen should be used. Hydrogen is the cleanest fuel and does not cause pollution during power conversion.
3. Electric vehicles or battery-operated vehicles should be used in place of IC-engine-based vehicles.

1.10.6 Various Pollutants and their Harmful Effects

1. *Particulate Matter* The presence of particulate matter

- reduces sunlight
- reduces visibility
- A level above 100 $\mu g/m^3$ (yearly average) results in respiratory problems
- A level above 300 $\mu g/m^3$ (yearly average) results in bronchitis (inflammation of mucus membrane inside the bronchial tubes, branches of the wind pipe)

The annual average permissible limit is 75 $\mu g/m^3$.

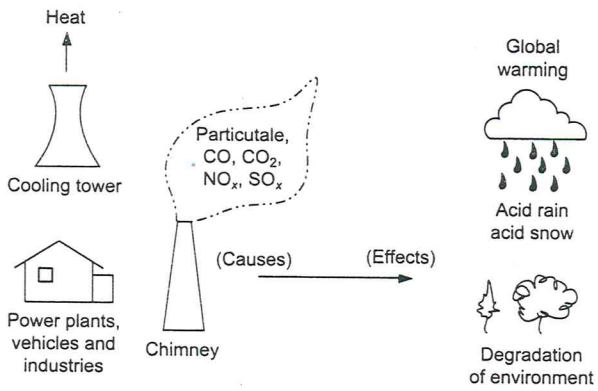


Fig. 1.4 *Causes and effect of pollution*

2. CO_2 Carbon dioxide is ordinarily not considered a toxic gas. It is essential for photosynthesis and production of essential oxygen and organic matter in nature. But increased concentration of CO_2 adversely affects the global climate. Excess emission of CO_2 in the atmosphere causes global warming due to greenhouse effect.

CO_2 in air during the 1940s was less than 312 ppm. During the 1960s it rose to 318 ppm and by 2000 it rose to about 350 ppm. The increasing CO_2 level is mainly due to

(a) large-scale combustion of fossil fuels in coal fired thermal power plants all over the world, and
(b) felling of trees on a large scale (deforestation) for urbanization, agriculture, and industrialization, resulting in reduced photosynthesis process.

3. CO CO is formed due to incomplete burning of carbon in inadequate air. It seriously impairs the oxygen-dependent tissues in the body, particularly the brain, heart and skeletal muscles. CO concentration of 100 ppm causes headache, 500 ppm causes collapse and 1000 ppm is fatal. Smokers inhale CO concentrations of 400 to 450 ppm.

4. SO_X The presence of SO_2 in the air is mainly due to manmade reasons involving combustion of fuels containing sulphur. The contribution from various sources is as follows:

Power plants	70%
Industry	15%
Motor vehicles	8%
Solid waste disposal	5%
Others	2%

SO_2 can further oxidize to form sulfur trioxide, which in turn forms sulphuric acid when absorbed in water.

Harmful Effects

(a) Causes respiratory deceases including asthma, and the irritates eyes and respiratory track
(b) Causes acid rains, which are harmful to agriculture, forest, vegetation, soil and stones (and thus to buildings)
(c) Causes corrosion of metals, deterioration of electrical contacts, paper, textile, building stones, etc.

The safe limit is 80 $\mu g/m^3$ (annual average).

NO_X Oxides of nitrogen such as N_2O, NO, NO_2, N_2O_3 are commonly referred as NO_X. About 80% of nitrogen oxides in the atmosphere are produced due to natural causes (biological reactions) and about 20% due to manmade causes—mostly due to combustion process in air at high temperature. NO_X is formed by the interaction of nitrogen and oxygen at high temperature. Manmade causes include:

(a) Motor vehicles	7%
(b) Industry	7%
(c) Power plants	4%
(d) Solid waste	2%

Harmful Effects

(a) Causes respiratory and cardiovascular illnesses
(b) It deprives the body tissues of oxygen
(c) It also forms acid in lungs and, therefore, is more toxic than CO

The safe limit is 100 $\mu g/m^3$.

1.10.7 Green Power

The term *green power* is used to describe sources of energy which are considered environmental friendly, non-polluting; and therefore may provide a remedy to the systemic effects of certain forms of pollution and global warming. This is, in fact, the renewable energy sourced from the sun, the wind, water, biomass and waste.

Green energy is commonly thought of in the context of electricity, heating, and cogeneration, and is becoming increasingly available. Consumers, businesses, and organizations may purchase green energy in order to support further development, help reduce the environmental impacts associated with conventional electricity generation, and increase their nation's energy independence. Renewable energy certificates (green certificates, or green tags) have been one way for consumers and businesses to support green energy.

1.11 ENVIRONMENT-ECONOMY-ENERGY AND SUSTAINABLE DEVELOPMENT

Global environmental degradation is one of the most serious threats facing mankind as a result of the expansion of its activities around the globe. One of the international responses to global environmental problems—the Framework Convention on Climate Change—was ratified and came into effect in March 1994. The convention aims not only at stabilizing CO_2 emissions in developed countries but also at ultimately reducing man-made CO_2 emissions globally so as to stabilize the global climate. However, with fossil fuels comprising nearly 90 per cent of primary energy sources in the world, the final target of the framework convention seems very ambitious.

Environmental degradation cannot be singled out as an independent matter among various global issues. Also important are the interactions among economic development, stable energy supplies, and globe environmental conservation. In the next few decades fossil fuels will continue to be the principal source of energy driving economic development. The source of fossil fuels is stable and their

world. Solar PV power is considered an expensive source of power. At present, the capital cost of a solar PV system is Rs 200.00 per W (Rs 20 crore/MW as against Rs 4 crore/MW for coal-fired thermal plant; 1 crore = 10 million).

(ii) Wind Energy The power available in the winds flowing over the earth surface is estimated to be 1.6×10^7 MW, which is more than the present energy requirement of the world. Wind power has emerged as the most economical of all renewable energy sources. The installation cost of wind power is Rs 4 crore/MW (which is comparable to that of conventional thermal plants). There has been remarkable growth of wind-power installation in the world. Wind-power generation is the fastest growing energy source. Wind-power installations worldwide have crossed 94,100 MW (at the end of 2007), which is about 1% of the world's electrical power generation capacity. It accounts for approximately 19% of electricity production in Denmark, 9% in Spain and Portugal, and 6% in Germany and the Republic of Ireland. Germany is the world leader in wind power with an installed capacity of 22,247 MW.

(iii) Biomass Energy Energy resources available from animal and vegetation are called biomass energy resources. This is an important resource for developing countries, especially in rural areas. The principal biomass resources are:

- Trees (wood, leaves and forest industry waste)
- Cultivated plants grown for energy
- Algae and other vegetation from oceans and lakes
- Urban waste (municipal and industrial waste)
- Rural waste (agricultural and animal waste, crop residue, etc.)

Solar energy absorbed by plants (through the photosynthesis process) is estimated to be 2×10^{21} J/year. Biomass material may be transformed by chemical or biological processes to produce intermediate bio-fuels such as biogas (methane), producer gas, ethanol and charcoal. At present, there are millions of biogas plants in the world, and most of them are in China.

(iv) Geothermal Energy Geothermal energy is derived from huge amounts of stored thermal energy in the interior of the earth, though its economic recovery on the surface of the earth is not feasible everywhere. Its overall contribution in total energy requirement is negligible. However, it is a very important resource locally. At the end of 2005, the world's total installed electrical power-generating capacity from geothermal resources was about 8,932 MW_e and direct thermal-use installed capacity was 28,266 MW_t. Globally, use of geothermal power is growing annually at a rate of about 3% electrical and 7.5% thermal. The island of Hawaii procures 25% of its electricity from geothermal resources. Likewise, geothermal electrical energy production in El Salvador is 23% of the country's total installed electricity-generation capacity. The oldest geothermal power generator is located

at Lordarello in Italy, commissioned in 1904 and presently producing 460 MW of power.

(v) Ocean Tidal Energy Tidal energy is a form of hydro power that converts energy of ocean tides into electricity or other useful forms of power. It is in the developing stage and although not yet widely used, tidal power has potential for future electricity generation. Tides are more predictable than wind energy and solar power. There are at present only a few operational tidal power plants. The first and the biggest, a 240-MW tidal power plant was built in 1966 in France at the mouth of the La Rance river, near St. Malo on the Brittany coast. A 20-MW tidal plant is located at Nova Scotia, Canada, and a 400-kW capacity plant is located at Kislaya Guba, near Murmansk, Russia, on the Barents Sea. Many sites have been identified in USA, Argentina, Europe, India and China for development of tidal power.

(vi) Ocean Wave Energy Wave power refers to the energy of ocean surface waves and the capture of that energy to do useful work. Good wave power locations have a flux of about 50 kilowatts per metre of shoreline. As per an estimate, the potential for shoreline-based wave power generation is about 50,000 MW. Deep-water wave-power resources are truly enormous, but perhaps impractical to capture. Some wave plants are recently deployed at few places. The world's first 2250-MW, commercial wave farm is based in Portugal. Other plans for wave farms include a 3 MW plant in the Orkneys, off northern Scotland, and the 20-MW wave-hub development off the north coast of Cornwall, England.

(vii) Ocean Thermal Energy Conversion OTEC technology is still in its infant stages. Conceptual designs of small OTEC plants have been finalized. Their commercial prospects are quite uncertain. The potential is likely to be more than that of tidal or wave energy.

1.14 ENERGY SCENARIO IN INDIA

1.14.1 Overall Production and Consumption

India is both a major energy producer and consumer. India currently ranks as the world's eleventh greatest energy producer, accounting for about 2.4% of the world's total annual energy production, and as the world's sixth greatest energy consumer, accounting for 3.3% of the world's total annual energy consumption. Thus, India is a net energy importer, mostly due the large imbalance between oil production and consumption. As per 2005 data for India, the total annual primary energy production and consumption was 11.73 Quad. BTU and 16.205 Quad. BTU respectively. The per capita primary energy consumption is 520 KGOE for India, whereas the world average is 2366 KGOE (2007 data). Similarly, the per capita annual electrical energy consumption in India is 702 kWh whereas the world average is 2600 kWh (2007 data).

Sector wise Energy Consumption

Table 1.4 *Sector wise energy consumption* [40]

Sector	*Percentage power consumption*
Industry	49%
Transport	22%
Residential	10%
Agriculture	5%
Others	14%

Electrical Power Generation The present total installed capacity of electrical power generation in India is 1,44,912 MW (as on June 30, 2008), produced from various resources as given in Table 1.5.

Table 1.5 *Electrical power generations as on June 30, 2008* [35]

Resource	*Production (MW)*	*Percentage share*
Thermal:		
Coal	76648	52.8
Gas	14716	10
Diesel	1199	0.8
	Total thermal = 92563	Total = 63.6
Nuclear	4120	2.8
Hydro	36033	24.8
Renewable energy sources (excluding hydro)	12194	8.4
Total	1,44,910	100

1.14.2 Availability of Primary Energy Resources

A. Conventional

(i) Fossil Fuel India has vast reserves of coal, the fourth largest in the world after the USA, Russia and China. According to a rough estimate, the total recoverable coal in India is 90 billion tonne, about 10% of the world's total. With the present rate of consumption, India will have enough coal for about 300 years. Indian coal has high ash content (25–50%), low heat value (3000–4000 kcal/kg) and low sulphur content (1%). We have only 0.6% of the world's oil and gas reserves. Oil and gas represent over 40 per cent of the total energy consumption in India. About 35% of oil needs are met through domestic production and the balance 65% through imports. Crude oil reserves are estimated as 600 million tonne, enough to last about 22 years at the present rate, if no further discovery is made. Natural gas reserves are estimated as 1000 billion m^3, enough to last for

30 years, if no further discovery is made. Oil and gas reserves are insufficient even for the transportation sector. The domestic production is decreasing slowly. However, recent findings of gas reserves in Rajasthan and the Krishna–Godavari basin off the Vishakhapatnam coast may change the trend. The actual impact will be known once these resources are fully developed and production begins.

(ii) Hydro Resources India stands seventh in the list of nations with hydro resources with a total potential of 100,000 MW of which approximately 36,033 MW has been developed. Huge installation cost, environmental and social problems are major difficulties in its development.

(iii) Nuclear Resources India has modest reserves of uranium, mostly located at Jadugoda, Jharkhand. Out of the total electrical power generation, 2.8% is being generated by nuclear means. Nuclear-power generation is planned to reach 10,280 MW by the year 2012 and 20,000 MW by 2020.

Thorium is available in abundance in India in the form of monazite (ore) in the sand beaches of Kerala. The economically viable reserve of thorium in India is estimated at 3,00,000 tonnes, which is 25% of the world's thorium reserves. Thorium is a fertile material, which is converted into a fissionable material U^{233} in an FBR. The U^{233} so obtained may be used in a normal thermal reactor such as PHWR. For the development of the nuclear energy technology, a research facility IGCAR (Indira Gandhi Centre for Atomic Research) has been established in 1971 at Kalpakkam, Tamil Nadu.

The founder of the country's atomic energy program Dr Homi Jehangir Bhabha outlined a three-stage program as far back as 1955.

Stage 1 In the first stage, Pressurized Heavy Water Reactors (PHWRs) using natural uranium (0.7% U^{235} and 99.23% U^{238}) as fuel and heavy water both as coolant as well as moderator, would be set up. A PHWR is a thermal reactor that consumes only the U^{235} part of the natural uranium and U^{238} is mostly left in spent fuel.

Stage 2 The second stage envisages the construction of FBRs, which will use spent fuel (depleted uranium) of the PHWRs, i.e., U^{238} and convert it to a fissionable material, plutonium^{239}. The plutonium^{239}, thus obtained, will be used as fuel in a thermal reactor.

Stage 3 In the third stage, thorium^{232} will be converted to U^{233} in a fast breeder reactor. The U^{233} will then be used as fuel in a thermal reactor.

The energy generated in the second stage is 60 times more than that available from PHWR by the same amount of natural uranium, as in this stage the uranium is fully utilized. However, in the first stage, only the U^{235} part, which accounts for 0.7% in the natural uranium, is utilized.

India has mastered the technology of the first stage with 15 commercial PHWRs plants (located at Narora, Rawatbhatta, Kakrapar, Kaiga, Kalpakkam, Kodamulam and Trombay) functioning in the country to date. However, natural uranium reserves are enough to generate only 12,000 MWe from PHWRs. But with FBRs that use plutonium, we can generate 3,50,000 MWe, which is a massive amount. The Stage 2 reactor at Kalpakkam (in FBTR, 'Fast Breeder Test Reactor') attained criticality in 1985. It is fully operational and feeding 1 MW power into the Tamil Nadu grid. However, certain technological difficulties are yet to be overcome. Construction work for a more advanced 500 MWe Prototype Fast Breeder Reactor (PFBR) has begun from 2002 at Kalpakkam and it is expected to reach criticality in 2009. R and D work on a Stage 3 reactor, ('Kamini reactor'), which will utilize thorium is also going on at IGCAR, Kalpakkam.

B. Non-conventional

Located in the tropical region, India is endowed with abundant renewable energy resources, i.e., solar, wind and biomass including agricultural residue which are perennial in nature. Harnessing these resources is best suited to meet the energy requirement in rural areas in a decentralized manner. India has the potential of generating more than 1,00,000 MW from non-conventional resources. Up to June 30, 2008, the electrical power generation by non-conventional resources has reached 12,194 MW, which is about 8.4% of total installed electrical power-generation capacity. The government plans to increase this share to 10% by 2012. The current status (as on 31.12.2007) of various resources are given in Table 1.6:

Table 1.6 *Renewable energy–estimated potential and cumulative achievements (Dec. 2007 data)* [39]

S. N.	Source/system	Estimated potential	Cumulative achievement
	Rural and decentralized energy system		
1.	Family type biogas plants (nos.)	120 lakhs	39.40 lakhs
2.	Solar photovoltaic programme Solar street-lighting system Home-lighting system Solar lantern Solar power plants	50 MW/sq. km – – – –	110 MWp (p-peak) 69,849 nos. 3,63,399 nos. 5,85,001 nos. 2.28 MWp
3.	Solar thermal programme Solar water heating system Solar cooker	140 million sq. m. collector area –	2.15 million sq.m. collector area 6.17 lakhs
4.	Wind pumps	–	1284 nos.
5.	Aero –generator/hybrid system		675.27 kW
6.	Solar photovoltaic pumps	–	7068 nos.
7.	Remote village electrification	–	3368/830 villages/hamlets
	Power from renewables		
	A. Grid interactive renewable power		
8.	Bio power (Agro residue and plantation)	16,881 MW	605.80 MW
9.	Wind power	45,195 MW	7,844.52 MW
10.	Small hydro power (up to 25 MW)	15,000 MW	2,045.61 MW
11.	Cogeneration–bagasse	5,000 MW	719.85 MW
12.	Waste to energy (urban and industrial)	2,700 MW	55.25 MW
13.	Solar power	–	2.12 MW
Total		84,776 MW	11,272.13 MW
	B. Captive/CHP/Distributed renewable power		
14.	Biomass/cogeneration (non bagasse)	–	95.00 MW
15.	Biomass gasifier	–	86.53 MW
16.	Energy recovery from waste	–	23.70 MW
Total			205.23 MW
	Other programmes		
17.	Energy parks		504 nos.
18.	Aditya solar shop		269 nos.
19.	Battery operated vehicles		270 nos.

(i) Wind Energy The highly successful wind power programme in India was initiated in 1983–84 and is entirely market driven. This sector has been growing at over 35% in the last three years. India currently (year 2008) stands fourth in the world among countries having installed large capacity wind generators, after Germany, USA and Spain. The current (July 2008) installed capacity for wind power stands at 8,696 MW, and is mostly located in Tamil Nadu, Gujarat, Maharashtra and Rajasthan. The government aims to add 10,000 MW from wind during XIth plan period (2007–2012).

(ii) Solar Energy India receives a solar energy equivalent of more than 5,000 trillion kWh per year, which is far more than its total annual consumption. The daily global radiation is around 5 kWh per sq. m per day with sunshine ranging between 2300 and 3200 hours per year in most parts of India. Though the energy density is low and the availability is not continuous, it has now become possible to harness this abundantly available energy very reliably for many purposes by converting it to usable heat or through direct generation of electricity. The

conversion systems are modular in nature and can be appropriately used for decentralized applications.

Solar Thermal Energy Programme Use of solar thermal energy is being promoted for water heating, cooking, drying and space heating through various schemes. The government is proposing to make solar-assisted water heating mandatory in certain categories of buildings through amendments in the building bylaws. Bangalore has been declared a solar thermal city with special attention to popularize solar water heaters, and Thane in Mumbai is to follow soon. Several large projects are under consideration at the Ministry of New and Renewable Energy Sources. India is planning on developing 60 'Solar Cities' based on a model already practiced in New York, Tokyo and London. The target is to reduce the use of the conventional energy resources by at least 10% over the next five years. Recently, the idea of an Integrated Solar City with ambitious 5 GW solar projects has been mooted by The Clinton Foundation for Gujarat.

Solar Photovoltaic Programme Solar PV energy is being used for solar lanterns, home-lighting systems, street lighting systems, solar water pumps and power plants. A number of 100-kW grid interactive plants are already in operation at various places in the country. A 200 kW plant is installed recently at the native village of Sardar Bhagat Singh (Village Khatkar Kalan, Dt. Nawanshahar, Punjab).

Aditya Solar Shops The ministry is promoting the establishment of special sales outlets under the name Aditya Solar Shops in major cities (104 cities so far). Different models of solar-system devices from various manufacturers are sold through these shops in order to provide the customer a wide choice.

(iii) Biomass Energy A large quantity of biomass is available in our country in the form of dry waste like agro residues, fuel wood, twigs, etc., and wet wastes like cattle dung, organic effluents, sugarcane bagasse, banana stems, etc. The potential for generation of electric power/cogeneration is 16,881 MW from agro residues and 5000 MW from bagasse through cogeneration. The potential from urban waste is 2,700 MW. Also, there is a vast scope for production of bio-diesel from some plants. These plants require little care, can be grown on fallow land and can survive in harsh climatic conditions. Energy farming may be adopted in marginal and infertile lands of the country.

(iv) Small Hydro Resources Hydro resources of capacity less than 25 MW are called small, less than 1 MW are called mini and less than 100 kW are called micro hydro resources. The total potential is 15,000 MW out of which 2,015 MW has been realized by approximately 611 plants.

(v) Geothermal Energy The potential in geothermal resources in the country is 10,000 MW. As a result of various resource assessment studies/surveys, nearly 340 potential hot springs have been identified throughout the country. Most of them are low-temperature hot-water resources and can best be utilized for direct thermal applications. Only some of them can be considered suitable for electrical power generation. The geothermal reservoirs suitable for power generation have been located at Tattapani in Chhattisgarh and Puga valley of Ladakh, Jammu and Kashmir. A 300 kW demonstration electric-power-production plant is being installed at Tattapani. Hot-water resources are located at Badrinath, Kedarnath and a few other locations in the Himalayan ranges and elsewhere. They are being used mostly for heating purposes and very little has been developed.

(vi) Ocean Tidal Energy There is no functional tidal plant at present and the total potential has been estimated as 9,000 MW. Three sites have been identified for development of tidal energy.

- Gulf of Kutch: potential = 900 MW, tidal range = 5 m
- Gulf of Cambay (Khambat): Potential = 7,000 MW, tidal range = 6 m
- Sundarbans: potential = 1,000 MW, tidal range = 3.9 m

The Ministry of Non-conventional Energy Sources has sponsored the preparation of a feasibility report by the West Bengal Renewable Energy Development Agency (WBREDA) to set up a 3.6 MW capacity demonstration tidal power plant at Durgaduani Creek in the Sunderbans area of West Bengal.

(vii) Ocean Wave and OTEC Resources A 150-kW pilot plant has been installed at Vizhingum harbour near Thiruvananthapuram, Kerala. The average potential (annual basis) for Indian coasts has been estimated at around 0.02 MW/m of wavefront. There is a proposal for an OTEC plant at the Minicoy island of Lakhshdweep.

Emerging technologies like 'fuel cell' and 'hydrogen energy' are suited for stationary and portable power generation, which suits transportation purposes. In view of the growing importance of fuel cells and hydrogen, a National Hydrogen Energy Board has been created. The board will provide guidance for the preparation and implementation of the National Hydrogen Energy Road Map, covering all aspects of hydrogen energy starting from production, storage, delivery, applications, safety issues, codes and standards, public awareness and capacity building. Eco-friendly electric vehicles for transportation are being field tested for improving their performance.

1.14.3 Growth of Energy Sector and its Planning in India

Energy is a critical building block for the development of the economy of a country. It is considered as a GDP multiplier. India is the sixth largest energy consumer in the world. To deliver sustained growth rate of 8–9% through the next 25 years till 2031–32, India needs to increase its primary energy supply 3–4 times and its electricity generation capacity about 6 times.

Electricity is an essential requirement for all facets of our life and it has been recognized as a basic human need. It is the key to accelerating economic growth, generation of employment, elimination of poverty and growth of human development especially in rural areas.

India's electric power sector has shown an annual growth rate of 5.1% during the last three years of the Xth 5-year plan. The demand for electric power is increasing at about 9%. Consequently, the supply–demand gap has been widening, resulting in an average annual peak shortfall of about 16%. This has resulted in load-shedding, under-frequency tripping, large blackouts and equipment failures. The installed capacity of electric-power generation has grown from 1,362 MW in 1947 to 1,44,564 MW as on June, 30, 2008 (Refer [35,36] for current updates). The capacity utilization is estimated as less than 60%. The energy planning during the past few 5-year plans is given in the following Table 1.7.

Table 1.7 *Energy planning during the past few 5-year plans*[34, 35]

By the end of 5-year plan	*Demand*	*Installed capacity*	*Shortage*
6th (1980–85)	52,000 MW	47,000 MW	5,000 MW
7th (1985–90)	75,000 MW	65,000 MW	10,000 MW
8th (1990–92, 92–97)	1,05,000 MW	85,000 MW	20,000 MW
9th (1997–2002)	1,32,000 MW	1,10,000 MW	22,000 MW
10th (2002–07)	1,46,000 MW	1,24,569 MW	21,431 MW
11th (2007-12)	2,05,000 MW		

To bridge the deficits and cater to future demands, the country needs an additional power generation capacity of approximately 100,000 MW over the next few years. The national goal of electrical power generation by 2012 is 2,00,000 MW in order to ensure reliable and quality power to all citizens. Out of this, about 10,000 MW will be sourced from non-conventional sources. The per capita energy consumption is targeted as 1000 kWh by 2012 against the present (year 2008) level of 702 kWh.

The growth in per capita electrical energy consumption and the growth projections of the power sector are given in Table 1.8 and Table 1.9 respectively.

Table 1.8 *Growth in per capita energy consumption*[42]

Year	*1950*	*1960*	*1970*	*1980*	*1990*	*2001*	*2004*	*2006*	*2012*
Per capita annual energy consumption (kWh)	16	35	84	131	238	408	592	631	1000

Table 1.9 *Growth projections of the power sector*[42]

Year	*2006*	*2012*	*2017*	*2022*	*2027*
Total installed generating capacity (GW)	124	216	333	512	790

The present (year 2008) household access to electricity is 56% and the rural household coverage is 44%. Electrification of rural areas is very important for a uniform development of the country. There are about 6 lakh villages in the country, and an estimated 80,000 villages are still to be electrified. Of these, there are about 20,000 villages in remote and difficult areas, which are unlikely to be electrified by conventional grid extension. Most of these villages are in hills, forests, deserts and islands. The government aims to electrify all the remaining unelectrified villages in the country in a timebound manner through special electrification programmes. The remote villages and hamlets are to be electrified through decentralized generation using non-conventional energy sources such as solar energy, biomass and micro/mini/small hydro resources. The government aims to electrify all such villages by the year 2007 and all households by 2012. The technology to be used will depend upon the size of the village and the resources available locally.

1.15 APPLIED THERMODYNAMICS—A REVIEW

Thermodynamics is an axiomatic science which deals with the relation between heat, work and properties of a system which are in equilibrium. It describes the state and the change in state of physical systems.

Thermodynamics basically entails four laws or axioms, known as the zeroth, first, second and third law of thermodynamics.

- The zeroth law deals with thermal equilibrium and establishes the concept of temperature.
- The first law throws light on the concept of internal energy.
- The second law indicates the limit of converting heat into work and introduces the principle of increase of entropy.
- The third law defines the absolute zero of entropy

1.15.1 Important Terms

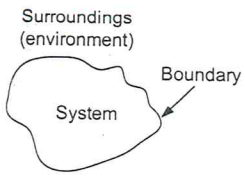


Fig. 1.5 *A system*

System A system is the finite quantity of matter or a prescribed region of space.

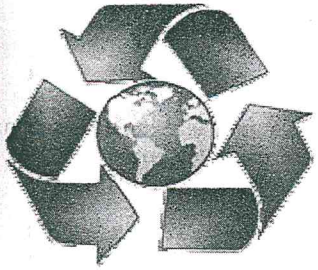
Boundary The actual or a hypothetical envelope enclosing a system is known as the boundary of the system. The boundary may be fixed or variable. The surroundings are external to the system.

(c) on the temperature of the sink only
(d) on the construction of the engine

18. The Rankine cycle efficiency of a good steam power plant may be in the range of
(a) 35–45% (b) 90–95% (c) 15–20% (d) 70–80%

19. The Rankine cycle efficiency of a steam power plant
(a) improves in winter as compared to that in summer
(b) improves in summer as compared to that in winter
(c) is unaffected by climatic conditions
(d) none of the above

20. Regenerative cycle thermal efficiency of a Rankine cycle
(a) is same as a simple Rankine cycle thermal efficiency
(b) is always less than that of a simple Rankine cycle thermal efficiency
(c) is always greater than that of a simple Rankine cycle thermal efficiency
(d) none of the above



2 Energy Conservation

Introduction

Energy is one of the basic and essential requirements of human life. In fact, it is the backbone of present-day civilization. We are aware of and have experienced the inconvenience caused due to sudden failure of electrical power supply for a short while, as numerous activities of our daily life are affected. Imagine the situation that would arise if the supply of the other sources of energy, such as gas and oil is also interrupted. Thus, energy is an indispensable component of industrial product, employment, economic growth, environment and comfort. Higher per capita energy consumption means a higher per capita Gross Domestic Product (GDP). The consumption of energy is increasing with improvement in per capita income, as there is a strong correlation between the standard of living and energy consumption.

One way to cope up with the increased energy demand is to expand energy production. The problem can also be solved to a great extent by conservation (saving) of energy. Increasing the energy production is an expensive and long-term option, whereas energy conservation offers a cost effective and immediate solution. As the present conventional energy assets are fast depleting and cost of energy is increasing, it is very important to conserve energy and utilize it more efficiently. This also helps in reducing the environment pollution. Thus, there are three major incentives in energy conservation: (i) decreasing the energy requirement, (ii) conserving the limited conventional assets of energy, and (iii) saving the environment. To create awareness about energy conservation, 14th December is observed as 'National Energy Conservation Day'. This day is also observed as 'World Energy Day' internationally. Experts have indicated a saving potential ranging from 10–25% in the total spectrum of Indian industries without any major investment. Developed countries have been able to reduce their consumption of energy through self-discipline and strict energy-conservation measures. Japanese primary energy consumption per unit GDP is the lowest in the world, owing to various energy conservation measures taken for the respective sectors. Energy consumption levels in the industrial sector of Japan are still at 1973 levels. In Denmark, energy consumption has increased by only 2% since 1980, while GDP growth is 56% in the same period.

Energy conservation means reduction in energy consumption but without making any sacrifice in the quality or quantity of production. In other words, it means increasing the production from a given amount of energy input by reducing losses/wastage and maximizing the efficiency.

Energy audit is an official, technical survey of the energy consumption of an organization / process/plant/equipment aimed at reduction of energy consumption without affecting productivity and to suggest methods for energy conservation and reduction in energy-acquiring cost. The suggestions/recommendations are known as ECOs (Energy Conservation Opportunities) and their implementation is known as ECMs (Energy Conservation Measures). The recommendations are presented in three categories.

(i) Category A: Minor ECOs

Minor ECOs are simple, easy to implement, and require less investment and implementation time. These are related to stopping of leakage points, avoiding careless waste, housekeeping, lapses and carelessness of O and M personnel.

(ii) Category B: Medium ECOs

Medium ECOs or intermediate ECOs are slightly complex, requiring additional investment and moderate implementation time.

(iii) Category C: Major ECOs

Major ECOs provide significant energy-conservation opportunity. These are high-tech., complex and require heavy investment and long implementation periods.

Energy management involves planning, directing, and controlling the demand and supply of energy to maximize productivity and comforts, and minimize the energy cost and pollution with conscious, judicious and effective use of energy. Energy audit and ECMs are essential functions of an energy-management plan which also deals with energy monitoring and implementing ECMs.

In most cases, the demand and supply of energy are managed independent of each other. These are known as two sides of energy management, i.e., *demand side management (DSM)* and *supply side management (SSM)*.

Some investment is made in order to implement energy-conservation measures; however, this investment is very small compared to that in generating the equivalent amount of energy that is saved through conservation. As per a popular slogan, 'Energy Saved is Energy Generated'. In fact, the energy saved is more than the energy generated because the energy is saved at the user's end which includes saving of transmission/transportation losses also, apart from usable energy. Thus, the cost of DSM is much less (only a fraction) as compared to that of SSM.

Energy strategy refers to selection of a particular course to be followed from available alternatives under prevailing constraints. Such a strategy gives guidelines to policy makers and planners.

India's energy strategy is to explore more oil reserves, consume coal as far as possible and encourage and tap the potential for renewable energy sources irrespective of capacity. India is predominantly an agricultural country and the strategy is to make the rural sector self-reliant in energy through locally available renewable energy resources.

Energy policy refers to an officially declared guideline for the purpose of planning and actions. In 1991, the then government of India declared reforms such as LPG (liberalization, privatization and globalization) as its energy policy.

Energy planning refers to detailed formulation of various actions in a given time frame to achieve the objectives. The strategy and policy are the guidelines for planning. Planning is an essential management tool. Planning of several activities includes forecast, budget, infrastructure, material, equipment, technology, financial resource, human resource and R and D planning. The time frame for planning is fixed in three categories: short-term planning (yearly, monthly, daily, hourly), mid-term planning (5 yearly), and long-term planning (15 years, 25 years, 50 years).

2.1 SALIENT FEATURES OF "ENERGY CONSERVATION ACT, 2001"

Energy conservation involves all the sectors of the economy. Although the importance of energy conservation has been discussed for quite some time, the efforts generated had been fragmented and half hearted. There has also been a lack of adequate focus on the institutional arrangements, which would devise suitable incentives and disincentives appropriate to each sector, backed by adequate statutory power enforcement.

During the Ninth Five Year Plan, the need for an energy conservation act was realized. Considering the vast potential of energy savings and benefits of energy efficiency, the Government of India (on 29 September, 2001) enacted the Energy Conservation Act, 2001. The Act provides the legal framework, institutional arrangement and a regulatory mechanism at the central and state levels to embark upon an energy-efficiency drive in the country. This act requires large energy consumers to adhere to energy-consumption norms; new buildings to follow the Energy Conservation Building Code; and appliances to meet energy-performance consumption labels. The act provides a long-range consequence, which is appended below:

- The establishment of a Bureau of Energy Efficiency (BEE) in place of the existing Energy Management Centre (EMC) to implement the provisions of the act
- Declaration of a user or class of users of energy as a designated consumer
- To lay down minimum energy-consumption standards and labelling for identified appliances/equipments and norms for industrial processes for energy intensive industries
- Formation of energy consumption codes
- Dissemination of information and best practices
- Establishment of an Energy Conservation Fund, both at the central and state levels
- Provision of penalties and adjudication-no penalties would be effective during the first five years as the focus during this period would be on promotional activities and creating the infrastructure for implementing the Act
- BEE to act as a facilitator for the evolution of a self-regulatory system and organizations to regulate on their own with a view to save energy and thereby bring the commercial concept in the organization

The central government has established the BEE with effect from 1 March, 2002. Further, the provision of sections 1–29 and sections 46–62 of the Energy Conservation Act relating to this have come into force from the same date.

The present (year 2007) potential of power saving though energy conservation measures is assessed as 20,000 MW. The potential harnessed during the Xth plan

period is 877 MW. The target set for the XIth plan period is 10,000 MW. The saving through demand side management is assessed as 15%.

VARIOUS ASPECTS OF ENERGY CONSERVATION

2.2 Saving of usable energy, which is otherwise wasted, has direct impact on economy, environment and long-term availability of non-renewable energy sources. Energy conservation implies reduction in energy consumption by reducing losses and wastage by employing energy efficient means of generation and utilization of energy. There are three important aspects of energy conservation:

(i) Economic Aspect

(a) Reduction in Cost of Product Energy conservation ultimately leads to economic benefits as the cost of production is reduced. In some energy-intensive industries like steel, aluminum, cement, fertilizer, pulp and paper, the cost of energy forms a significant part of the total cost of the product. Energy cost as a percent of the total cost of the product in the entire industrial sector in India varies from as low as 0.36% to as high as 65%. We must strive for good energy economy using energy-efficient technologies. This will reduce the manufacturing cost and lead to production of cheaper and better quality products. This is essential to stay in step with our commercial rivals.

(b) New Job Opportunities Energy conservation usually requires new investments in more efficient equipments to replace old inefficient ones, monitoring of energy consumption, training of manpower, etc. Thus, energy conservation can result in new job opportunities.

(ii) Environmental Aspect Every type of energy generation/utilization process affects the environment to some extent, either directly or indirectly. The extent of degradation of the environment depends mainly on the type of primary energy source. Also, during every energy-conversion stage a part of energy escapes to the surroundings and appears in the form of heat. Thus, energy is generated and utilized at the expense of adverse environmental impacts. Adoption of energy-conservation means can minimize this damage.

(iii) Conservation of Non-renewable Energy Assets

The vast bulk of energy used in the world today comes from fossil fuels, which are non-renewable. These resources were laid down many millions of years ago and are not being made any longer. This finite, non-renewable asset is being used up very fast. The quantity of fossil fuels that the world community uses up in one minute actually took the earth a millennium to create. Therefore, its prices are bound to go up relative to everything else. We must abandon wasteful practices in energy utilization and conserve this resource by all means for future generations.

PRINCIPLES OF ENERGY CONSERVATION

2.3 Some general principles of energy conservation are explained below:

(a) Recycling of Waste Every finished product has an intrinsic value depending upon original energy input during its production process. For example, newspaper material has more gained energy than the energy in the raw material that goes in making the paper. Reducing the waste and reclaiming the useful waste material by its recycling can save that invisible energy which was used in producing and processing the material. It has three benefits. (i) Saving of energy as (in general) the energy spent in recycling is only a fraction of the energy needed in extraction of fresh material from raw source. Thus, recycling saves and recovers a part of energy that has already been spent to process the fresh material. (ii) Extraction of the same amount of new (virgin) material is also displaced. (iii) It also solves the problem of waste disposal to a great extent.

Recycled aluminum cans require only 6% of the energy needed to make the can in the first place. Recycling of one aluminum can would save enough energy to run a TV for 3 hours. Japan serves as an example of a premiere recycling country. Half of its waste material is recycled. This includes 95% of all newspapers and 50% of all other papers.

(b) Modernization of Technology Developed countries have been able to reduce the energy consumption significantly compared to developing countries by adopting energy-efficient modern technology. For instance, energy used by the Indian steel industry is 9.50 million kCal per ton, which is more than double the amount used by Italy or Japan, who use around 4 million kCal per tonne. Similarly, in case of the cement industry, the energy requirement works out to be around 2 million kCal per ton as against 0.95 million kCal per tonne in USA and 0.89 million kCal per tonne in Italy. Therefore, modern energy efficient technology should be adopted by replacing/retrofitting the existing old inefficient equipments.

(c) Waste Heat Utilization Various industrial processes require heat of different grades. Waste heat from one process can serve the need of another, which requires heat at a lower grade. Let us consider an example of glass industry:

- The glass industry requires heat to melt glass at about 1500°C. It produces waste heat at about 400–500°C in the form of flue gases from the furnace.
- Flue gases may be used to raise medium pressure steam and fed to backpressure turbine to generate electric power. (In a backpressure turbine, the exhaust steam is not condensed but is withdrawn at desired pressure for process use as against condensing turbine where the steam leaves the turbine at a very low pressure.)
- The exhaust from backpressure turbine, which is at about 120°C, may further be used for crop drying or for paper drying. (In the paper industry, 1.5 tonnes of water have to be evaporated for each tonne of paper produced.

Approximately 30% of the total energy required for paper production is utilized for drying purposes.)

- The condensed water vapour, which is at about 60°C, may be used for heating of space, fish farm or greenhouse.

(d) Proper Housekeeping

(e) Judicial Use of Proper Types of Energy Although all forms of energy are expressed in the same unit (joules), the financial value of energy varies enormously with its grading. Some of the energy forms are mentioned here in decreasing order of grading:

- Electrical energy (top-grade energy)
- Mechanical energy
- Thermal energy

  (i) High-grade thermal energy (500°C and above)
  (ii) Medium-grade thermal energy (150–500°C)
  (iii) Low-grade thermal energy (80–150°C)

For economic reasons, one should never use a higher-grade energy than required. For example, electrical energy should preferably not be used for heating purpose; instead, thermal energy, which may be obtained directly by burning of fuel or by solar thermal system, may be used.

(f) Judicial Use of Proper Type of Fuel A cheaper primary source should be preferred wherever possible in place of a costly one. For example, coal (gasified, pulverized or other forms) and bio-fuel may be considered in place of oil or gas, which are costlier.

(g) Cogeneration Cogeneration (generation of electricity and useful heat in a single installation) should be used where ever feasible and economically viable, instead of separate generation of electricity and heat. In some industries, cogeneration may result in 30% lower fuel consumption as compared to that where electricity and heat are generated separately.

(h) Training of Manpower Manpower should be trained to adopt habits in efficient use of energy.

(i) Adopting Daylight Saving Time *Daylight saving time* may be adopted to save a significant amount of energy during a certain season in a year. In summer, when the sun rises early, the clock may be set one hour ahead of the local standard time. This increases the number of useful hours of the daylight and provides extra sunlight in the evenings. Due to this, daily activities of many people are over earlier and bedtime comes soon after it is dark. As a result, they do not have to use artificial light and could save fuel and electricity. The idea of daylight saving was introduced by Benjamin Franklin in the 18th century to the people of Paris,

but it was not adopted then. Later, during World War I, daylight saving laws were passed. Germany was the first country to adopt daylight saving time in 1915, followed by England (1916) and the US (1918).

(j) Proper Operation and Maintenance Leakages must be carefully plugged. Proper lubrication should be maintained in moving parts. Proper thermal insulation should be utilized in thermal systems.

2.4 GENERAL ELECTRICAL ECO'S (ENERGY CONSERVATION OPPORTUNITIES)

Class A. Simple Electrical ECO's

1. Switching off the loads (i.e., lights, heaters, ACs, TVs, etc.) when not in use
2. Changing from electrical heating to solar heating or gas-burner heating wherever possible
3. Proper housekeeping
4. Reducing peak demand by staggering the use of large loads
5. Providing automatic thermostatic (or any other) control to water heaters, refrigerators, air conditioners, etc.
6. Using recently developed 'tiny switches' which switch off the electronic apparatus during their sleeping mode
7. Changing operating cycle of electrical equipment to conserve energy. For example, electrical furnaces may be used continuously in three shifts (instead of two shifts) for better economy
8. Replacing inefficient lamps by energy-efficient lamps

Class B. Intermediate Electrical ECO's

1. Installation of static VAR sources at substations
2. Employing automatic controlled load switches
3. Heat recovery from cooling oil/water associated with transformers
4. Automatic voltage control of power consuming devices by means of ON-load tap changer
5. Installation of shunt capacitors near inductive load for power-factor improvement and reducing kVA demand
6. Improvement in operation and maintenance, reducing down time

Class C. Comprehensive Electrical ECO's

1. Modern, more efficient and easy to maintain plant equipments may replace old less efficient ones
2. The simple manual/semi manual controlled equipments in an electrical plants are retrofitted with energy efficient computer controlled equipments. The energy input is matched with optimum energy requirement.

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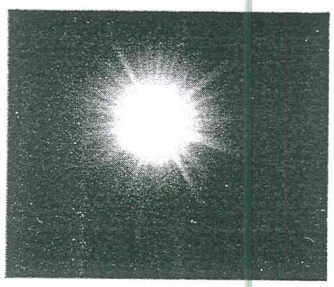

Solar Energy — Basics

Introduction

The sun radiates energy uniformly in all directions in the form of electromagnetic waves. The sun provides the energy needed to sustain life in our solar system. It is a clean, inexhaustible, abundantly and universally available source of renewable energy. The major drawbacks of solar energy are that it is a dilute form of energy, which is available intermittently and uncertainly, and not steadily and continuously. However, it is more predictable than wind energy. Also, peak solar insolation (incident solar radiation) often coincides with peak daytime demand; it can be well matched to suit commercial power needs. The output of the sun is 2.8×10^{23} kW/year. The energy reaching the earth is 1.5×10^{18} kWh/year.

Solar energy can be utilized directly in two ways: (i) by collecting the radiant heat and using it in a thermal system, or (ii) by collecting and converting it directly to electrical energy using a photovoltaic system. The former is referred as 'Solar Thermal' and the latter as 'Solar Photovoltaic' (SPV) system.

Solar energy is also used by various well-known natural effects and appears in nature in some other forms of energy. These are indirect forms of solar energy. Thus, solar energy is the mother of all forms of energy: conventional or non-conventional, renewable or non-renewable, the only exception being nuclear energy. Various sources of energy find their origin in the sun, as mentioned below:

1. Wind energy
2. Biomass energy
3. Tidal energy
4. Ocean wave energy
5. Ocean thermal energy
6. Fossil fuels and other organic chemicals
7. Hydro energy

Warming the body during winter is perhaps the earliest use of direct solar heat that man has made. Drying of clothes, timber, fodder, salt water (to get salt) and agricultural produce remain the most extensive use of direct solar energy in the history of mankind. All other devices for harnessing direct solar energy are of fairly recent origin.

Archimedes (212 BC), it is said, set the Roman fleet on fire by concentrating solar radiation using a large number of small plane mirrors at a distance of several hundred feet from the fleet. Antoine Lavoisier (1740–1794), achieved temperatures up to 1700°C by concentrating the sun's rays through a magnifying glass. Solar steam boilers were developed in late 19th century to produce steam to run steam engines. In the 1870s, a large-scale project using solar energy was installed in Chile where 6000 gallons of fresh water was produced per day

in a desalination plant by collecting solar energy in an area of 50,000 sq. ft. In subsequent years, the development of solar energy declined due to availability of cheap fossil fuels. However, after the oil crisis of 1973, solar energy (as well as other non-conventional energy sources) received renewed interest from mankind.

THE SUN AS A SOURCE OF ENERGY

4.1 The sun, which is the largest member of the solar system, is a sphere of intensely hot gaseous matter having a diameter of 1.39×10^9 m, and, at an average distance of 1.495×10^{11} m from the earth. As observed from the earth, the sun rotates on its axis about once in every four weeks, though it does not rotate as a solid body. The equator takes about 27 days and the polar region takes about 30 days for each rotation. At the innermost region, the core, the temperature is estimated between 8×10^6 to 40×10^6 °K. The core has a density of about 100 times that of water and a pressure of 10^9 atm. Such a high inner temperature is maintained by enormous energy released due to continuous fusion reaction. Thus, the sun is a big natural fusion reactor with its constituent gases as the 'containing vessel' retained by gravitational forces. Several fusion reactions have been suggested to be the source of the energy radiated by the sun. The most important of them is a reaction in which four hydrogen atoms (protons) combine to form one helium atom. The mass of the helium nucleus is less than that of four protons, the difference of mass having been converted to energy in a fusion reaction as follows:

$$4({}_1H^1) \longrightarrow {}_2He^4 + 26.7 \text{ MeV}$$

The surface of the sun is maintained at a temperature of approximately 5800°K.

THE EARTH

4.2 The earth is shaped as an oblate spheroid—a sphere flattened at the poles and bulged in the plane normal to the poles. However, for most practical purposes, the earth may be considered as a sphere with a diameter of about 1.275×10^7 m. The earth makes one rotation about its axis every 24 hours and completes a revolution about the sun in a period of approximately 365.25 days. Its axis is inclined at an angle of 23.5°. As a result, the length of days and nights keep changing. The earth reflects about 30% of the sunlight that falls on it. This is known as the earth's *albedo*.

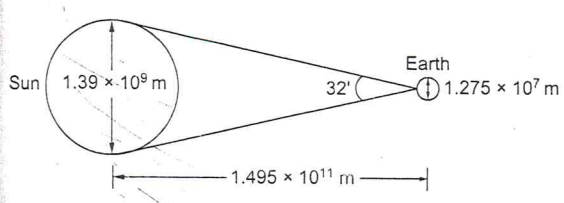

Fig. 4.1 *Sun–earth relationship*

The geometry of the earth–sun relationship is shown in Fig. 4.1. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by ±1.7%. The sun subtends an angle of 32' on the earth

at an average sun – earth distance of 1.495×10^{11} m, a distance of one *astronomical unit.*

4.3 SUN, EARTH RADIATION SPECTRUMS

The energy radiated away from a black body at temperature T and wavelength λ can be obtained from Planck's black-body radiation formula:

$$W_\lambda = \frac{2\pi h^2 \lambda^{-5}}{e^{\frac{hc}{\lambda k T}} - 1} \text{ (W/m}^2\text{/unit wavelength in m)} \quad (4.1)$$

where $h = 6.63 \times 10^{-34}$ watt-sec^2 (Planck's constant) and

$k = 1.38 \times 10^{-23}$ Joules/K (Boltzmann's constant)

Using this formula, the energy-density distribution of solar radiation at the surface of the sun considering the surface temperature to be 5760°K can be calculated. Also, the same for the earth surface can be found out assuming the average earth temperature to be 288°K (15°C). The comparison of these radiations from the sun and the earth is shown in Fig. 4.2. It is clear from Fig. 4.2 (a) and (b) that the radiation emitted from the sun at about 5760°K lies in the range of short wavelengths, peaking around 0.48 μm and that from the earth at 288°K (15°C) lies in the range of long wavelengths, peaking around 10 μm.

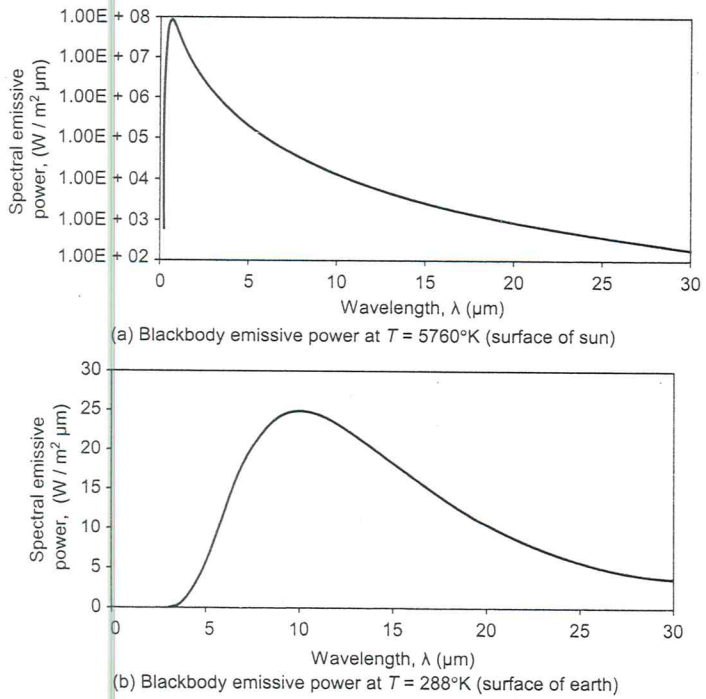

Fig. 4.2 *Radiant powers per unit wavelength at the surface of the sun and earth*

The term *irradiance* is defined as the measure of power density of sunlight received at a location on the earth and is measured in W/m². *Irradiation* is the measure of energy density of sunlight and is measured in kWh/m². It is generally denoted by the symbol H. Irradiance and irradiation apply to all components of solar radiation.

4.4 EXTRATERRESTRIAL AND TERRESTRIAL RADIATIONS

The intensity of solar radiation keeps on attenuating as it propagates away from the surface of the sun, though the wavelengths remain unchanged. Solar radiation incident on the outer atmosphere of the earth is known as *extraterrestrial radiation*, I_{ext}. The *solar constant*, I_{sc} is defined as the energy received from the sun per unit time, on a unit area of surface perpendicular to the direction of propagation of the radiation at the top of the atmosphere and at the earth's mean distance from the sun. The World Radiation Center (WRC) has adopted the value of the solar constant as 1367 W/m² (1.940 cal/cm² min, 432 Btu/ft² h or 4.921 MJ/m² h). This has been accepted universally as a standard value of solar constant.

The extraterrestrial radiation deviates from the solar-constant value due to two reasons. The first is the variation in the radiation emitted by the sun itself. The variation due to this reason is less than ±1.5% with different periodicities. The second is the variation of the earth–sun distance arising from the earth's slightly elliptic path. The variation due to this reason is ± 3% and is given by

$$I_{ext} = I_{sc}\,[1.0 + 0.033 \cos (360\, n/365)] \text{ W/m}^2 \quad (4.2)$$

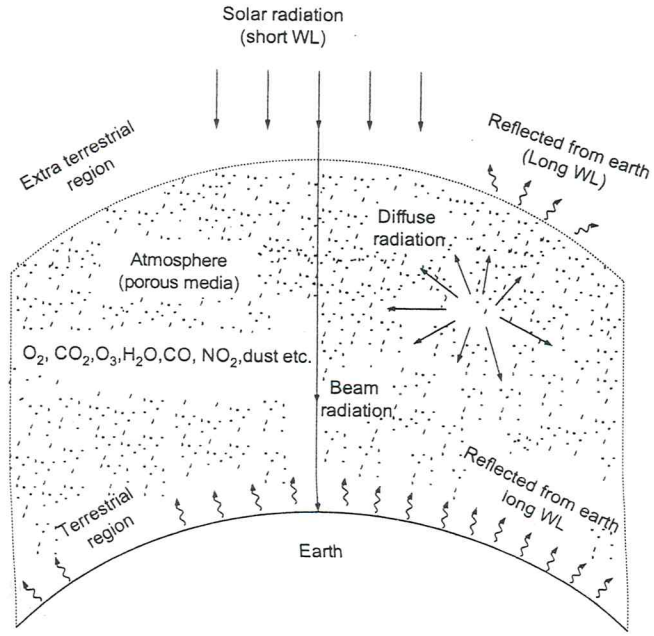

Fig. 4.3 *Propagation of solar radiation through the atmosphere*

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The extraterrestrial radiation, being outside the atmosphere, is not affected by changes in atmospheric conditions. While passing through the atmosphere, it is subjected to mechanisms of atmospheric absorption and scattering depending on atmospheric conditions, depleting its intensity. The solar radiation that reaches the earth surface after passing through the earth's atmosphere is known as *terrestrial radiation*. The term *solar insolation* (incident solar radiation) is defined as the solar radiation received on a flat horizontal surface on the earth. The positions of extraterrestrial and terrestrial regions are indicated in Fig. 4.3.

4.5 SPECTRAL ENERGY DISTRIBUTION OF SOLAR RADIATION

Solar radiation covers a continuous spectrum of electromagnetic radiation in a wide frequency range. About 99% of the extraterrestrial radiation has wavelengths in the range from 0.2 to 4 μm with maximum spectral intensity at 0.48 μm (green portion of visible range). About 6.4% of extraterrestrial radiation energy is contained in the ultraviolet region ($\lambda < 0.38$ μm); another 48% is contained in the visible region (0.38 μm $< \lambda <$ 0.78 μm) and the remaining 45.6% is contained in the infrared region ($\lambda > 0.78$ μm). There is almost complete absorption of short-wave radiation in range ($\lambda < 0.29$ μm) and infrared radiation in range ($\lambda > 2.3$ μm) in the atmosphere. Thus, from the point of view of terrestrial applications of solar energy, the radiation only in the range of wavelengths between 0.29 and 2.3 μm is significant. The spectral solar-irradiation distribution, both for extraterrestrial and terrestrial radiation, is shown in Fig. 4.4. The areas under these curves indicate the total radiation intensities in W/m^2 respectively for extraterrestrial and terrestrial regions.

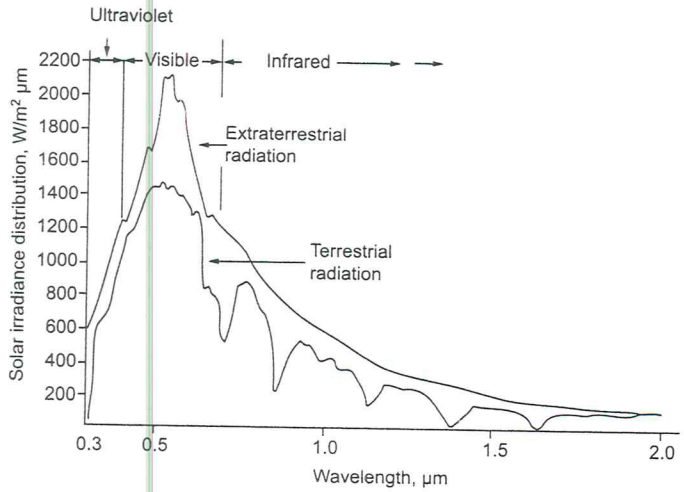


Fig. 4.4 *Spectral solar irradiation, exterrestrial and terrestrial*

4.6 DEPLETION OF SOLAR RADIATION

The earth's atmosphere contains various gaseous constituents, suspended dust and other minute solid and liquid particulate matter. These are

air molecules, ozone, oxygen, nitrogen, carbon dioxide, carbon monoxide, water vapour, dust, and water droplets. Therefore, solar radiation is depleted during its passage through the atmosphere. Different molecules do different things as explained below:

1. **Absorption** Selective absorption of various wavelengths occurs by different molecules. The absorbed radiation increases the energy of the absorbing molecules, thus raising their temperatures:

   (a) Nitrogen, molecular oxygen and other atmospheric gases absorb the X-rays and extreme ultraviolet radiations.
   (b) Ozone absorbs a significant amount of ultraviolet radiation in the range ($\lambda < 0.38$ μm).
   (c) Water vapour (H_2O) and carbon dioxide absorb almost completely the infrared radiation in the range ($\lambda > 2.3$ μm) and deplete to some extent the near infrared radiation below this range.
   (d) Dust particles and air molecules also absorb a part of solar radiant energy, irrespective of wavelength.

2. **Scattering** Scattering by dust particles and air molecules (or gaseous particles of different sizes) involves redistribution of incident energy. A part of the scattered radiation is lost (reflected back) to space and the remaining is directed downwards to the earth's surface from different directions as *diffuse radiation*. It is the scattered sunlight that makes the sky blue. Without the atmosphere and its ability to scatter sunlight, the sky would appear black as it does on the moon.

In a cloudy atmosphere, (i) a major part of the incoming solar radiation is reflected back into the atmosphere by clouds, (ii) another part is absorbed by the clouds, and (iii) the rest is transmitted downwards to the earth surface as diffused radiation. The energy reflected back to the space by (i) reflection from clouds, (ii) scattering by the atmospheric gases and dust particles, and (iii) by reflection from the earth's surface is called the *albedo* of the earth–atmosphere system and has a value of about 30% of the incoming solar radiation for the earth as a whole. Thus, on the surface of the earth, we have two components of solar radiation: (i) *direct or beam radiation*, unchanged in direction, and (ii) *diffuse radiation*, the direction of which is changed by scattering and reflection. The total radiation at any location on the surface of the earth is the sum of beam radiation and diffused radiation, and is known as *global radiation*. These terms may be properly defined as follows:

Beam Radiation Solar radiation propagating in a straight line and received at the earth surface without change of direction, i.e., in line with the sun is called beam or direct radiation.

Diffused Radiation Solar radiation scattered by aerosols, dust and molecules is known as diffused radiation. It does not have a unique direction.

Global Radiation The sum of beam and diffused radiation is referred as total or global radiation.

Even on clear days, there will be some diffused radiation depending upon the amount of dust particles, ozone and water vapour present in the atmosphere. On overcast days when the sun is not visible, all the radiation reaching the ground will be diffused radiation.

In general, the intensity of diffused radiation coming from various directions in the sky is not uniform. The diffused radiation is therefore said to be anisotropic in nature. However, in many situations (like heavy cloud cover), the intensity from all directions tends to be reasonably uniform and it thus becomes isotropic in nature.

The radiation thus available on the earth's surface is less that what is received outside the earth's atmosphere and this reduction in intensity depends on the atmospheric conditions (amount of dust particles, water vapour, ozone content, cloudiness, etc.) and the distance travelled by beam radiation through the atmosphere before it reaches a location on the earth's surface. The latter factor in turn depends on solar altitude. The path length of a solar beam through the atmosphere is accounted for in the term *air mass*, which is defined as the ratio of the path length through the atmosphere, which the solar beam actually traverses up to the ground to the vertical path length (which is minimum) through the atmosphere. Thus at sea level the air mass is unity when the sun is at its *zenith* (highest position), i.e., when the inclination angle α is 90°. Mathematically,

$$\text{Air mass, } m = \frac{\text{path length traversed by beam radiation}}{\text{vertical path length of atmosphere}}$$

The abbreviation AM_0 refers to zero atmosphere (radiation in outer space), AM_1 refers to $m = 1$ (i.e., sun overhead, $\theta_z = 0$), AM_2 refers to $m = 2$ ($\theta_z = 60°$); and so on.

From Fig. 4.5, the air mass may be written as

$$m = (BA)/(CA)$$

$$= \sec \theta_z$$

$$= \operatorname{cosec} \alpha \qquad (\text{as } \alpha + \theta_z = 90°)$$

where α is the inclination angle

and θ_z is the zenith angle

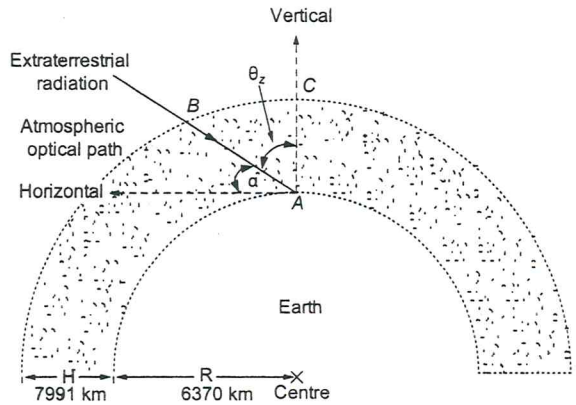


Fig. 4.5 *Direction of sun's ray with respect to atmosphere*

4.7 MEASUREMENTS OF SOLAR RADIATION

Solar radiation data are measured mainly by the following instruments:

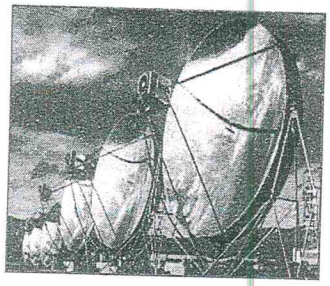
(i) Pyranometer A pyranometer is designed to measure global radiation, usually on a horizontal surface, but can also be used on an inclined surface. When shaded from beam radiation by using a shading ring, a pyranometer measures diffused radiation.

(ii) Pyrheliometer An instrument that measures beam radiation by using a long narrow tube to collect only beam radiation from the sun at normal incidence.

(iii) Sunshine Recorder It measures the sunshine hours in a day.

4.7.1 Pyranometer

A precision pyranometer is designed to respond to radiation of all wavelengths and hence measures accurately the total power in the incident spectrum. It contains a thermopile whose sensitive surface consists of circular, blackened, hot junctions, exposed to the sun, the cold junctions being completely shaded. The temperature difference between the hot and cold junctions is the function of radiation falling on the sensitive surface. The sensing element is covered by two concentric hemispherical glass domes to shield it from wind and rain. This also reduces the convection currents. A radiation shield surrounding the outer dome and coplanar with the sensing element, prevents direct solar radiation from heating the base of the instrument. The instrument has a voltage output of approximately 9μV/W/m² and has an output impedance of 650 Ω. A precision spectral pyranometer (model: PSP) of Eppley Laboratory is shown in Fig. 4.6. The pyranometer, when provided



Solar Thermal Systems

Introduction

5 Solar energy can be utilized directly by two technologies, namely, (i) Solar Thermal, and (ii) Solar Photovoltaic. Solar thermal systems provide thermal energy for various processes. In regions of cold climates a large amount of low-grade thermal energy is required to heat air for comfort, and hot water for washing, cleaning and other domestic and industrial needs. Various industrial surveys show that up to 24% of all industrial heat is consumed for heating fluids to a moderate temperature. Thus, solar energy is best suited for low-grade thermal applications. Even in high-temperature heating applications, a significant amount of fuel can be saved by using solar energy for preheating (up to about 180°C). Due to this reason, manufacture of solar-water heaters has become a thriving industry in several countries, especially Australia, Israel, USA and Japan. Solar thermal energy is also being utilized in drying and process industries. It can also be converted and utilized as mechanical and electrical energy in the same way as in any conventional thermal system. Solar thermal systems will be discussed in detail in this chapter and solar PV systems will be dealt with in the next chapter.

5.1 SOLAR COLLECTORS

Solar power has low density per unit area (1 kW/sq. m. to 0.1 kW/sq. m.). Hence, it is collected by covering a large ground area by solar thermal collectors. A solar thermal collector essentially forms the first unit in a solar thermal system. It absorbs solar energy as heat and then transfers it to the heat transport fluid efficiently. The heat-transport fluid delivers this heat to a thermal storage tank/boiler/heat exchanger to be utilized in the subsequent stages of the system.

5.1.1 Classification

The overall view of classification of solar collectors into categories and subcategories is shown in Fig. 5.1. The classification is based on the way they collect solar radiation. The non-concentrating type absorbs the radiation as it is received on the surface of the collector while the concentrating type first increases the concentration of radiation per unit area before absorbing it. Further, based on the techniques employed for concentration of radiation, the concentrating type is further subdivided into focus and non-focus types. The focus type is further divided into line or point focus depending on the focusing method.

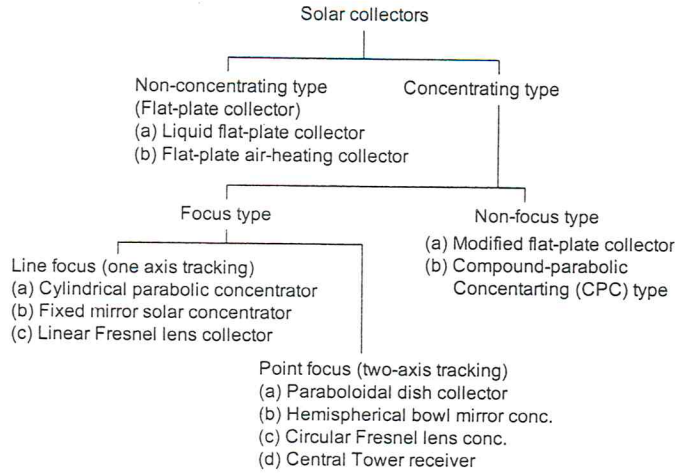


Fig. 5.1 *Types of solar collectors*

5.1.2 Comparison of Concentrating and Non-concentrating Types (Flat-plate Type) of Solar Collectors

In concentrating-type solar collectors, solar radiation is converged from a large area into a smaller area using optical means. Beam radiation, which has a unique direction and travels in a straight line, can be converged by reflection or refraction techniques. Diffused radiation however, has no unique direction and so does not obey optical principles. Therefore, the diffused component cannot be concentrated. Thus, concentrating-type solar collectors mainly make use of the beam radiation component (plus very little diffuse-component coming directly over the absorber), while non-concentrating (flat plate) collectors absorb both beam as well as diffused radiation, a distinct advantage of a flat-plate collector.

A flat-plate collector is simple in construction and does not require sun tracking. Therefore, it can be properly secured on a rigid platform, and thus becomes mechanically stronger than those requiring flexibility for tracking purpose. As the collector is installed outdoors and exposed to atmospheric disturbances (rain, storm, etc.), the flat-plate type is more likely to withstand harsh outdoor conditions. Also, because of its simple stationary design, a flat-plate collector requires little maintenance.

The principal disadvantage of a flat-plate collector is that because of the absence of optical concentration, the area from which heat is lost is large. Also, due to the same reason high temperatures cannot be attained.

The main advantage of concentrating-type collectors is that high temperatures can be attained due to concentration of radiation. This also yields high-temperature thermal energy.

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5.2 SOLAR WATER HEATER

The details of the most common type of solar water heater are shown in Fig. 5.18. A tilted flat-plate solar collector with water as a heat-transfer fluid is used. A thermally insulated hot-water storage tank is mounted above the collector. The heated water of the collector rises up to the hot water tank and replaces an equal quantity of cold water, which enters the collector. The cycle repeats, resulting in all the water of the hot water tank getting heated up. When hot water is taken out from the hot water outlet, the same is replaced by cold water from a cold-water make up tank fixed above the hot water tank. The scheme is known as *passive heating scheme*, as water is circulated in the loop naturally due to thermo-siphon action. When the collector is fixed above the level of the hot-water tank, a pump is required to induce circulation of water in the loop and the scheme will be known as active (or forced) solar thermal system. An auxiliary electrical emersion heater may be used as a back-up for use during cloudy periods. In average Indian climatic conditions, a solar water heater can be used for about 300 days in a year. A typical 100-litres per day (LPD) rooftop solar water heater costs approximately Rs. 18,000–21,900 (year 2008) and delivers water at 60–80 °C. It has a life span of 10–12 years and a payback period of 2–6 years.

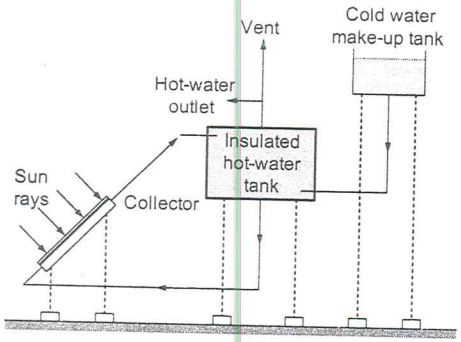


Fig. 5.18 *Solar water heater*

In other schemes, the hot water from the collector delivers heat to service water through a heat exchanger. In this scheme, an anti-freeze solution may be used as the heat-transport medium to avoid freezing during cold nights.

5.3 SOLAR PASSIVE SPACE-HEATING AND COOLING SYSTEMS

Solar energy is also used for heating or cooling a building to maintain a comfortable temperature inside. Passive systems do not require any mechanical device and make use of the natural process of convection, radiation and conduction for transport of heat. Use of passive heating/cooling systems puts restrictions on the building design to make possible the flow of heat naturally. Such a specially designed building is called a *solar house*. The technology for passive cooling is much less developed than that for passive space heating. Natural passive cooling may not always be sufficient to meet the requirement and at peak load, auxiliary means may also be needed, but it greatly reduces the load on the air-conditioner plant.

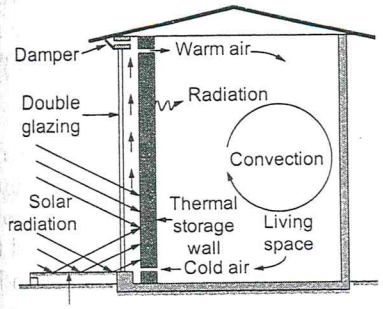


Fig. 5.19 *Solar space heating*

Active heating/cooling systems employ mechanical devices, e.g., pumps, blowers, etc., to circulate the working fluid for transportation of heat and, therefore, a special building design is not necessary as required in the case of passive heating. Nevertheless, careful building design and insulation is desirable and will be less expensive than an additional heating/cooling load due to poor design.

A solar passive space-heating system is shown in Fig. 5.19. The south-facing thick wall, called *Trombe Wall* is made of concrete, adobe, stone or composites of brick blocks and sand, designed for thermal storage. In order to increase the absorption, the outer surface is painted black. The entire south wall is covered by one or two sheets of glass or plastic with some air gap (usually 10–15 cm) between the wall and inner glazing. Solar radiation after penetration through the glazing is absorbed by the thermal storage wall. The air in the air gap between the glazing and the wall thus gets heated, rises up and enters the room through the upper vent while cool air from the room replaces it from the bottom vent. The circulation of air continues till the wall goes on heating the air. Thus, the thermal wall collects, stores and transfers the heat to the room. Heating can be adjusted by controlling the air flow through the inlet and outlet vents by shutters. Opening the damper at the top of the glazing allows the excess heat to escape outside, when heating is not required.

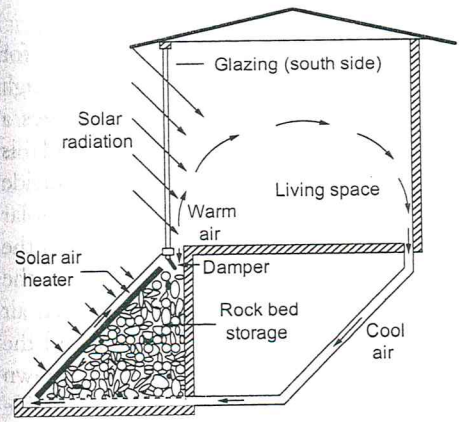


Fig. 5.20 *Solar space heating with rock bed storage*

Sometimes, a reflective horizontal surface is also provided to make available the additional radiation for thermal storage. A movable insulation cover (not shown in the figure) is also sometimes used to cover the glaze to reduce the heat loss from the storage wall to outdoors during night. In some models, the thermal storage wall is made up of water drums stacked over one another to increase the thermal storage capacity. In another variation, the thermal storage mass is provided above a metallic roof of the building instead of a wall.

A flat–plate collector is used to supply heat to the generator and water vapours are raised at a temperature lower than 100°C at low pressure. These vapours are condensed in a condenser by cooling water supplied from a cooling tower. The condensed water is evaporated by passing it through the expansion valve and maintaining lower pressure in the evaporator. A cooling effect is produced here and heat is absorbed from the space to be cooled through the heat-transport fluid. The water vapours from the evaporator go to the absorber where they are absorbed in lithium bromide solution. In the absorber, the liberated heat due to the absorption process is removed by cooling water from the cooling tower. The generator temperature is maintained between 75–100°C to avoid crystallization of lithium bromide, which may lead to choking of the system. The main advantages of the lithium bromide–water cooling cycle are (i) the system is comparatively simpler, (ii) it works at a comparatively higher COP, (iii) less pumping power is required due to low pressure, (iii) the refrigerant, i.e., water has high latent heat of vaporization, (iv) lithium bromide absorbent is non-volatile and therefore, avoids the need of rectifying equipment which is necessary in an ammonia–water cycle, (v) water–lithium bromide solution is non-toxic, and (vi) non-inflammable. It also has some disadvantages, such as (i) it can be used for air-conditioning only (temperatures not lower than 4°C), (ii) the LiBr–water solution is corrosive, (iii) the system works under high vacuum conditions, and (iv) it requires a water-cooled condenser to attain temperatures corresponding to air conditioning, as the refrigerant is water.

5.5.2 Aqua–Ammonia Absorption Cooling System

The Aqua–ammonia absorption system is similar to the LiBr–water absorption system explained above. It also has all the basic building blocks as shown for LiBr–water system but the operating pressures and temperatures are quite different. It can produce cooling up to –5°C and therefore, is suitable for refrigeration too. A rectifier and an analyzer is added after the generator to check and stop water vapour from reaching the evaporator, otherwise it will freeze in the evaporator and may choke the system. The required temperature in the generator is around 120°C if the condenser and absorber are water-cooled. In case of an air-cooled condenser and absorber, the required operating temperature of the generator may be as high as 180°C. This is too high for a simple flat-plate collector to attain and a concentrating collector may be required. In the equilibrium state, the approximate pressures and temperatures maintained in four major components of the system is given in Table 5.2.

Table 5.2 *Temperatures and pressures in various components of aqua–ammonia system*

S N	*Name of component*	*Pressure (atm.)*	*Temperature (°C)*
1.	Generator	10	120
2.	Condenser	10	40
3.	Evaporator	1	–5
4.	Absorber	1	40

The main advantages of the aqua–ammonia absorption system are (i) it can provide both air conditioning and refrigeration, (ii) the refrigerant has low molecular weight and therefore, a high heat of vaporization, and (iii) the absorbent (water) is non-toxic and inexpensive. The disadvantages are (i) as the absorbent (water) is volatile, a rectifier unit is required to separate and drain it out, (ii) a comparatively high pumping power is required to pump working fluid from absorber pressure to the generator pressure, and (iii) ammonia is inflammable and toxic. Therefore, special precautions are required in its use.

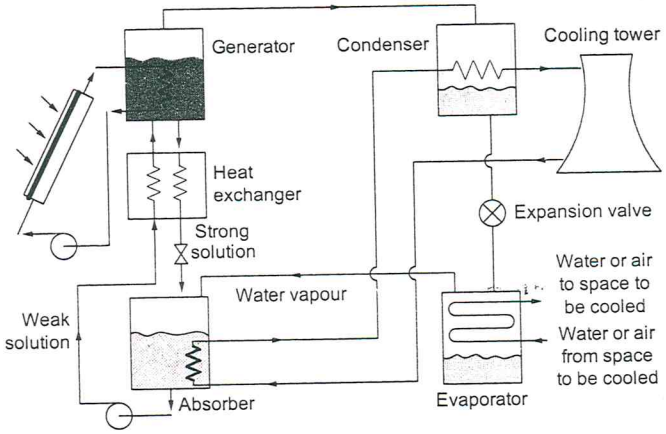


Fig. 5.26 *LiBr–H_2O absorption cooling system*

5.6 SOLAR COOKERS

Thermal energy requirements for cooking purpose forms a major share of the total energy consumed, especially in rural areas. A variety of fuels like coal, kerosene, cooking gas, firewood, dung cakes and agricultural wastes are used to meet the requirements. Fossil fuel is a fast-depleting resource and needs to be conserved. Firewood for cooking causes deforestation and cow dung, agricultural waste, etc., may be better used as good fertilizers. Harnessing solar energy for cooking purposes is an attractive and relevant option. A variety of solar cookers have been developed, which can be clubbed in four types of basic designs: (i) box type solar cooker, (ii) dish-type solar cooker, (iii) community solar cooker, and (iv) advanced solar cooker.

5.6.1 Box-Type Solar Cooker

The construction of the most common box-type solar cooker is schematically shown in Fig. 5.27. The external dimensions of a typical family-size (4 dishes) box-type cooker are 60 cm × 60 cm × 20 cm. This cooker is simple in construction and operation. An insulated box of blackened aluminum contains the utensils filled with food material. The box receives direct radiation and also reflected radiation from a reflector mirror fixed on the inner side of the box cover hinged to one

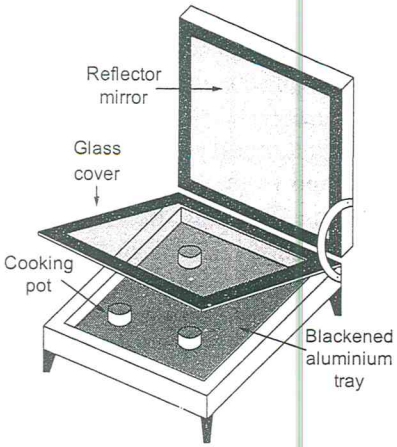


Fig. 5.27 *Box-type solar cooker*

side of the box. The angle of the reflector can be adjusted as required. A glass cover consisting of two layers of clear-window glass sheets serves as the box door. The glass cover traps heat due to greenhouse effect. The maximum air temperature obtained inside the box is around 140–160°C. This is enough for cooking boiling-type food-stuffs slowly in about 2–3 hours. It is capable of cooking 2 kg of food and can save up to 3–4 LPG cylinder fuel in a year. Electrical backup is also provided in some designs for use during non-sunshine hours. Its cost varies from Rs 1,800 to Rs 2,800 (year 2008) depending on the type, size, quality and electrical backup facility. A more affordable, folding-type model of solar cooker made of cardboard material has also been developed.

5.6.2 Paraboloidal Dish-type (Direct Type) Solar Cooker

A specially designed paraboloidal reflector surface concentrates the beam radiation at its focus, where a cylindrical brass vessel containing food material is placed. A commercial dish-type solar cooker, SK 14, developed by EG solar, an NGO of Germany, and being manufactured in India is shown in Fig. 5.28. The vessel directly receives the concentrated solar radiation. The reflector is periodically adjusted to track the sun. A fairly high temperature of about 450°C can be obtained and a variety of food requiring boiling, baking and frying can be cooked for 10–15 persons. It can save on fuel for up to 10 LPG cylinders annually on full use. The cooking time is approximately 20–30 minutes. The approximate cost of the cooker is Rs 8,500 (year 2008).

Fig. 5.28 *Paraboloidal dish-type solar cooker Source: MNES Annual Report*

5.6.3 Community Solar Cooker

Community solar cookers have been developed for indoor cooking. A community solar cooker has a large automatically tracked paraboloidal reflector standing outside the kitchen. The reflector reflects the sun's rays into the kitchen through an opening in its north wall. A secondary reflector further concentrates the rays on to the bottom of the cooking pot, which is painted black. It can cook all types of food for about 40–50 people and can save up to 30 LPG cylinders in a year with optimum use.

In another design of a community solar cooker, large number of automatically tracked paraboloidal reflectors are installed in series and parallel combinations and generate steam for cooking in a community kitchen. It can cook food for thousands of people in a short time depending upon its capacity. It is normally installed in conjunction with a boiler that may also use conventional fuel when necessary.

5.6.4 Advanced Solar Cooker

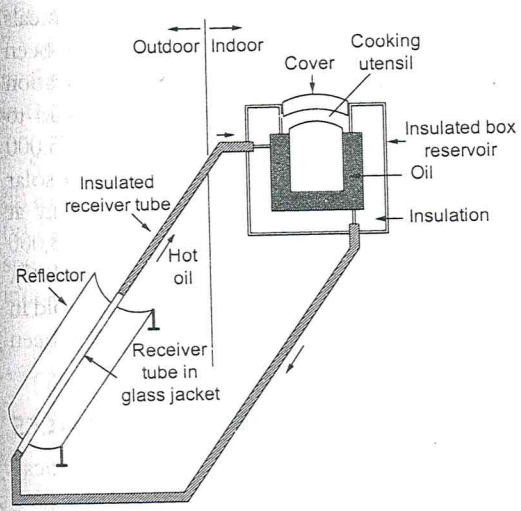


Fig. 5.29 *Advanced solar cooker*

The main disadvantage of the above cookers is that there is no provision for storing thermal energy; hence, cooking is possible only when the sun is available (unless an auxiliary source is also available). An advanced type cooker has been designed to overcome these difficulties. The cooker is schematically shown in Fig. 5.29. Basically, it consists of two parts: (i) an outdoor, parabolic cylindrical reflector of a size, typically 3 m× 2 m × 0.5 m, and (ii) an indoor, insulated hot-box reservoir of a size typically 0.4 m× 0.4 m × 1.2 m, kept at a level higher than the collector. Oil is used as a heat-transport fluid from the collector to hot-box reservoir. The oil in the receiver tube rises up due to natural convection after absorbing heat from the reflector and stores it in the reservoir. The reflector has an equatorial mounting with adjustments for seasonal variation of the sun or an arrangement for automatic solar tracking using a simple clock mechanism. The temperature at the top of the reservoir on sunny days reaches 150°C and rarely falls below 100°C even during nights. All types of cooking, except those which require frying and roasting, can be done with this cooker. Some other variations in the basic design such as use of a large hemispherical

bowl-type collector, use of a heat exchanger to raise steam from heated oil for steam cooking are also possible. Such types of solar cookers are especially useful as large-size community cookers for military camps, temples, ashrams, gurdwaras and hostels.

There are four principal ways of cooking: (i) boiling, (ii) baking, (iii) frying, and (iv) roasting. Box-type cookers are suitable for boiling and baking. Paraboloidal dish-type cookers are suitable for boiling, baking and frying as higher temperatures are achieved. Advanced type cookers can perform boiling and baking only but have the advantage of thermal storage and indoor use. The major reasons for non-acceptability of a solar cooker are: (i) it is too expensive for individual family ownership, (ii) it is incompatible with traditional cooking practices, (iii) it requires comparatively more time and the menu has to be preplanned, (iv) it is to be used outdoors (except community and advance cookers), and (v) cannot be used during nights and cloudy days (except advanced cooker).

A 15-m diameter community solar cooker has been developed at the Centre for Scientific Research (CSR), Auroville (Pondicherry). Around 600 kg of steam per day could be generated from this bowl, which is sufficient to cook two meals for about 1000 people. A very large community solar cooker has recently been installed at Tirumala Tirupathi Devasthanam at AP, under the demonstration scheme of the Ministry of Non-conventional Energy Sources. This is said to be the largest solar cooker in the world and is used for cooking food for 15,000 devotees daily. It has 106 automatic solar-concentration collectors (Scheffler solar concentrator), each of 9.2 sq. m diameter, produce 4000 kg of steam daily at 180°C and 10 kg/cm^2 for steam cooking. The system is expected to save 1,18,000 litres of diesel annually. The total cost of the system is Rs 110 lakhs (year 2003). So far about 5,55,000 box-type and 2000 dish-type solar cookers have been sold in the country. About 100 community solar cookers with steam cooking have been installed in the country.

5.7 SOLAR FURNACES

A solar furnace is an ideal tool to study the chemical, optical, electrical and thermodynamic properties of the materials at high temperatures. It is basically an optical system in which solar radiations are concentrated over a small area. It has two main components: (i) a concentrator, and (ii) a single piece of a large-sized heliostat or a system of a large number of small heliostats. The basic principle is shown in Fig 5.30. The large number of heliostats direct solar radiation onto a paraboloidal reflector surface. The heliostats are adjusted such that they direct the radiation parallel to the optical axis of the paraboloid. Accurate sun tracking is required for this purpose. The concentrators focus the incoming rays at the target placed at their focii.

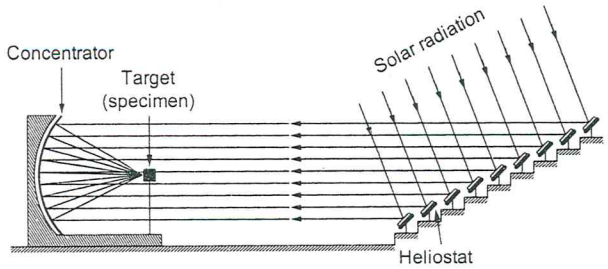


Fig. 5.30 *Solar furnace*

There is another possible configuration of a solar furnace, where the optical axis is vertical. A large heliostat directs the radiation upwards and the concentrator reflects it downward at its focus. In this arrangement, the unmelted portion of a specimen forms a crucible to hold the melted portion and is suitable for fusion studies.

There are few solar furnaces in countries like France, USA, Germany and Russia for scientific study. One of the world's largest solar furnace of 1000 kW output was installed at Odeillo, Font–Romeo, France in 1970. It has 63 heliostats, each 7.5 m × 6 m in size. The parboloidal concentrator is 40 m high, 54 m wide and 13 m above the ground level with a focal length of 18 m. Temperatures obtained are in the range of about 3,500°C.

Some of the advantages of a solar furnace are (i) heating without contamination, (ii) easy control of temperature, (iii) simple working, (iv) high heat flux obtainable, (v) continuous observation possible, and (vi) absence of electromagnetic field. In spite of the many advantages of solar furnaces, these have not become popular in industries due to the following reasons:

(i) Their use is limited to sunny days and that too for 4–5 hours only.
(ii) Their cost is high.
(iii) Very high temperatures are obtained only over a very small area.

5.8 SOLAR GREENHOUSE

A greenhouse is an enclosure where proper environment is provided for growth and production of crops, vegetable and flower plants under adverse climatic conditions. By controlling the environment, a particular vegetable or flower can be grown throughout the year. The design of a greenhouse depends on local climatic conditions. In cold countries, winter greenhouses provide supplementary heat to maintain adequate temperature during the cold months when solar insolation is low. In tropical countries, the solar insolation and ambient temperatures are quite high and therefore summer greenhouses are used to maintain low temperatures inside and allow just sufficient sunlight for photosynthesis. Greenhouses for arid zones are designed to conserve water resources. Although, there is slight variation in the environmental needs of each variety of plant for best production, basically

direct use of solar energy. The customary way is to spread the material to be dried in a thin layer on the ground. The disadvantages associated with this method are (i) the process is slow, (ii) the product is vulnerable to attack by insects, and (iii) dust gets mixed with the product. The use of a solar dryer helps eliminate these disadvantages. Also, the drying may be made a faster and controlled process, and a better-quality product can be produced.

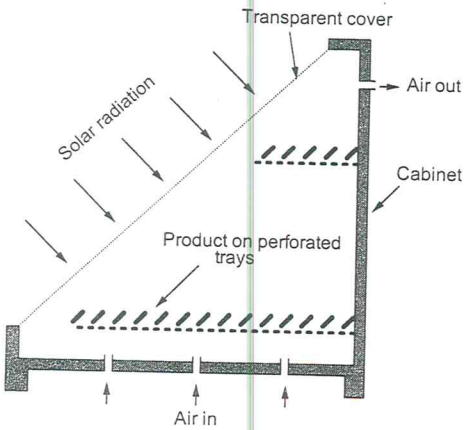


Fig. 5.34 *Solar cabinet dryer*

A simple cabinet-type solar dryer is shown in Fig. 5.34. It is an enclosure with a transparent cover, similar to a greenhouse. The material to be dried is placed on perforated trays. Solar radiation enters the enclosure and is absorbed by the product as well as the surrounding internal surfaces of the enclosure, increasing its temperature. The inside air heats up to a temperature ranging from 50 to 80°C, and rises above. Natural circulation of air is ensured by providing suitable openings at the bottom and top. The circulating air removes the moisture from the product.

For large-scale drying, forced circulation of air may be used by employing a blower. In case of green lumber, where direct exposure to the sun tends to produce curling and wrapping or for products where direct sunlight is not adequate, controlled temperature drying known as *kiln drying* may be used. Here, the air is heated separately in an array of solar air heaters and then ducted to the chamber where the product to be dried is stored. Such dryers are also suitable for foodgrains and products like tea and tobacco.

5.10 SOLAR DISTILLATION (OR DESALINATION OF WATER)

Potable or fresh water (water with less than 500 ppm salt content) is one of the fundamental necessities of life for humans. Industries and agriculture also require fresh water without which they cannot thrive. Humankind has been dependent on rivers, lakes and underground water reservoirs to fulfill his need of fresh water, an act that is intimately associated with the evolution of civilization. Because of rapid industrialization and the population explosion, the demand of fresh water has increased enormously. With the rise in the standard of living, the average per capita consumption of water has also increased. Due to climate changes and less rainfall in many parts of the world, fresh water, which was available in abundance from rivers, lakes and ponds, is becoming scarce. Also,

the available resources are getting polluted due to discharge of industrial effluents and sewage in large quantities. Thus, due to climate change, pollution and over-consumption, at present more than 2000 million people have no regular access to adequate safe water. In some villages, people travel up to 30 km to collect fresh water. According to one estimate, about 79 per cent of water available on the earth is salty, 20 per cent is brackish (less salty water from wells) and only one per cent is fresh. Therefore, conversion of brackish or saline water to fresh water through the distillation process using solar energy is a good idea where plenty of saline water and sun are available.

The use of solar energy for desalting sea water and brackish well water has been demonstrated in several moderate-sized pilot plants in the United States, Greece, Australia and several other countries. The idea was first applied in 1872 at Las Salinas, Chile, in a plant supplying drinking water for animals working in nitrate-mining areas and for transport. The conversion device is known as *solar still*. Modern developments in solar distillation have been directed to the use of materials and designs for economic and durable construction with increased output, in order to reduce the product cost. Several types of solar stills have evolved. However, only the basin-type has been tried commercially on a large scale.

A simple basin-type solar still consists of a shallow blackened basin filled with saline or brackish water to be distilled. The depth of water is kept about 5–10 cm. It is covered with a slopey transparent roof. Solar radiation, after passing through the roof, is absorbed by the blackened surface of the basin and thus increases the temperature of water. The evaporated water increases the moisture content, which gets condensed on the cooler underneath the glass. The condensed water slips down the slope and is collected through the condensate channel attached to the glass. The construction is schematically shown in Fig. 5.35.

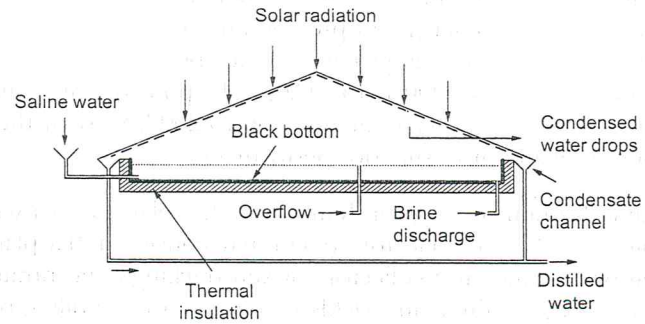


Fig. 5.35 *Simple basin-type solar still*

The still is erected in an open area with its long axis facing the East–West direction. The still can be fed with saline water either continuously or intermittently. The supply is generally kept at twice the rate at which the fresh water is produced but may vary depending on the initial salinity of input water. The output of

a typical solar still in Indian climate varies from 5.3 l/m² day (in summer) to 0.9l/m² day (in winter).

5.11 SOLAR THERMO-MECHANICAL SYSTEMS

It is possible to convert solar thermal energy to mechanical energy through heat engines using Rankine cycle, Stirling cycle or Brayton cycle. The mechanical energy thus produced may be used for applications requiring shaft power such as water lifting, cooling (through vapour compression method), etc., or may be converted to electrical energy using an alternator. Effective conversion of solar thermal energy to mechanical energy is associated with many limitations. Some of them are as follows:

1. The efficiency of a collector system decreases as the collection temperature increases while the efficiency of a heat engine increases as the working fluid temperature increases.
2. The conversion efficiency is low (about 9 to 18 per cent).
3. A part of thermal energy is lost during the transportation of the working fluid from the collector to the heat engine.
4. Solar collectors are generally more expensive than engines.
5. A very large area is required to install the solar-collector system.
6. Due to the intermittent nature of solar energy, storage of thermal energy is also required, which has its own problems like degradation of storage material with time.

5.11.1 Solar Thermal Water Pump

Some features of solar energy make its utilization attractive for irrigation water pumping. These are (i) more irrigation water is required in summer when solar energy is available most, (ii) intermittent pumping is tolerable and can serve the purpose, and (iii) surplus energy can provide pumped storage in the form of a pond. Several solar irrigation pumps have recently been tested in many countries. While in the lower range (i.e., 200 W to 5 kW), solar photovoltaic pumps are more successful, in higher ratings (i.e., in range 1 kW to 200 kW) solar thermal pumps become economical and offer superior performance.

A schematic diagram of a typical Rankine cycle, solar thermal water pump is shown in Fig. 5.36. A solar-collector system may consist of flat plate-collectors, non-focusing type (stationary) collectors or sun-tracking concentrators. Water is used as a heat-transport fluid, and yields its heat to a low-boiling point organic working fluid (such as Freon R113, R12, isobutane etc.) in a heat exchanger. Surplus heat is stored in the thermal storage to be used later when the sun is not available. The high-pressure vapours of the working fluid expand in the turbine, condense in the condenser and return in the heat exchanger (boiler). A part of the irrigation-pumped water is diverted through the condenser for cooling purposes.

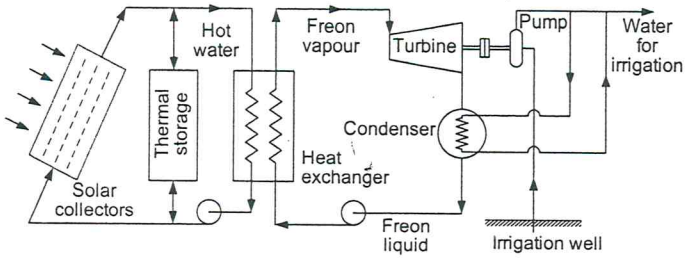


Fig. 5.36 *Solar thermal water pump*

5.11.2 Solar Vapour Compression Refrigeration

A cooling system based on the vapour-compression principle has the advantage that the system, apart from cooling, can also be used in a heat-pump mode. In the cooling mode, the system absorbs heat from space to be cooled and delivers it to the ambient, which is at a higher temperature, whereas, in a heat-pump mode. the system absorbs heat from the ambient and delivers it to a space, which is at a higher temperature. A solar-power based vapour compressor cooling system is shown in Fig. 5.37.

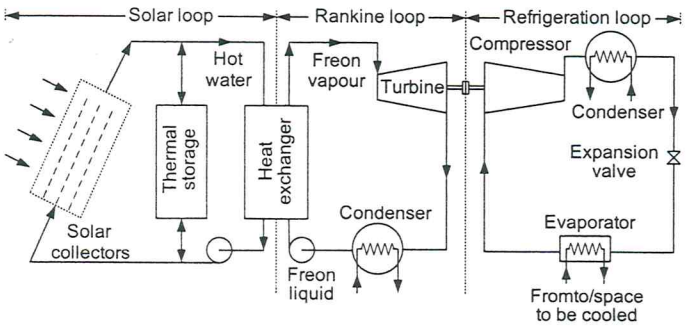
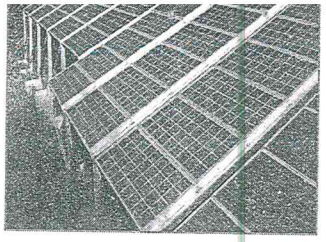


Fig. 5.37 *Solar-vapour compression refrigeration system*

Here, solar power is first converted to mechanical power in the same way as explained above. The shaft power thus produced drives the compressor of a conventional vapour compression refrigerator. A suitable refrigerant vapour is compressed and then condensed to a liquid, rejecting heat to the ambient. Now, the pressure is reduced by passing it through an expansion valve where it gets evaporated at low pressure, producing a cooling effect. Thus, the refrigerant absorbs heat in the evaporator, from the space to be cooled and rejects it in the condenser.

5.11.3 Solar-Pond Electric-Power Plant

A solar-pond electric power plant is shown in Fig. 5.38. A non-convective solar pond serves the purpose of a large flat-plate collector as well as a long-term thermal storage and can provide sufficient heat for the entire year. The



6 Solar Photovoltaic Systems

Introduction

Solar photovoltaic (PV) systems convert solar energy directly into electrical energy. The basic conversion device used is known as a solar photovoltaic cell or a solar cell. Although other light sources may also produce photovoltaic electricity, only sunlight-based PV cells are considered in this chapter. A solar cell is basically an electrical current source, driven by a flux of radiation. Solar cells were first produced in 1954 and were rapidly developed to provide power for space satellites based on semiconductor electronics technology. Its terrestrial applications were considered seriously only after the oil crisis of 1973 when a real need of alternative energy sources was felt globally for the first time. Efficient power utilization depends not only on efficient generation in the cell, but also on the dynamic load matching in the external circuit.

A solar cell is the most expensive component in a solar PV system (about 60% of the total system cost) though its cost is falling slowly. Commercial photocells may have efficiencies in the range of 10–20% and can produce electrical energy of 1–2 kWh per sq. m per day in ordinary sunshine. Typically, it produces a potential difference of about 0.5 V and a current density of about 200 A per sq. m of cell area in full solar radiation of 1 kW per sq. m. A typical commercial cell of 100 sq. cm area, thus produces a current of 2 A. It has a lifespan in excess of about 20 years. As a PV system has no moving parts, it gives almost maintenance-free service for long periods and can be used unattended at inaccessible locations.

The major uses of photovoltaics have been in space satellites, remote radio-communication booster stations and marine warning lights. These are also increasingly being used for lighting, water pumping and medical refrigeration in remote areas especially in developing countries. Solar-powered vehicles and battery charging are some of the recent interesting applications of solar PV power.

The major advantages of solar PV systems over conventional power systems are given here:

(i) It converts solar energy directly into electrical energy without going through the thermal–mechanical link. It has no moving parts.
(ii) Solar PV systems are reliable, modular, durable and generally maintenance-free.
(iii) These systems are quiet, compatible with almost all environments, respond instantaneously to solar radiation and have an expected lifespan of 20 years or more.
(iv) A solar PV system can be located at the place of use and hence no or minimum distribution network is required, as it is universally available.

It also suffers from some disadvantages such as given here:

(i) At present, the costs of solar cells are high, making them economically uncompetitive with other conventional power sources.
(ii) The efficiency of solar cells is low. As solar radiation density is also low, a large area of solar cell modules are required to generate sufficient useful power.
(iii) As solar energy is intermittent, some kind of electrical energy storage is required, which makes the whole system more expensive.

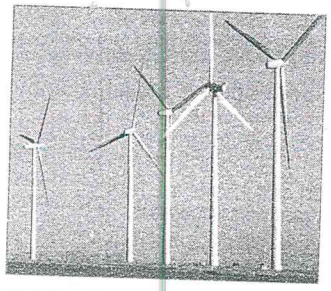
6.1 SOLAR CELL FUNDAMENTALS

6.1.1 Semiconductors

The best conductors (silver, copper and gold) have one valence electron, whereas the best insulators have eight valence electrons. A semiconductor is an element with electrical properties between those of a conductor and an insulator and therefore best semiconductors (Si and Ge) have four valence electrons. Various favourable characteristics of Si have made it the semiconductor of choice. It is the most abundant element on earth after oxygen. However, the refining process is costly. An isolated silicon atom has 14 protons and 14 electrons. The outermost orbit (valence orbit) contains four electrons. When silicon atoms combine to form a solid, they arrange themselves into an orderly pattern called a *crystal*. Each silicon atom shares its electrons with four neighbouring atoms in such a way as to have eight electrons in its valence orbit. Thus, each pair of electrons belongs to two neighbouring atoms and is attracted by them with equal and opposite forces, which keeps them bonded together. Such a chemical bond is known as a *covalent bond*. This covalent bond holds the crystal together and gives it solidity.

At absolute zero temperature, a semiconductor is a perfect insulator with no charge carriers available for conduction of current. However, when temperature is increased, the vibration of atoms can occasionally dislodge an electron from the valence orbit. The dislodged electron is known as a *free electron* and the vacancy thus created in the valence orbit is known as a *hole*. Thus, with breaking of a covalent bond a free electron-hole pair is produced. At room temperature, thermal energy produces only few electron-hole pairs. Electron-hole pairs can also be produced by imparting energy by some other means such as light (photons). In a pure silicon crystal, thermal energy creates an equal number of free electrons and holes. The free electrons move randomly throughout the crystal. Occasionally, a free electron will approach a hole, feel its attraction, and fall into it. This merging of free electrons and a hole is known as *recombination*. The amount of time between creation and disappearance (due to recombination) of an electron-hole pair is called *lifetime*. It varies from a few nanoseconds to several microseconds, depending on how perfect the crystal is and also some other factors. At any instant, the following conditions exists within the Si crystal:

(i) Some free electron-holes are being created.
(ii) Some free electron-holes are being recombined.
(iii) Some free electron and holes exist temporarily, awaiting recombination.



7 Wind Energy

Introduction

Wind energy is the kinetic energy associated with movement of large masses of air. These motions result from uneven heating of the atmosphere by the sun, creating temperature, density and pressure differences. It is estimated that 1 per cent of all solar radiation falling on the face of the earth is converted into kinetic energy of the atmosphere, 30 per cent of which occurs in the lowest 1000 m of elevation. It is thus an indirect form of solar energy. In contrast to diurnal availability of direct solar radiation, wind energy can be available continuously throughout a 24-hour day for much longer periods, though it can vary a great extent including no wind periods. It is a clean, cheap, and eco-friendly renewable source. The main disadvantages are that it is a dispersed, erratic and location-specific source. Wind energy is harnessed as mechanical energy with the help of a wind turbine. The mechanical energy thus obtained can either be used as such to operate farm appliances, and water pumping or converted to electric power and used locally or fed to a grid. A generator coupled to a wind turbine is known as *aero-generator*. Very slow winds are useless, having no possibility of power generation. On the other hand, very strong stormy winds cannot be utilized due to safety of turbine. Moderate to high-speed winds, typically from 5 m/s to about 25 m/s are considered favourable for most wind turbines. The global potential in winds for large-scale grid-connected power generation has been estimated as 9,000 TWh/year or 1 TW_e ($1T = 10^{12}$). It is also estimated that favourable winds for small-scale applications such as wind pumps, battery chargers, heaters, etc., are available on about 50% of the earth's surface which means that small-scale wind turbines can be practical in many parts of the world.

The idea of harnessing winds is not new. It was one of the first natural energy sources to be used by mankind. There are indications that windmills were used in Babylon and China around 2000 to 1700 BC to pump water and grind grains. Egyptians used wind power to sail ships in the Nile some 5000 years ago. It has traditionally been used worldwide for ship propulsion until the start of the industrial era. In Persia and Afghanistan, windmills were used around the 7th century AD for grinding grains. Europeans imported the technology from the east and were probably the first to introduce the horizontal axis windmill around the 12th century, and by 1750, Holland had 8,000 windmills and England had 10,000. Their use however, declined after the introduction of James Watt's steam engine in the late 18th century and further declined in the 20th century as a result of availability of cheap, reliable fossil fuels and hydro power. The electric power generation through wind was first proposed in Denmark in 1890 and many aero-generators were built in Europe and elsewhere.

The interest in wind energy has renewed after the oil crisis of 1973. Most modern, large-scale wind-energy systems have been built after 1980 using modern engineering designs, materials and incorporating microelectronics monitoring and control. Several demonstration and commercial plants of different sizes, from few kW to few MW are in operation in different parts of the world. Improved turbine designs and plant utilization have contributed to

reduction of a large-scale wind energy generation cost from Rs 17.00 per kWh in 1980 to about Rs 2.50 per kWh at present, at favourable locations. With modern blade materials, the expected life of a wind turbine has exceeded 20 years. The installation cost has come down to a level comparable to that of a conventional thermal plant, i.e., about Rs 4.00 crore/MW. The energy payback period of a wind turbine is about one year. Due to these reasons, wind energy is gaining increasing acceptance and competing with conventional power sources. It is the fastest-growing energy source among all renewables in recent years. UK is building 15 huge offshore wind farms, to provide most of the added electricity England will need in the coming two decades.

The global installed capacity by end of the year 2007 had reached 94,123 MW which is 1% of the global electricity production. During year 2007 alone, the installed capacity has grown by 27%. An addition of 7500 MW is expected during 2008. The global growth pattern of wind energy is shown in Fig. 7.1 [44].

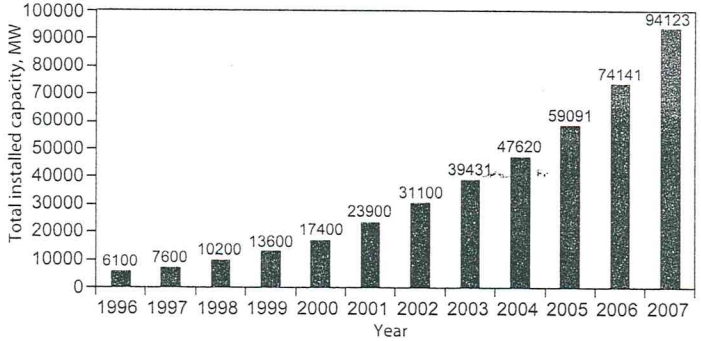


Fig. 7.1 *Global growth pattern of wind energy*

Globally, wind energy has become a mainstream energy source and an important player in the world's energy markets, and it now contributes to the energy mix in more than 70 countries across the globe. Germany is, at present (year 2008), the world leader in the installed capacity followed by USA, though the annual wind-energy generation in USA is more due to strong winds. USA is expected to overtake Germany by 2009 in respect of installed capacity also. By year 2030, 20% of the electricity may be provided through wind generation in USA. The (year 2007) total installed capacity of the top ten countries is tabulated in Table 7.1 [44]. India ranks fourth in respect of installed capacity.

Table 7.1 *Wind-power installed capacity of top ten countries (2007 end)*[44]

S. No.	*Country*	*Installed Capacity (MW)*	*%age*	
1.	Germany	22,247	23.6	Total top ten (86.2%)
2.	USA	16,818	17.9	
3.	Spain	15,145	16.1	
4.	India	8,000	8.5	
5.	China	6,050	6.4	
6.	Denmark	3,125	3.3	
7.	Italy	2,726	2.9	
8.	France	2,454	2.6	

these periods. Also no generation is possible if wind speed is very high, i.e., 25 m/s and above. The best sites are those where favourable winds (with speeds 5–25 m/s) are available for most of the time (typically 70 to 80 per cent of the time).

7.3 WIND TURBINE SITING

The power available in wind increases rapidly with wind speed. Therefore, the main consideration for locating a wind-power generation plant is the availability of strong and persistent wind. A suitable site should preferably have some of the following features:

1. No tall obstructions for some distance (about 3 km) in the upwind direction (i.e., the direction of incoming wind) and also as low a roughness as possible in the same direction
2. A wide and open view i.e., open plain, open shoreline or offshore locations
3. Top of smooth well-rounded hill with gentle slopes (about 1:3 or less) on a flat plain
4. An island in a lake or the sea
5. A narrow mountain gap through which wind is channelled
6. Site reasonably close to power grid
7. Soil conditions must be such that building of foundations of the turbines and transport of road-construction materials loaded in heavy trucks is feasible.
8. Production results of existing wind turbines in the area to act as a guide to local wind conditions.

7.4 MAJOR APPLICATIONS OF WIND POWER

Wind turbines have been built-in power output range from a kilowatt to a few MW to suit a wide range of applications. Major applications may be grouped in three categories.

1. Applications Requiring Mechanical Power

(i) Wind Pumps Low-power turbines are used for producing mechanical power for pumping water in remote areas. These are also known as wind pumps. Simple and reliable traditional reciprocating pumps or centrifugal pumps are used. These wind pumps are used to supply water for livestock, small-scale irrigation, low head pumping for aquatic breeding and domestic water supply. Mechanical power is also used to operate farm appliances.

(ii) Heating The direct dissipation of mechanical power produces heat with 100% efficiency using a paddle wheel and other turbulent fluid systems. The available hot water is used as such or employed for space heating.

(iii) Sea Transport The old square-rigged sailing ships were inefficient as they were operated by drag forces (to be discussed later). Modern racing yachts, with a subsurface keel, harness lift forces and are much more efficient and can sail faster than the wind. Large cargo ships requiring power in MW range, driven by improved efficient sails, are now being designed. Also, wind turbines are installed onboard to power propellers in ferries operating on short routes.

2. As Off-Grid Electrical Power Source

(i) Machines of low power with a rotor diameter of about 3 m and 40–1000 W rating can generate sufficient electrical energy for space heating and cooling of homes, water heating, battery charging and for operating domestic appliances such as fan, lights and small tools.

(ii) Applications for somewhat more powerful turbines of about 50 kW are producing electrical power for navigation signal (e.g., lighthouse), remote communication, weather stations and offshore oil-drilling platforms.

(iii) Intermediate power range, roughly 100 to 250 kW aero-generators can supply power to isolated populations, farm cooperatives, commercial refrigeration, desalination and to other small industries. The generator may operate in stand-alone mode or may be connected to a mini-grid system.

(iv) For lifting water to a hill, aero-generator is installed on the top of hill and electrical energy is transmitted to a pump fixed at a lower level. The same principle is utilized to store excess generated power using a pumped storage system to be utilized later during no wind periods.

3. As Grid-Connected Electrical Power Source

Large aero-generators in the range of a few hundred kW to a few MW are planned for supplying power to a utility grid. Large arrays of aero-generators, known as *wind farms,* are being deployed in open plains or offshore in shallow water for this purpose.

7.5 BASICS OF FLUID MECHANICS

7.5.1 Terms and Definitions

Fig. 7.7 shows the position of a rotor blade and various forces acting over it along with the various components of speed, for the purpose of illustration and to show correlation among these factors.

Blade Element Incremental cross section of the rotor blade as shown in Fig. 7.7 (a).

Width of the blade or distance from one edge of the blade to the other (i.e., length of blade element as shown in Fig. 7.7 (b)).

Wind Velocity, u_o Velocity of free air in the neighborhood of a wind turbine (at a distance where the disturbances due to the rotation of a turbine does not reach).

designed as to crudely maintain the speed as constant. Such a machine is known as *stall regulated*. This is a simple system requiring only passive technique, as there are no moving blade surfaces or complicated hardware. However, power capture is somewhat less due to rounding of power curve.

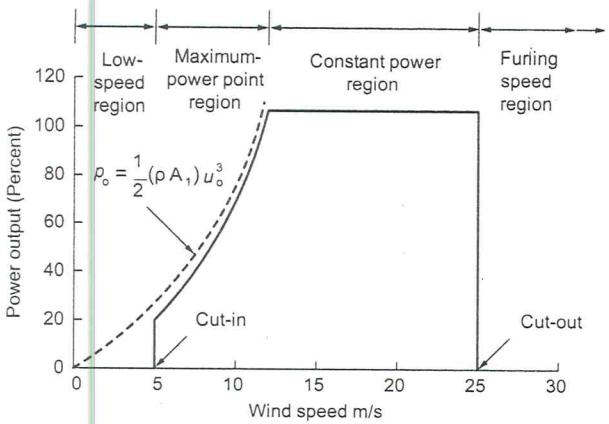


Fig. 7.21 *Power versus wind speed characteristics*

In case of fixed-blade rotor, the flow over the blade stalls. The stall performance depends on the twist of the blade tip from the root and thickness of blade sections. The lift and drag coefficients change so as to flatten out the peak of the power curve. Thus, the power output of the wind turbine is limited as shown in Fig. 7.22. Stall regulation can be used without much problem up to about a 25-m diameter rotor. Above this size, severe vibration problems associated with the stalled flow in high wind speeds, have been encountered. Thus, large HAWTs always have variable pitch control.

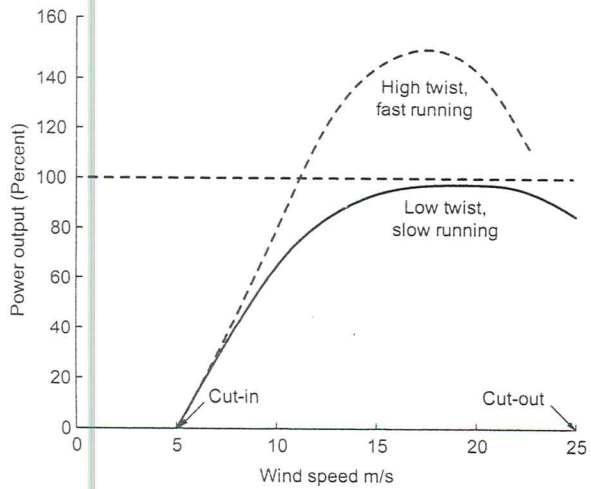


Fig. 7.22 *Power versus wind-speed characteristics with stall regulation*

At still higher wind speeds, such as gusts, constant speed operation is maintained by employing additional means such as some kind of braking (e.g., eddy current braking).

(iv) *Furling Speed Region (Cut-out Speed and Above)* Beyond a certain maximum value of wind speed (around 25 m/s), the rotor is shut down and power generation is stopped to protect the blades, generator and other components of the system.

7.8 WIND ENERGY CONVERSION SYSTEMS (WECS)

A wind-energy conversion system converts wind energy into some form of electrical energy. In particular, medium and large scale WECS are designed to operate in parallel with a public or local ac grid. This is known as a *grid-connected system*. A small system, isolated from the grid, feeding only to a local load is known as *autonomous*, remote, decentralized, stand-alone or isolated power system. A general block diagram of a grid-connected WECS is shown in Fig. 7.23. The turbine shaft speed is stepped up with the help of gears, with a fixed gear ratio, to suit the electrical generator and fine-tuning of speed is incorporated by pitch control. This block acts as a drive for the generator. Use of variable gear ratio has been considered in the past and was found to add more problems than benefits. Hence dc, synchronous or induction generators are used for mechanical to electrical power conversion depending on the design of the system. The interface conditions the generated power to grid-quality power. It may consist of a power electronic converter, transformer and filter, etc. The control unit monitors and controls the interaction among various blocks. It derives the reference voltage and frequency signals from the grid and receives wind speed, wind direction, wind turbine speed signals, etc., processes them and accordingly controls various blocks for optimal energy balance.

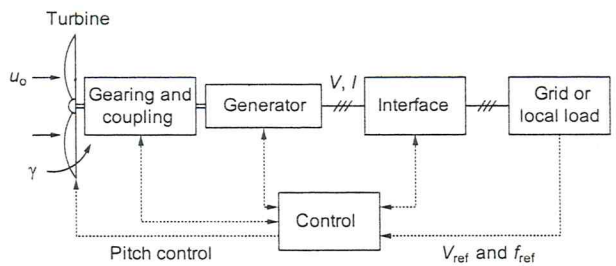


Fig. 7.23 *General block diagram of a WECS*

The main features of various types of generators and their suitability in wind power generation are discussed below:

(i) *DC Generator* Conventional dc generators are not favoured due to their high cost, weight and maintenance problems of the commutator. However, permanent-magnet (brushless and commutator-less) dc machines are considered in small-rating (below hundred kW) isolated systems.

A3

(ii) *Synchronous* Generator Synchronous generators produce high-quality output and are universally used for power generation in conventional plants. However, they have very rigid requirement of maintaining constant shaft speed and any deviation from synchronous value immediately reflects in the generated frequency. Also, precise rotor speed control is required for synchronization. Due to this reason, a synchronous machine is not well suited to wind power generation. Requirement of dc current to excite rotor field, which needs sliding carbon brushes on the slip rings also poses limitations on its use. The need of a dc field current and brushes can be eliminated by using reluctance rotor. The reliability is greatly improved while reducing the cost. The machine rating, however, is limited to tens of kW. Synchronization of a wind-driven generator with the power grid also poses problems especially during gusty winds. The main advantage is that it generates both active as well as reactive powers.

(iii) *Induction Generator* The primary advantages of an induction machine are the rugged, brushless construction, no need of separate dc field power and tolerance of slight variation of shaft speed (±10%) as these variations are absorbed in the slip. Compared to dc and synchronous machines, they have low capital cost, low maintenance and better transient performance. For these reasons, induction generators are extensively used in wind and micro-hydroelectric plants. The machine is available from very low to several megawatt ratings.

The induction machine requires ac excitation current, which is mainly reactive. In case of a grid-connected system, the excitation current is drawn from the grid and therefore, the network must be capable of supplying this reactive power. The voltage and frequency are determined by the grid. In a standalone system, the induction generator is self-excited by shunt capacitors.

Based on the generator drive, two schemes have been developed for the operation of WECS: (i) fixed speed drive scheme, and (ii) variable speed drive scheme.

7.8.1 Fixed-Speed Drive Scheme

In this scheme, constant speed is maintained at the shaft of a generator by pitch control. A synchronous or induction generator is used to generate electrical energy. Induction generators are gaining more acceptability due to their ability to absorb small variations in shaft speed. Two types of fixed-speed drive schemes are possible:

(a) *One Fixed-speed Drive* The shaft speed is held fixed for the whole range of wind speed. The major disadvantage of one fixed-speed drive is that it never captures the wind energy at the peak value of the power coefficient C_p. Wind energy is wasted when wind speed is higher or lower than the optimal value, corresponding to $C_{P,MAX}$. Because of the low annual energy yield, the use of one fixed-speed drive is limited to small machines.

(b) *Two Fixed-speeds Drive* Two fixed-speeds drive, increases the energy capture, reduces the electrical losses and reduces the gear noise. The speed setting is changed by changing the gear ratio. The two operating speeds are selected to optimize the annual energy production with expected annual wind-speed distribution at the site. The power production from a typical WECS using two fixed-speed drive is shown in Fig. 7.24. In this particular example, the gear ratio is changed at a wind speed of 10 m/s.

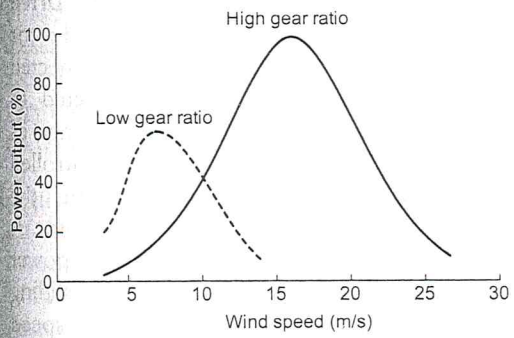


Fig. 7.24 *Power output Vs wind speed for two fixed-speed drives*

The induction generator is designed to operate at two speeds. This is achieved by either (i) having two stator windings with different number of poles, or (ii) using single winding with pole changing arrangement by connecting the winding coils in series and/or parallel. In separate winding machines, matching with system requirement is easy and change of speed setting is made without losing the control of the machine. However, separate windings are difficult to accommodate. While in the pole-changing method, the poles are either P or $2P$, the only possible speed ratio is 2:1. Also, a dead time is to be allowed for coils reconnection during every speed transition.

7.8.2 Variable Speed Drive Scheme

The recent advancement in power electronics has paved the way for a variable speed drive system. In this scheme, rotor speed is allowed to vary optimally with the wind speed to capture maximum power. As a result, it can capture about one third more power per year as compared to a fixed speed drive system. The following types of variable speed-drive systems are possible:

(a) *Variable Speed-drive Using Power Electronics* Modern variable speed-drive schemes make use of power electronic converters for power conditioning. The variable voltage and variable frequency output available from a generator (synchronous or self-excited induction generator) is first rectified to dc and then converted to fixed frequency and fixed voltage ac using an inverter. The harmonics are filtered out to get grid quality output before connecting to the grid. The rectifier, inverter, filter and transformer constitute the main parts of the interface.

Apart from higher energy yield, use of power electronics offers remotely adjustable and controllable quality of power. This has two major benefits not

in a negative way. This will limit the penetration of wind power into the grid. The optimum penetration depends on specific circumstances and characteristics of the utility system. In most cases, a wind-power penetration level less than 10% of the total electricity production will cause no severe problem and will not cause any economic disadvantage. For higher penetration, total electricity production system is to be re-optimized. This may require integration of some more peak load units or storage capacity plants. Also, the distance of the wind resource from the grid poses another limiting factor as it influences the economics of wind power. A distance of less than 50 km is generally considered as economically feasible.

WIND-ENERGY STORAGE

7.11 A major problem with wind power is intermittency. It does not garner higher prices from the purchaser because it is not schedulable. Higher prices may be obtained if it is available on demand. This can be made possible if provision of energy storage is available. For example, if the wind is blowing hardest at 11 p.m. at night, a wind-farm operator could store the energy generated from the wind and release it at 11 a.m. the next morning when the demand for power starts spiking up.

In place of a generator, a compressor is used in the nacelle. The highly compressed air is sent down the tower into underground storage such as caves or depleted gas wells through pipelines. The pressurized air can be released when needed to power an electricity generator, even if the wind is not spinning the turbine.

Mechanology, a compressor research and development firm, have designed a compressor and have tested a prototype wind-energy storage system. The company plans to build its large-scale version now.

ENVIRONMENTAL ASPECTS

7.12 In general, the use of energy in any form affects the environment in one way or the other at different levels. Wind energy is no exception. Although, these effects are of far less consequence as compared to that related to other sources of energy.

In terms of causing stress on water resources, wind energy is one of the most benign sources of energy. A major advantage of wind generation relative to any thermal based generation (nuclear, geothermal, fossil fuel and solar thermal) is that it does not need cooling water.

The main environmental concerns are discussed below:

(i) *Indirect Energy Use and Emissions* Energy is required to produce material used to construct the wind turbine and its installation. This energy is paid back in a period of few months to about a year, what is known as energy payback period. Some pollution (emission of CO_2, etc.) is caused due to use of energy during construction. But in total, the so-called indirect CO_2 emission over the total operating life of the wind generator is very low (about 1% of the system using coal).

(ii) *Bird Life* Large wind turbines pose a threat to bird life as a result of collision with tower or blades. Their resting and breeding patterns are also affected.

(iii) *Noise* The disturbance caused by the noise produced by a wind turbine is one of the important factors that prevent its siting close to inhabited areas. The acoustic noise is composed of (a) mechanical noise due to movement of mechanical parts in the nacelle (mainly gear and also other equipments), which can be reduced by good design and acoustic insulation, and (b) aerodynamic noise (swishing sound from the rotating blades), which is a function of wind speed and which cannot be avoided. Some of this noise is of infra sound, at frequencies below the audible range. This infrasound may cause houses and other structures to vibrate. Analysis shows that for turbines with rotor diameters up to 20 m, the mechanical component dominates, whereas for larger rotor diameters the aerodynamic component is predominant.

The sound level of a 500-kW machine rotating at 18 revolutions per minute at the hub is typically 102 dBA, which reduces down to 60 dBA at a distance of 50 m and declines very rapidly afterwards. A sound level of 35 dBA (noise limit for residential areas in many countries) is reached only after a distance of 500 m.

(iv) *Visual Impact* Wind turbines are massive structures quite visible over a wide area in most locations. The visual impact of wind turbines is qualitative in nature. In a study, it was found that public appreciation of a landscape decreases as more and more wind turbines are installed. A special case of visual impact is the effect of shadow of the turbine, particularly of the rotor blades. The rotational frequency plays an important role in determining the disturbance level. Offshore wind farms, being away from inhabited areas, do not in general create the same severity of visual intrusion.

(v) *Telecommunication Interference* Wind turbines present an obstacle for incident electromagnetic waves (i.e., TV or microwave signals). These waves can be reflected, scattered and dithered. Thus, they interfere with telecommunication links and badly affect the quality of radio and TV reception. The effect can be mitigated by the use of cable system or by installing powerful antennas.

(vi) *Safety* Accidents with wind turbines are rare but they do happen, as in other industrial activities. For example, a detached blade or its fragment may be thrown a considerable distance and can harm people and property. However, most wind turbines are located in isolated areas, which make it less likely to cause any damage. The International Electrical Committee (ICE) has taken the initiative to produce an international standard on safety.

44a

(vii) *Effects on Ecosystems* Large-scale use of wind generation can reduce wind speed and cause stress to an ecosystem. Lakes that are downhill from the wind turbines might become warmer because of reduced evaporation from their surface. Soil moisture might also increase. Nevertheless, these impacts may not be of great consequence except in certain sensitive areas.

7.13 WIND-ENERGY PROGRAMME IN INDIA

The wind-energy programme was initiated in India in 1983–84. The programme has been managed and implemented by the Ministry of Non-conventional Energy Sources, Government of India. The potential in wind has been estimated as 45,000 MW, assuming 1% of land available for wind-power generation in potential areas. Wind-resource assessment is a continuous process for identification of potential areas for wind farming. There are 216 sites having wind-energy densities of 200 W/m^2 (corresponding to wind speeds of 6.93 m/s) and above at 50-m height. These have been identified as potential sites. The total installed wind-generation capacity in India, as of July 2008, has reached 8696 MW. This sector has been growing at over 35% in the last three years. It is estimated that 6,000 MW of additional wind-power capacity will be installed in India by 2012. Despite the fact that wind power accounts for 6% of India's total installed power capacity, it generates only 1.6% of the country's power. The statewise potential as well as installed capacity is given in Table 7.5. The gross potential is estimated as 45,000 MW in the potential areas. However, the technical potential is limited to only 13,000 MW assuming 20% grid penetration, which will go up with the augmentation of grid capacity in potential states. Wind electric generators of unit sizes between 225 kW and 1.65 MW have been deployed across the country. The distribution of wind power density in the country is shown in Fig. 7.27. A view of the wind farm at Jogimatti, Karanataka, is given in Fig. 7.28.

Table 7.5 *Statewise wind power (Source: MNRES Annual Report, 2007–08)*[45]

SN	*State (Sites)*	*Gross potential (MW)*	*Technical potential (MW)*	*Installed capacity (MW)*
1.	Andhra Pradesh	8275	1750	123
2.	Gujarat	9675	1789	1253
3.	Karnataka	6620	1120	1011
4.	Kerala	875	605	12.5
5.	Madhya Pradesh	5500	825	126
6.	Maharashtra	3650	3020	1756
7.	Rajasthan	5400	895	539
8.	Tamil Nadu	3050	1750	3873
9.	West Bengal		450	2
10.	Others	1700		1.6
Total		45,195	12875	8,696

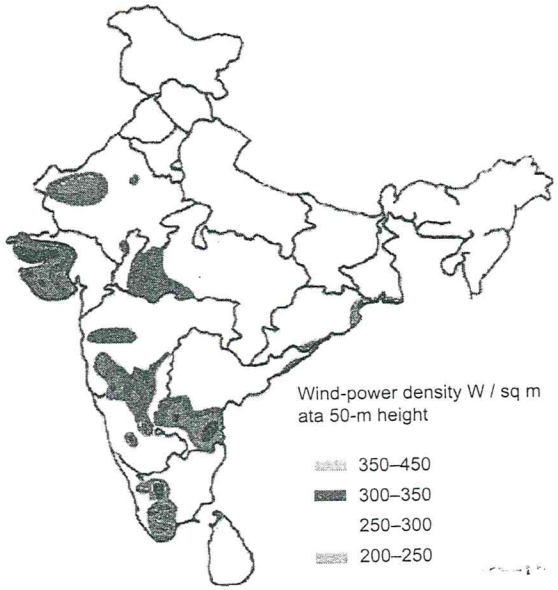


Fig. 7.27 *Wind map of India. Source. MNES Annual Report*

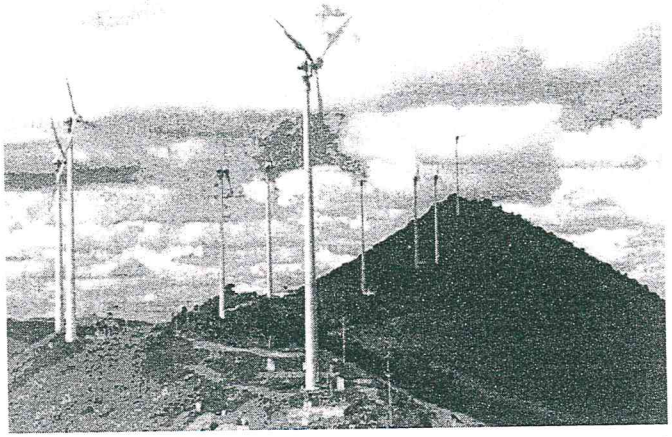
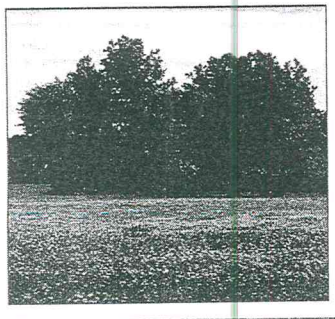


Fig. 7.28 *A 8.4-MW commercial wind farm at Jogimatti (Karnataka)*
Source. *MNES Annual Report*

The Ministry of New and Renewable Energy (MNRE) has fixed a target of 10,500 MW between 2007–12, but an additional generation capacity of about 6,000 MW might be available for commercial use by 2012.

A wind–diesel hybrid project is under implementation at Sagar Island in West Bengal. Proposals for similar projects are being prepared for Lakshadweep and Andaman and Nicobar Islands.



8 Biomass Energy

Introduction

Biomass is a general term for living material—plants, animals, fungi, bacteria. Taken together, the earth's biomass represents an enormous store of energy. It has been estimated that just one-eighth of the total biomass produced annually would provide all of humanity's current demand for energy. And since biomass can be re-grown, it is a potentially renewable resource.

The energy obtained from biomass is known as *biomass energy*. Animals feed on plants, and plants grow through the photosynthesis process using solar energy. Thus, the photosynthesis process is primarily responsible for generation of biomass energy. A small portion of the solar radiation is captured and stored in plants during the photosynthesis process. Therefore, it is an indirect form of solar energy. The average efficiency of photosynthetic conversion of solar energy into biomass energy is estimated to be 0.5–1.0%.

To use biomass energy, the initial biomass may be transformed by chemical or biological processes to produce more convenient intermediate bio-fuels such as methane, producer gas, ethanol and charcoal. On combustion, it reacts with oxygen to release heat, but the elements of the material should be available for recycling in natural ecological or agricultural processes. Thus, the use of industrial bio-fuels, when linked carefully to the natural ecological cycle, may be non-polluting and sustainable. For biomass to be considered as renewable, growth must at least keep pace with its use. It is disastrous that forest and firewood consumption is significantly outpacing their growth in ever-increasing areas of the world. It is estimated that biomass, 90% of which comprises plant matter, is equivalent to the current proven extractable fossil-fuel reserves in the world. The dry-matter mass of biological material cycling in the biosphere is about 250×10^9 t/y. The associated energy bound in photosynthesis is 2×10^{21} J/y (0.7×10^{14} W).

Although fossil fuels have their origin in ancient biomass, they are not considered biomass by the generally accepted definition because they contain carbon that has been 'out' of the carbon cycle for a very long time. Their combustion therefore disturbs the carbon dioxide content in the atmosphere.

Biomass, mainly in the form of wood, is mankind's oldest form of energy. It has traditionally been used both in domestic as well as industrial activities, basically by direct combustion. As industrial activities increased, the growing demand for energy depleted biomass natural reserves. The development of new, more concentrated and more convenient sources of energy has led to its replacement to a large extent by other sources. However, it still plays a significant role in the supply of primary energy in many countries of the world. Though biomass energy share in primary energy supply for the industrialised countries is not more than 3%, a number of developing countries still use a substantial amount of it mostly in the form of non-commercial energy.

The main advantages of biomass energy are

(i) it is a renewable source,
(ii) the energy storage is an in-built feature of it,
(iii) it is an indigenous source requiring little or no foreign exchange,
(iv) the forestry and agricultural industries that supply feed stocks also provide substantial economic development opportunities in rural areas,
(v) the pollutant emissions from combustion of biomass are usually lower than those from fossil fuels,
(vi) commercial use of biomass may avoid or reduce the problems of waste disposal in other industries, particularly municipal solid waste in urban centres,
(vii) use of biogas plants, apart from supplying clean gas, also leads to improved sanitation, better hygienic conditions in rural areas as the harmful decaying biomass get stabilized,
(viii) the nitrogen rich bio-digested slurry and sludge from a biogas plant serves as a very good soil conditioner and improves the fertility of the soil, and
(ix) varying capacity can be installed; any capacity can be operated, even at lower loads, with no seasonality involved.

Its main disadvantages are

(i) it is a dispersed and land-intensive source,
(ii) it is often of low energy density,
(iii) it is also labour intensive and the cost of collecting large quantities for commercial application is significant. Most current commercial applications of biomass energy, use material that has been collected for other reasons, such as timber and food processing residues and urban waste,
(iv) capacity is determined by availability of biomass and not suitable for varying loads, and
(v) not feasible to set up at all locations.

8.1 PHOTOSYNTHESIS PROCESS

Solar radiation incident on green plants and other photosynthetic organisms performs two basic functions: (i) temperature control for chemical reactions to proceed, and (ii) photosynthesis process. The fundamental conversion process in green plants is *photosynthesis*, which is the process of combining CO_2 from the atmosphere with water plus light energy to produce oxygen and carbohydrates (sugars, starches, celluloses and hemicelluloses). They are the ultimate source of most of our foods and other necessities of daily life such as clothes (in the form of cotton), furniture (in the form of wood), etc.

$$x\,CO_2 + y\,H_2O + \text{light energy} \xrightarrow{\text{Photosynthesis}} x\,O_2 + C_x\,(H_2O)_y \qquad (8.1)$$

The generalized symbol $C_x\,(H_2O)_y$ is used to indicate the carbohydrates. The products of this reaction are about 5 eV per C atom higher in energy than the initial material. Photosynthesis is a complex process. It involves several successive

stages, but the overall basic reaction is the formation of hexose (glucose, fructose, etc.) as represented by

$$6CO_2 + 6H_2O + \text{light energy} \xrightarrow{\text{Photosynthesis}} 6O_2 + C_6H_{12}O_6 \quad (8.2)$$

More complex hydrocarbons (sucrose, starch, cellulose etc.) are formed by a chain of these simple structures. The reverse of this process is called *respiration*, in which CO_2, H_2O and energy are produced using carbohydrate and oxygen. The energy produced in the plants by respiration is used in several processes such as to draw moisture and nutrients through its roots. In green plants, both photosynthesis and respiration occur during the day and only respiration at night. This is symbolically shown in Fig. 8.1. There is a net overall gain of energy in the process, as the rate of energy loss in respiration is much less as compared to the rate of energy gain during photosynthesis process. The process also results in net gain of oxygen and fixation of carbon in the form of biomass. The net energy absorbed from solar radiation during photosynthesis can be measured from its combustion:

$$x\,CO_2 + y\,H_2O + \Delta Q \underset{\text{Combustion}}{\overset{\text{Photosynthesis}}{\rightleftharpoons}} x\,O_2 + C_x(H_2O)_y \quad (8.3)$$

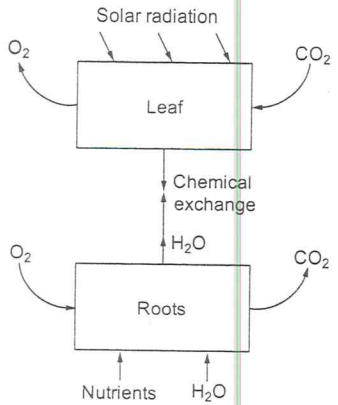


Fig. 8.1 *Photosynthesis and respiration processes in a plant*

ΔQ is the enthalpy change of the combustion process, equal to the energy absorbed from photons of solar radiation minus the energy of respiration during growth. The value of ΔQ is 4.8 eV per carbon atom, 470 kJ per mole of carbon or 16 MJ/kg of dry carbohydrate material. It is to be noted that combustion requires the temperature of approximately 400°C, whereas respiration occurs at 20°C through catalytic enzyme reactions.

The intake of CO_2 by a plant leaf is function of many factors, especially temperature, CO_2 concentration and the intensity and wavelength distribution of light. Solar radiation incident on a leaf is reflected, transmitted and absorbed. Part of the absorbed radiation (< 5%) provides the energy stored in the photosynthesis and produces oxygen and carbohydrate; the remainder is absorbed in the plant as sensible heat raising its temperature, or as latent heat for water evaporation. Absorption is usually most marked in the blue and red regions.

8.2 USABLE FORMS OF BIOMASS, THEIR COMPOSITION AND FUEL PROPERTIES

Biomass is organic material that reacts with oxygen in combustion and natural metabolic processes to release heat. Sometimes, it is used as such in its

original form but more often it is transformed into modern energy forms such as liquid and gaseous fuels, electricity, and processes heat to provide energy services needed by rural and urban populations and also by industry. Some of its forms available to users are discussed below:

(i) *Fuel Wood (Virgin Wood)* Wood is the most obvious and oldest source of biomass energy. This was the main source of energy used by mankind for centuries. Direct combustion is the simplest way to obtain heat energy. Its energy density is 16–20 MJ/kg. It can also be converted to more useful forms such as charcoal or producer gas.

About half of the world population depends on fuel wood or other biomass such as cow dung, crop residue, etc., for cooking and other domestic uses. Because of inefficient use of fuel wood in conventional household stoves (*chulha*), only 5% of the heat is utilized. The remainder is lost due to wind, incomplete combustion, radiation losses and other losses resulting from mismatch of fire and pot size. Considerable energy is also wasted in evaporation from the uncovered pot and from the use of wet fuel. Smoke, which is in fact unburnt tar and carbon, is a health hazard. There is little control over the rate at which wood is burnt. Improved household stoves and use of pressure cooker is being encouraged for better fuel utilization.

(ii) *Charcoal* Charcoal is a clean (smokeless), dry, solid fuel, black in colour. It has 75–80% carbon content and has energy density of about 30 MJ/kg. It is obtained by the carbonisation process of woody biomass to achieve higher energy density per unit mass, thus making it more economical to transport. It can be used as fuel in domestic environment as it burns without smoke. In the industrial sector it is used in specialised applications where specific fuel characteristics are required, such as high carbon and low sulphur content. Chemical grade charcoal has many uses in laboratory and industrial chemical processes. It is also used for making high-quality steel. It is in common use in many developing countries such as Brazil.

(iii) *Fuel Pellets and Briquettes* Crop residues such as straw, rice husk and waste wood are pressed to form lumps, known as fuel pellets or briquettes and used as solid fuel. The purpose is to reduce moisture content and increase the energy density of biomass making it more feasible for long distance transportation.

(iv) *Bio-diesel* Some vegetable oils, edible as well as non-edible, can be used (after some chemical processing) in pure form or blended with petroleum diesel as fuel in a compression–ignition (diesel) engine. Bio-diesel is simple to use, biodegradable, non-toxic, and essentially free of sulphur and aromatics. In fact, Rudolf Diesel demonstrated an engine that could run on peanut oil. He believed that the utilization of biomass fuel was the real future of his engine. August 10 has been declared as 'International Bio-diesel Day'.

A6

Raw vegetable oil is upgraded as bio-diesel through a chemical process called *trans-esterification* whereby the glycerin is separated from the animal fat or vegetable oil. The process leaves behind two products—methyl (or ethyl) esters (the chemical name for bio-diesel) and glycerin (a valuable byproduct usually used in soaps and other products). Bio-diesel can be produced from vegetable oils, animal fats or recycled restaurant greases.

Fuel-grade bio-diesel must be produced to strict industry specifications (such as ASTM D6751) in order to insure proper performance. Bio-diesel that meets the prescribed specifications and is legally registered with the Environmental Protection Agency is a legal motor fuel for sale and distribution. Raw vegetable oil cannot meet bio-diesel fuel specifications, since it is not registered with the EPA, and it is not a legal motor fuel. Bio-diesel refers to the pure fuel before blending with diesel fuel. Bio-diesel blends are denoted as, 'BXX' with 'XX' representing the percentage of bio-diesel contained in the blend (i.e., B20 is 20% bio-diesel and 80% petroleum diesel, B100 is pure *biodiesel*).

Jatropha and Karanj are the most promising bio-diesel resources. Some plants, e.g., *Euphorbia lathyris*, produce latex, which can be processed to obtain hydrocarbons, which have molecular weights very close to petroleum. It also produces sugar as a byproduct. However, the technology is at the research stage and its economic viability has not been assessed yet.

(v) *Bio-ethanol* Ethanol (C_2H_5OH) is a colourless liquid biofuel. Its boiling point is 78°C and energy density is 26.9 MJ/kg. It can be derived from wet biomass containing sugars (e.g., sugarcane, sugarbeet, sweet sorghum), starches (grains and tubers such as potato, cassava) or cellulose (woody matter). The main constituents of woody matter are *legnin* (fibrous part) and *cellulose* (juicy part). Ethanol is largely produced from sugar cane (maize in the USA due to surplus production). Commercial ethanol is used in specially designed IC engines with 25% mileage penalty compared to conventional vehicles. Blend of up to 22% anhydrous ethanol with gasoline, requires no engine modification and incurs no mileage penalty. It is being used by a large number of automobiles in the world. Brazil, the biggest producer of sugar cane, presently produces around 24.4 billion litres/year (2008) of ethanol representing 18% of the country's automotive fuel. Major bio-ethanol programmes are also being developed in USA, Zimbabwe and Malawi.

(vi) *Biogas* Organic wastes from plants, animals and humans contain enough energy to contribute significantly to energy supply in many areas, particularly the rural regions of developing countries. Aquatic biomass can also be used. Biogas is produced in a biogas fermentor or digester. Nitrogen-rich sludge (fertilizer) is also produced as a byproduct with improved sanitation as an added bonus. If raw material is cow manure, the output biogas will contain about 50–60% CH_4, 30–40% CO_2, 5–10% H_2, N_2 0.5–0.7% with trace amounts of O_2 and H_2S. Its energy density is about 23 MJ/m^3. It is used for cooking, lighting (using mantle lamps), heating and operating small IC engines. It is unlikely to be used for mobile vehicles on a large scale because of low pressure and high inert fraction. Use of biogas is widespread in rural China and India. Two-third of China's rural families use biogas as their primary fuel.

(vii) *Producer Gas* Woody matter such as crop residue, wood chips, bagasse (fibrous residue of sugar cane after juice extraction), rice husk and coconut shells, can be transformed to producer gas (also known as synthesis gas, syn gas, wood gas, and water gas or blue gas) by a method known as *gasification* of solid fuel. The composition of gas produced depends upon the type of biomass and the design of the gasifier. For wood chips as input, the typical gas composition is 19% CO, 18% H_2, 1% CH_4, 11% CO_2 and the rest N_2. It has a typical energy density of 4–8 MJ/m^3 (5–10 MJ/kg). This can be used to fuel IC engines (diesel, dual fuel-mode engines) for irrigation pumps, motor vehicles, and small-scale power generation or to produce process heat.

The commercial diesel engine has to be modified to a dual-fuel mode engine. The air intake manifold is modified to a suck (air + producer gas) mixture. Limited quantity of diesel is required to initiate the ignition. The engine is started with diesel fuel only and subsequently the quantity of diesel is reduced as producer gas is mixed with air. About 85–87% diesel replacement can be obtained.

8.3 BIOMASS RESOURCES

Biomass resources for energy production encompass a wide spectrum of materials ranging from silviculture (forest), agriculture (field), aquaculture (fresh and sea water) and industrial and social activities that produce organic waste residues (food processing, urban refuse etc). When plants are cultivated especially for the purpose of energy, it is known as *energy farming*.

(i) *Forests* Forests, natural as well as cultivated, serve as a source of fuel wood, charcoal and producer gas. Forest waste and residues from forest-processing industries can be utilized at the mill itself. Forest resource is consumed, not just for firewood but also for sawn timber, papermaking and other industrial purposes. Some fast-growing energy intensive trees such as *eucalyptus*, *poplar*, *pine* are specially cultivated for the purpose of energy.

Some plants produce seeds (or nuts) to yield vegetable oil on pressing. This serves as a liquid biofuel (bio-diesel). There are two categories of oil-producing plants: (a) wild plants, e.g., *jojoba* (a shrub, producing nuts) *and karanj* (a tree generally seen on roadsides in India, produces small seeds) that take care of themselves, and (b) agricultural crops, e.g., *Jatropha curcas (Ratanjyot)* which require common agricultural techniques. There are more than 300 different species of oil-bearing trees; most of them are wild and do not require much care and effort. These plants are quite hardy, require little water, can resist severe drought and pests, can survive in hot and cold climates and can grow on most soil types. In

India, the experience with a wild, oil-bearing tree, *karanj (Pongamia pinnata)*, has been encouraging. It is estimated that its plantation on 30 million hectares would produce enough biofuel that could completely replace the current use of fossil fuels in the country.

(ii) *Agricultural Residues* Crop residues such as straw, rice husk, coconut shell, groundnut shell, sugar cane bagasse are gasified to obtain producer gas. Alternatively, these are converted to fuel pellets or briquettes and used as solid fuel.

(iii) *Energy Crops* Certain cultivated plants produce raw material for biofuels. The greatest potential for energy farming occurs in tropical countries, especially those with adequate rainfall and soil conditions.

- *Sugar Plants*

Sugar cane is a major raw material source for bio-ethanol. Various products from sugar cane are shown in Fig. 8.2. Alcohol represents only 30% of the total sugar cane energy. About 35% is available in bagasse and another 35% in leaves and tops of the sugar-cane plant.

Sweet Sorghum also supplies raw material for ethanol production, especially during off-season supply for the sugar mills.

Sugar Beet supplies raw material for ethanol production.

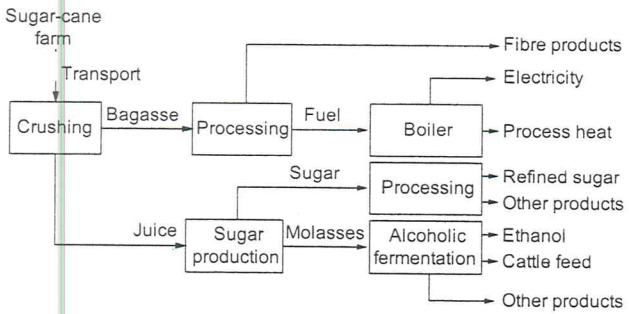


Fig. 8.2 *Sugar-cane industry products*

- *Starch Plants*

Jerusalem Artichoke provides raw material for bio-ethanol. It is a tubular plant and can be grown on marginal lands and relatively poor soil. It is able to withstand adverse conditions such as cold and draught conditions.

Cassava is also a tubular plant. It is seen as complementary to sugarcane as it can be cultivated in areas with acidic infertile soils, whereas cane requires more amenable soil. It also provides raw material (starch) for bio-ethanol. Potatoes and sweet potatoes also fall in the same category.

Grains, such as maize, barley, rice and wheat provide starch, which can be converted to ethanol.

- *Oil-producing Plants*

In a short-term diesel engine test, over 40 different plant-derived oils have been evaluated including *sunflower, rapeseed, palm oil, castor oil, soybean, groundnut and cottonseed.* The benefits to be derived from a plant-oil fuel industry are the following

- Most of these plants are very adaptable and hardy.
- Because of the relatively simple technology involved in oil extraction and filtering, the oil can be produced right on the farm.
- The leftover biomass after the extraction of oil, known as cake, can be used to produce biogas in a biogas plant and the sludge produced thereof can be used as a quality fertilizer.
- The by-products from the oil press can often be used as a high-protein animal feed.
- Most of these plants require low cost and low input.
- Plant oils are safe to handle and store.
- Marginal lands and wasteland can be used for cultivation.
- It will increase the employment opportunities in rural areas and boost the economy.

(iv) *Aquatic Plants* Some water plants grow faster than land-based plants and provide raw materials for producing biogas or ethanol. These are *water hyacinth, kelp, seaweed* and *algae.*

(v) *Urban Waste* Urban waste is of two types: (a) Municipal Solid Waste (MSW or garbage), and (b) sewage (liquid waste). Energy from MSW can be obtained from direct combustion (incineration) or as a landfill gas. Sewage can be used to produce biogas after some processing.

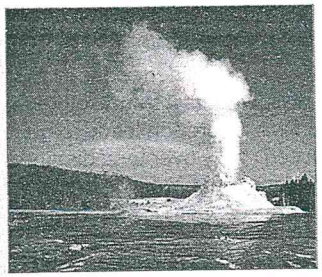
8.4 BIOMASS CONVERSION TECHNOLOGIES

There are many different ways of extracting energy from biomass. These energy-conversion technologies may be grouped into four basic types: (i) physical method, (ii) incineration (direct combustion), (iii) thermochemical method, and (iv) biochemical method. The general outlines of these technologies are briefly described here.

8.4.1 Physical Method

The simplest form of physical conversion of biomass is through compression of combustible material. Its density is increased by reducing the volume by compression through the processes called *briquetting* and *pelletization.*

5. The water content in anhydrous ethanol is
   (a) 20% (b) 10% (c) 5% (d) 0.7%
6. The percentage of ethanol in blended petrol (gasohol) is
   (a) 20% (b) 30% (c) 4% (d) 50%
7. Compared to a petrol-operated engine, an ethanol-operated engine
   (a) produces 50% more power (b) produces 20% more power
   (c) produces comparable amount of power (d) produces 20% less power
8. Increasing the pressure inside a biogas plant
   (a) increases the gas production (b) decreases the gas production
   (c) has no effect on gas production (d) causes explosion
9. When ambient temperature of biogas plant decreases below 20°C
   (a) the gas production increases
   (b) the gas production first increases and then decreases
   (c) the gas production decreases
   (d) remains unaltered
10. The optimum solid concentration in a biogas is
    (a) 37–39 % (b) 27–29 % (c) 17–19 % (d) 7–9 %
11. Which material should be added in the feed of a biogas plant to increase nitrogen content?
    (a) Lignin (b) Carbohydrate
    (c) Chopped leguminous plants (d) Night soil
12. Compared to the fixed-dome model of a biogas plant, a floating-drum-type plant
    (a) is more efficient (b) is less efficient
    (c) is equally efficient (d) is very cheap
13. In energy farming, the plantation and harvesting is planned and managed so as to
    (a) reduce manual labour
    (b) insure the sustainability of the resource
    (c) insure multiple harvesting per year
    (d) minimize the cost involved
14. Bio-diesel is
    (a) obtained from fermentation of sugars
    (b) obtained from pyrolysis process
    (c) exudates of plants
    (d) an upgraded vegetable oil
15. Liquefaction of biomass is carried out at
    (a) high temperature and low pressure
    (b) relatively low temperature and high pressure
    (c) relatively low temperature and normal pressure
    (d) room temperature and high pressure



9 Geothermal Energy

Introduction

Geothermal energy originates from the earth's interior in the form of heat. Volcanoes, geysers, hot springs and boiling mud pots are visible evidence of the great reservoirs of heat that lie beneath the earth. Although the amount of thermal energy within the earth is very large, useful geothermal energy is limited to certain sites only, as it is not feasible to access and extract heat from a very deep location. Where it is available near the surface and is relatively more concentrated, its extraction and use may be considered feasible. These sites are known as *geothermal fields*. As per US Geological Survey, the entire heat content of the earth's crust up to a depth of 10 km above 15°C is defined as *geothermal resource*. As such, the geothermal resource of the earth is estimated to be more than 2.11×10^{25} J, which is equivalent to 10^9 MTOE (million tonnes of oil equivalent). This is a huge amount of energy, enough to supply our energy needs at current rates for 3,50,000 years. Thus, it is considered an inexhaustible and renewable source. However, it is a low-grade thermal-energy form and its economic recovery is not feasible everywhere on the surface of the earth. Practically, it is not the size of the resource that limits its use but the availability of technology that can tap the resource in an economic manner.

Low temperature resources, i.e., 'geysers' have been used from time immemorial for applications such as therapeutic hot baths, cooking, space and water heating. Most geothermal resources produce low-grade heat at about 50–70°C, which can be used directly for thermal applications. Occasionally, geothermal heat is available at temperatures above about 90°C, and so electrical power production from turbines can be contemplated. The world's total present (end of year 2005) installed electrical power-generating capacity from geothermal resources is about 9,031 MW_e and direct thermal use installed capacity is 29,668 MW_t. Globally, generation of geothermal power is growing steadily at a rate of about 3% per year as electrical energy and 8.5% per year as direct thermal energy. The current (year 2008) installed geothermal power capacity of USA is around 3000 MW, 90% of which is located in California ('at the Geysers'). The island of Hawaii provides 25% of its electricity from geothermal resources. Likewise, geothermal electrical energy production in El Salvador is 23% of the country's total installed electricity generation capacity. At present the capital cost of a geothermal power plant is about Rs 6–10 crore (1.5–2.5 million US dollars) per MW of electric capacity. The geothermal electricity cost is about Rs 2–3.20 (5–8 cents) per kWh.

The main advantages of geothermal energy are (i) it is a reliable and cheap source of energy, (ii) it is available 24 hours per day, (iii) its availability is independent of weather, (iv) it has inherent storage feature so no extra storage facility is required, (v) geothermal plants require little land area, and (vi) feasibility of modular approach represents a lot of opportunities for development of relatively quick, cost-effective geothermal projects.

The major disadvantages are (i) it is site specific—there are not many places where you can build a geothermal power station, (ii) generally, energy is available as low-grade heat,

(iii) continuous extraction of heated ground water may lead to subsidence (setting or slumping) of land, (iv) geothermal fluid also brings with it dissolved gases and solute (as high as 25 kg/m³) which leads to air and land pollution, (v) drilling operation leads to noise pollution, (vi) the available thermal energy cannot be distributed easily over long distances (longer than ~ 30 km), and (vii) corrosive and abrasive geothermal fluid reduces the life of the plant.

APPLICATIONS

9.1 Geothermal energy is useful for a number of applications, although restricted to a specific geographical area.

(i) Direct Heat Use Geothermal resources have a great range of temperatures and local peculiarities. In general, although abundant energy is accessible, its thermodynamic quality is low. The source shares many similarities with industrial waste heat. The low and moderate temperature hydrothermal fluids can be used as direct heat source for space and water heating, for industrial processes such as drying applications in food, chemical and textile industries, crop drying, washing, for warming fish ponds in aquaculture and for agricultural applications such as soil and space heating of glasshouses. As heat cannot be distributed easily over distances greater than ~ 30 km, concentrated uses near the point of supply are needed. In cold climates, it can be used for space heating and hot water supply for public institutions, or business district heating for a group of buildings. Thus, a 100 MW_t plant might serve an urban area of about 20 km × 20 km. Such geothermal schemes have long been established in Iceland and on smaller scales, in New Zealand. About 80% of the population of Iceland use geothermal space heating. More than 9000 thermal wells and springs are now in use. These applications are saving the energy equivalent of almost 2 million barrels of oil per year.

(ii) Electric Power Generation If temperatures are high enough (> 90 °C), the preferred use of a geothermal resource is the generation of electricity, which would either be fed into the utility grid or be used to power the industrial processes on the site. It is normally used for base load power generation. The reason is related to the difficulty of control for peak load and with the scaling/corrosion problems, which would occur, if the various vessels and turbines are not kept full of fluid and air is allowed into them. However, this does not apply to dry steam fields. Several important electric power plants are fully established, especially in Italy, New Zealand and the USA. Electricity was first generated from naturally occurring geothermal steam at Larderello, Italy, in 1904. This was followed by commercial plants at Wairakei field in New Zealand in 1958 and 'The Geysers' in California in 1960.

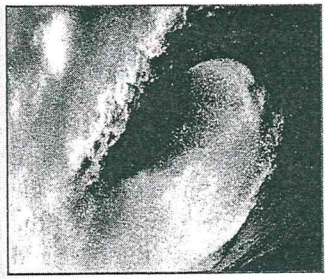
The geothermal power production in some countries of the world is listed in Table 9.1.

Table 9.1 *Geothermal energy: electricity generation and direct use at end of-2005* [38]

Country	*Electricity generation Installed capacity (MW_e)*	*Direct use Installed capacity (MW_t)*
Algeria		152
Kenya	115	10
Tunisia		25
Canada		422
Costa Rica	163	1
El Salvador	151	
Guatemala	33	2
Mexico	953	156
Nicaragua	77	
U. S. A.	2,564	8,670
Argentina		150
Colombia		14
China	28	3,687
Georgia		250
India		203
Indonesia	797	2
Japan	535	822
Korea (Republic)		17
Philippines	1,978	3
Turkey	20	1,229
Vietnam		31
Austria	1	1,134
Bulgaria		110
Croatia		114
Czech Republic		205
Denmark		330
Finland		260
FYR Macedonia		62
France	15	308
Germany		505
Greece		75
Hungary		694
Iceland	232	1,804
Ireland		20

(Contd.)

5. The temperature in the crust increases with depth at a rate of about
   (a) 300°C/km (b) 10°C/km (c) 1°C/km (d) 30°C/km
6. The temperature at the inner core of the earth is about:
   (a) 1000°C (b) 4000°C (c) 40000°C (d) 500°C
7. The zone of likely geothermal sites corresponds roughly to:
   (a) cold, hilly regions (b) hot, flat regions
   (c) tropical regions (d) the regions of seismic and volcanic activities
8. Most of the world's geothermal sites today are located
   (a) in south hemisphere of the globe (b) near the coast of Atlantic ocean
   (c) near the edges of Pacific plate (d) near the equator
9. The average thickness of the crust is about
   (a) 30 km (b) 3 km (c) 300 km (d) 1000 km
10. In most hydrothermal fields, hot spots occur at a depth of about
    (a) 10 km (b) 10 m (c) 2 to 3 km (d) 30 km
11. Compared to a conventional steam plant, the temperature and pressure in a geothermal plant are
    (a) comparable (b) much higher (c) higher (d) lower
12. In a geopressured resource, the pressure can go as high as
    (a) 160 atm (b) 1350 atm (c) 15000 atm (d) 10 atm
13. Name the country where the world's largest EGS project is currently under development
    (a) Italy (b) USA (c) New Zealand (d) Australia
14. A geothermal resource tapped for electricity generation could provide energy for about
    (a) 50 years (b) 1000 years (c) 5 years (d) 1 year
15. Compared to a conventional steam plant, the efficiency of geothermal plant is
    (a) Very high (b) higher (c) comparable (d) lower



10 Ocean Energy

Introduction

Oceans cover about 71% of the earth's surface. They receive, store and dissipate energy through various physical processes. As per present technological status, recoverable energy in oceans exists mainly in the form of waves, tides and temperature difference (between surface and deep layers). Tides and waves produce mechanical energy whereas temperature difference produces thermal energy. Tidal energy technology is relatively more developed compared to the other two, which are still undergoing evaluation and initial development stages. The main disadvantages common to all of them are (i) low energy density, and (ii) their occurrence at distances remote from the consumption centre. Because of the diversity in the physical processes involved, the exploitation techniques and state of development, these are discussed in three different sections.

TIDAL ENERGY

10.1 Tidal energy exploits the natural rise and fall of coastal tidal waters caused principally by the interaction of the gravitational fields of the sun and the moon. The ocean level difference caused due to tides contains large amount of potential energy. The highest level of tidal water is known as *flood tide* or *high tide*. The lowest level is known as *low tide* or *ebb*. The level difference between the high and low tide is known as *tidal range*. The tidal range varies greatly with location. Only sites with large tidal ranges (about 5 m or more) are considered suitable for power generation. The total combined potential at these sites is estimated as 1,20,000 MW.

Tidal mills were in use on the coasts of Spain, France, UK and China during medieval period, around 1100 AD. They remained in common use for many centuries, but were gradually replaced by more convenient and cheaper sources made available due to the industrial revolution. The principle used for harnessing this energy consisted of a pond filled through *sluice* (rapid controlled gates) when tides are high and emptying it during low tides via an undershot waterwheel, producing mechanical power. Even now, the same basic principle with improvements in the design, material and operation techniques is being used to generate electricity in the same manner as in a hydroelectric plant.

10.1.1 Origin and Nature of Tidal Energy

Tides are produced by the gravitational attraction of the moon and the sun acting upon the rotating earth. The moon exerts a larger gravitational force (about 70 per cent of the tide-producing force) on the earth, as it is a great deal closer than the sun. Surface water is pulled away from the earth on the side facing the moon, and at the same time the solid earth is pulled away from the water on the opposite side. Thus the ocean height increases at both the near and far sides of the earth as shown in Fig. 10.1. The solid earth rotates with a period of one day underneath these two bulges. These bulges are swept westward, due to the earth's rotation, as deep ocean waves lasting a period 12 hours and 25 minutes. The sun's effect is similar but smaller in magnitude (about 2.2 times less than lunar), and with a period of 12 hours. These are thus semi-diurnal changes of ocean level. Due to slight difference of periods, the solar tide moves in and out of phase with the lunar tide. When the sun, earth and moon are aligned (approximately) in conjunction, the lunar and solar tides are in phase, producing net tides of maximum range. These are the *spring tides* occurring twice per lunar month at times of both full and new moon. When sun–earth and moon–earth directions are perpendicular (in quadrature), the solar and lunar tides are out of phase producing net tides of minimum range. These are the *neap tides* that again occur twice per month at times of half moon (first and third quarter cycle of the moon) as shown in Fig. 10.2.

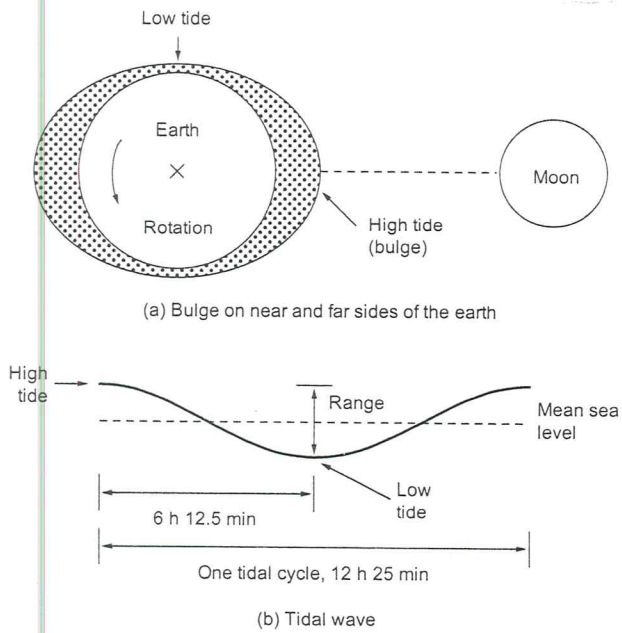


Fig. 10.1 *Origin of tides*

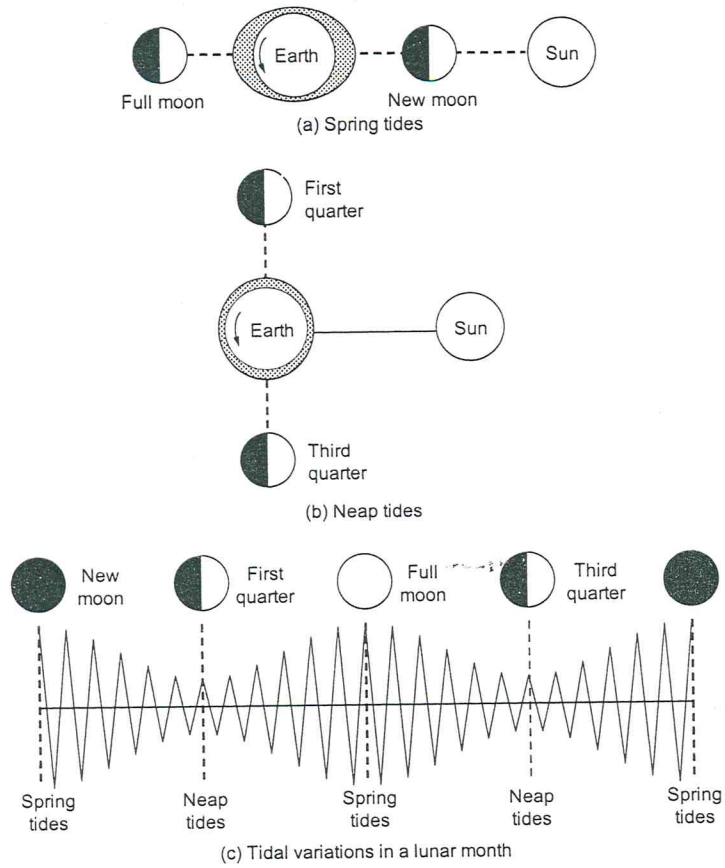


Fig. 10.2 *Nature of tides*

Superimposed on these short-term variations caused by the sun–moon system, there are many other cycles of small magnitudes with periods ranging from days to years. For example, (i) long-term (yearly) variations arise from the changes in the distance of the earth from the sun during a year, (ii) variations as the moon–earth distance oscillates slightly in a period of 27.55 solar days, (iii) variations as the moon's plane of motion moves about 2° in and out of the earth–sun ecliptic plane, and also (iv) other variation cycles that last for many years, arising out of complex interactions between the gravitational fields.

In open oceans, tidal ranges are commonly of the order of 0.6 m to 0.9 m. However, when the ocean tidal waves impinge on continental shelves and coastlines, their ranges can amplify substantially through (i) run-up, (ii) funneling, and (iii) resonance, depending on the nature of the coastline. Thus, tidal range varies from place to place. In some places such as shallow bays and estuaries, the amplification is considerable. Exceptionally high tides with a tidal range of about 11 m (or more) occur in the Bay of Fundy on the Atlantic coast of Canada

near Maine. Despite their complexity, tides at any location can be predicted with high accuracy.

Ocean tides derive their energy from the rotation of the earth, slowing it down a bit in the process. However, the slowing down of the earth is very insignificant over human time spans and would not be increased by tidal power development. This will not have any significant effect for billions of years. Therefore, for human purposes, tidal energy can be considered a sustainable and renewable energy resource. The total dissipation of energy by water tides in the earth is estimated to be 3000×10^3 MW.

10.1.2 Limitations of Tidal Energy

The main limitations of tidal energy are the following:

(i) Economic recovery of energy from tides is feasible only at those sites where energy is concentrated in the form of tidal range of about 5 m or more and the geography provides a favourable site for economic construction of a tidal plant. Thus it is site specific.
(ii) Due to mismatch of lunar driven period of 12 hours 25 min and human (solar) period of 24 hours, the optimum tidal power generation is not in phase with demand.
(iii) Changing tidal range in two-week periods produces changing power.
(iv) The turbines are required to operate at variable head.
(v) Requirement of large water volume flow at low head necessitates parallel operation of many turbines.
(vi) Tidal plant disrupts marine life at the location and can cause potential harm to ecology.

10.1.3 Tidal Energy Technology

The main components of a tidal plant, as shown in Fig. 10.3 are

(i) *dam, barrage or dyke*—a barrier constructed to hold water,
(ii) *sluice ways* rapid controlled gates, used to fill a basin during high tides or emptying it during low tides, and
(iii) *a special, bulb-type power turbine-generator set* steel shell containing an alternator and special Kaplan turbine with variable pitch blades. The tidal power associated with single filling or emptying of a basin may be estimated as follows.

Tidal Range Power

Consider water trapped at high tide in a basin of area A, and allowed to run out through a turbine at low tide as shown in Fig. 10.3. The potential energy in the mass of water stored in incremental head dh above the head h is:

$$dW = dm \,.\, g \,.\, h$$

but $dm = \rho \,.\, A.\, dh$

Thus $dW = \rho \,.\, A.\, g.\, h \,.\, dh$

Total potential energy of water stored in the basin is:

$$W = \int_0^R \rho \,.\, A.\, g.\, h \,.\, dh$$

$$W = \frac{1}{2} \rho \,.\, A.\, g.\, R^2 \text{ joules}$$

where ρ = density of water

g = gravitational constant

As the time between consecutive high and low tides is 6 hours 12.5 min (= 22,350 s), this power is to be utilised within this period.

Assuming an average sea-water density of 1025 kg/m^3, the average theoretical power generated in one filling or emptying of the basin is:

$$P_{av} = \frac{1025 \times 9.80 \times A \times R^2}{2 \times 22{,}350}$$

$$P_{av} = 0.225 \times A \times R^2 \text{ watts}$$

Thus, the tidal power developed is directly proportional to (i) area of basin, and (ii) square of the range.

The actual power generation by a practical system would be less than the average theoretical power given in the above expression due to frictional losses of the fluid, conversion efficiency of the turbine and generator and due to the fact that the turbine cannot be operated down to zero head, and thus full power generation potential cannot be utilized. The turbine has to be stopped when the head reaches a minimum value r below which the operation becomes uneconomical; the above expressions are modified as:

$$W = \int_r^R \rho \,.\, A.\, g.\, h \,.\, dh \text{ joules}$$

$$W = \frac{1}{2} \rho \,.\, A.\, g.\, (R^2 - r^2)$$

$$P_{av} = 0.225 \times A \times (R^2 - r^2) \text{ watts}$$

$$P_{av}/A = 0.225 \times (R^2 - r^2) \text{ MW/km}^2$$

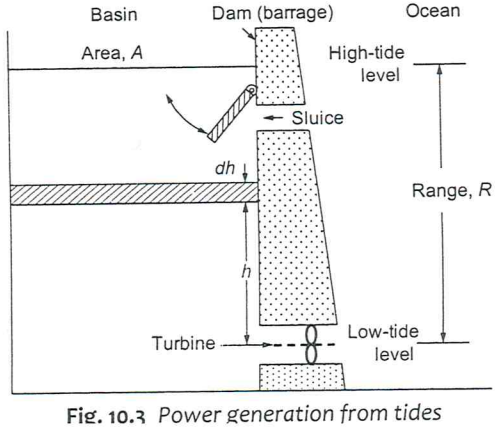


Fig. 10.3 Power generation from tides

Ocean Tidal Energy Conversion Schemes

The main tidal energy conversion schemes are (i) single basin: single

effect, (ii) single basin: double effect, (iii) two basin: linked basin, (iv) two basin: paired basin, and (v) tidal flow (or tidal current) schemes.

(i) Single Basin: Single-effect Scheme The single-basin scheme has only one basin as shown in Fig. 10.4. In the single-effect scheme, power is generated either during filling or emptying the basin. Two types of operation cycles are possible. In the *ebb generation cycle* operation, the sluice way is opened to fill the basin during high tide. Once filled, the impounded water is held till the receding cycle creates a suitable head. Water is now allowed to flow through the turbine coupled to the generator till the rising tide reduces the head to the minimum operating point. The flow is held till the next generating cycle. The sequence of events is illustrated in Fig. 10.4. This cycle is repeated and power is generated intermittently. In the *flood generation cycle* operation, the sequences are altered to generate power during filling operation of the basin. However, the sloping nature of the basin shores usually makes ebb generation the more productive method.

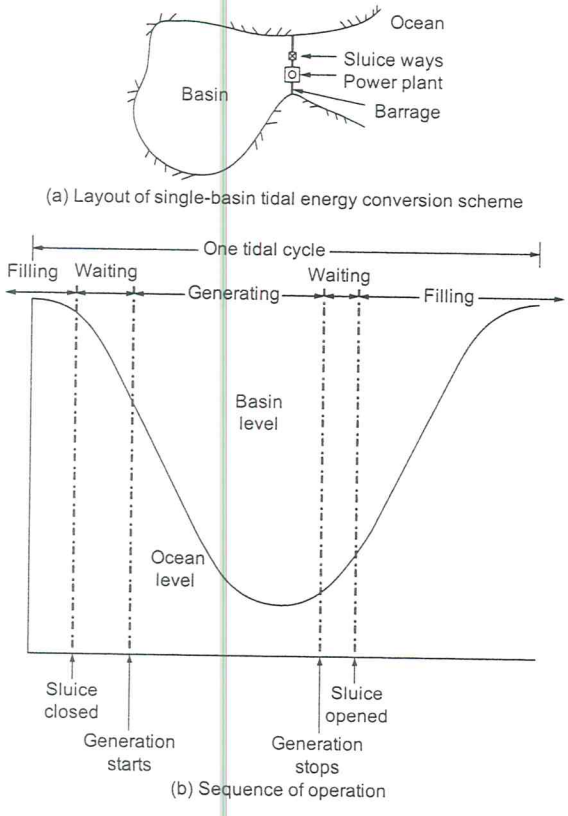


Fig. 10.4 *Single-basin, single-effect tidal energy conversion scheme*

Increased output can also be obtained by pumping during high tide to increase the basin level and therefore the generation head. The energy required for pumping must be borrowed and repaid. The pumping is done against a small head at high tide, whereas the same water is released through the turbine during low tide at a great head, producing a net energy gain.

(ii) Single Basin: Double-effect Scheme In the single-basin, double-effect scheme, power is generated on both flood and ebb. Two-way (reversible) hydraulic turbines are used. Pumping may also be used to increase the output. The routine is as follows:

1. Inward sluicing to fill the basin
2. Holding period
3. Ebb generation
4. Outward sluicing to empty the basin
5. Holding period
6. Flood generation

The routine is shown graphically in Fig. 10.5.

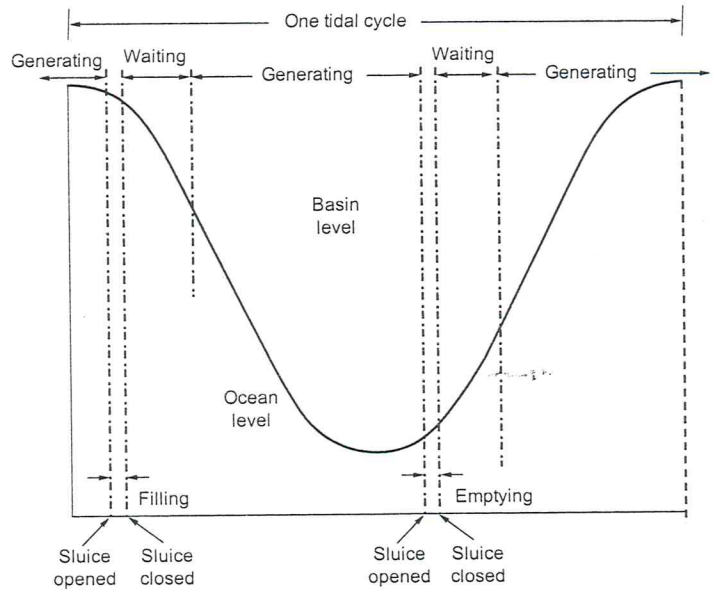


Fig. 10.5 *Single-basin, double-effect tidal energy conversion scheme*

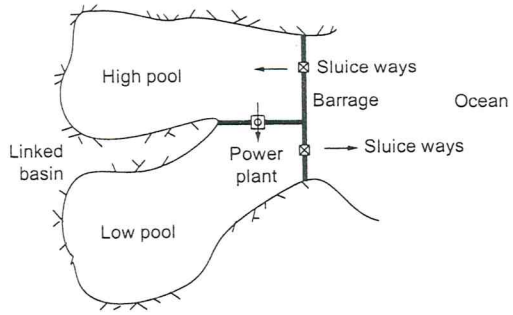


Fig. 10.6 *Linked-basin tidal-energy conversion scheme*

(iii) Two Basin: Linked-basin Scheme In order to maintain continuity of power supply, linked and paired basins schemes are used. The linked-basin scheme consists of two basins, one topped up at high tide, and the other emptied at low tide. Thus, a permanent head is created between the two basins. Water flows through a turbine from the high basin to the low basin. The layout of such a scheme is shown in Fig. 10.6.

(iv) Two basin: paired-basin scheme A paired basin consists essentially of two single-basin schemes. One scheme generates on flood and the other on the ebb cycle.

The output is almost, but not quite, continuous. Two basin schemes are generally found to be economically inferior to single-basin schemes.

(v) Tidal Current Schemes In order to explore the possibility of dispensing with the dam, its associated cost and environmental impacts, extraction of energy from tidal currents have been considered. Strong tidal currents (as high as about 5 m/s) are found in shallow seas, particularly where natural constrictions exist, such as around headlands or between islands. The practical devices for tidal flow power will be similar to that used in river flow power systems. The theory of tidal flow power is similar to wind power with the advantage of predictable velocities of high-density fluid. However, in this case the fluid velocities are much less as compared to wind and the operation is carried out in a marine environment. The generation will be intermittent and total power available may not be very large. The capital cost per unit of power produced appears to be high. As the tidal flow power lags about $\pi/2$ behind the range power from a single basin, the two systems could be complementary.

10.1.4 Present Status

Certain coastal regions experience high tides than others. This is a result of amplification of tides caused by local geographical features such as bays and inlets. In order to produce practical amount of power (electricity), a tidal range of at least 5 m is required. Also, the geographic features should permit enclosure of large areas with reasonable short dam or barrage. Few sites are identified for substantial tidal power development as shown in Fig. 10.7. Important sites of the world with substantial estimated potential are (i) Cook Inlet in Alaska with 57,000 MW potential, and 9 m maximum range, (ii) Bay of Fundy with 29,000 MW potential and 11 m maximum range, (iii) White sea with 16,000 MW potential and 7 m maximum range, and (iv) estuary of Severn river, England, with 11,000 MW potential (which is about 10% of the country's electricity need) and 8 m maximum tidal range.

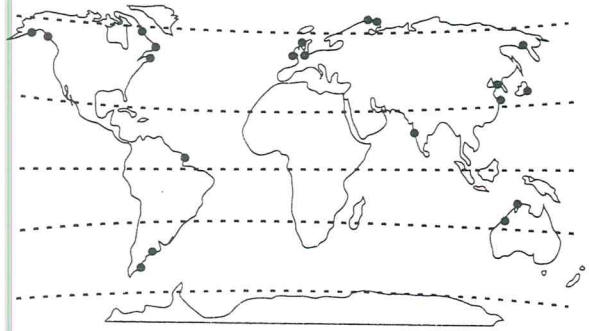


Fig. 10.7 *Potentail sites for tidal power development*

The best-known large-scale electricity generating commercial plant is the 240 MW system, at an estuary of La Rance river into the Gulf of St Malo in Brittany, France. This is a single basin, double-effect scheme with pumping and operating since 1966. There are 24 bulb turbines having variable pitch blades, coupled directly to generators, each of 10 MW capacities. The details of existing tidal plants are shown in Table 10.1. None of these countries have progressed to further development. The main barrier to the increased use of tidal energy is the construction cost.

Full-scale prototype tidal-current systems are now being deployed. If these schemes continue to prove successful, commercial systems will follow.

Table 10.1 *Existing tidal plants*

S N	*Site*	*Mean tidal range (m)*	*Basin area (km^2)*	*Installed capacity (MWe)*	*Year of installation*
1.	La Rance (France)	8	17	240	1966
2.	Kislaya Guba (near Murmansk, on Barents sea, Russia)	2.4	2	0.4	1968
3.	Jiangxia (China)	7.1	2	3.2	1980
4.	Annapolis (in Nova Scotia, Bay of Fundy, Canada)	6.4	6	17.8	1984

In India, potential sites identified are Gulf of Cambay and Gulf of Kutch in Gujarat with maximum tidal range as 11 m and 8 m, average tidal range of 6.77 m and 5.23 m respectively and power generation potentials of 7,000 MW and 1,200 MW (installed capacity) respectively. A potential of 100 MW with a maximum tidal range of 5 m and an average tidal range as 2.97 m has been estimated at the Durgadurani creek of the Sundarbans area. Some potential also exists at Belladona creek in West Bengal with a mean tidal range of 3.6 m.

The Ministry of New and Renewable Energy Sources has supported the setting up of the first demonstration tidal power project at the Durgaduani Creek in the Sunderbans area of West Bengal through the West Bengal Renewable Energy Development Agency (WBREDA). The main objective of the project is to supply power to 11 remote and unelectrified villages in Gosaba and Bali Bijaynagar islands located in South 24 Parganas District of West Bengal. The detailed project report (DPR) for setting up the 3.75-MW capacity tidal power project at Durgaduani was updated by the National Hydroelectric Power Corporation (NHPC), Faridabad, and submitted to the Ministry in November 2007. The project is likely to be taken up for implementation shortly.

Tidal current technology is in its infancy and going through evaluation and experimental stage. A 5 kW tidal current plant has been operating in Japan since

1990. In 1993, a 10-kW tidal current machine was deployed experimentally in UK and is still being assessed.

10.1.5 Environmental Impacts

Tidal energy is a renewable source of energy, which does not result in emission of gases responsible for global warming or acid rain associated with the use of fossil fuels. Changing tidal flows by damming a bay or estuary could, however, result in negative impacts on aquatic and shoreline ecosystems, as well as navigation and recreation. The barrage destroys the places that are home to many birds, fish and other animals.

Studies undertaken so far indicate that the impact at each site is different and depends greatly upon local geography. Very little is understood about how altering the tides can affect incredibly complex aquatic and shoreline ecosystems.

Example 10.1

A single-basin-type tidal power plant has a basin area of 2 km². The tide has an average range of 13 m. Power is generated only during the ebb cycle. The turbine stops operating when the head on it falls below 3 m. Calculate the average power generated by the plant in single emptying process of the basin if the turbine generator efficiency is 0.7. Estimate the average annual energy generation of the plant.

Solution Given: Amplitude $R = 13$ m

$r = 3$ m

Basin area, $A = 2$ km2

Gen-turb. $\eta = 0.7$

Density of sea water may be assumed as $\rho = 1025$ kg/m³

Average power potential available $= 0.225 \times A\,(R^2 - r^2)$ watts

$= 0.225 \times 2 \times 10^6 \times (13^2 - 3^2)$

$= 72$ MW

Average power generated $= 72 \times 0.7$

$= 50.4$ MW

Energy available in single emptying $= \frac{1}{2}\rho A g\,(R^2 - r^2)$

$= \frac{1}{2} \times 1025 \times 2 \times 10^6 \times 9.8 \times (13^2 - 3^2) = 1607200$ MJ

One ebb cycle duration = 12 h 25 min = 12.42 h

Number of ebb cycles in a year $= 365 \times 24/12.42 = 705.5 \approx 706$

Average annual energy generation $= 1607200 \times 706 \times 0.7$ J

$= 2.2 \times 10^8$ kWh

10.2 WAVE ENERGY

Waves are caused by the transfer of energy from surface winds to the sea. The rate of energy transfer depends upon the wind speed and the distance over which it interacts with water. The energy flux in waves is more than that available from solar, wind and other renewable sources. The power in the waves is directly proportional to the square of its amplitude and to the period of motion. The energy stored is dissipated through friction at shore and turbulence at rates depending on characteristics of wave and water depth. Larger waves in deep sea lose energy quite slowly and can effectively store it for many days and transmit it over great distances. For instance, large waves appearing off Europe might have been initiated in stormy weather in the mid-Atlantic or as far as the Caribbean Sea. Wave energy in open oceans is likely to be inaccessible. The resource potential near coastlines is estimated as in excess of 20,00,000 MW. Wave power is usually expressed in kilowatts per m, representing the rate at which energy is transferred across a line of 1-m length parallel to the wave front.

The main advantages of wave power are (i) the availability of large energy fluxes (as will be seen in the next section), and (ii) predictability of wave conditions over periods of days.

Difficulties in the development of wave power are encountered mainly due to the following reasons:

(i) Irregularity of wave patterns in amplitude, phase and direction, which makes it difficult to extract power efficiently.

(ii) The power extraction system is exposed to occasional extreme stormy conditions. During unusual extreme conditions, once in several years, the wave amplitude may reach as high as 10 times the normal value and the associated power is about 100 times the normal value. The devastating tsunami near the coast of Indonesia towards the end of December 2004 is the most recent example in hand. Allowing for this is expensive and would reduce normal efficiency of power extraction.

(iii) The peak power of deep water waves is available in open sea, where it is difficult to construct, operate and maintain a system and transmit power to the shore.

(iv) The slow and irregular motion of a wave is required to be coupled to an electrical generator requiring high and constant speed motion.

10.2.1 Power in Waves

The characteristics of an ideal deep-water surface wave (water depth more than about half the wavelength) are shown in Fig. 10.8. The wave motion may be expressed mathematically by the following general traveling wave equation:

$$y = a \sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right) \tag{10.1}$$

where $u = \frac{v}{2}$ is called the group velocity of deep water waves, i.e., the velocity at which the energy in the group of waves is carried forward. Thus P can be written as:

$$P = \left(\frac{\rho g^2}{8\pi}\right) a^2 T = \left(\frac{\rho g \sqrt{g}}{4\sqrt{2\pi}}\right) a^2 \sqrt{\lambda} \text{ kW/m} \tag{10.9}$$

Thus the power in waves is directly proportional to the square of the amplitude and to the period of wave. Therefore, the attraction for long periods and large amplitude to wave power engineers is apparent. The annual average wave energy is usually expressed in MWh/m.

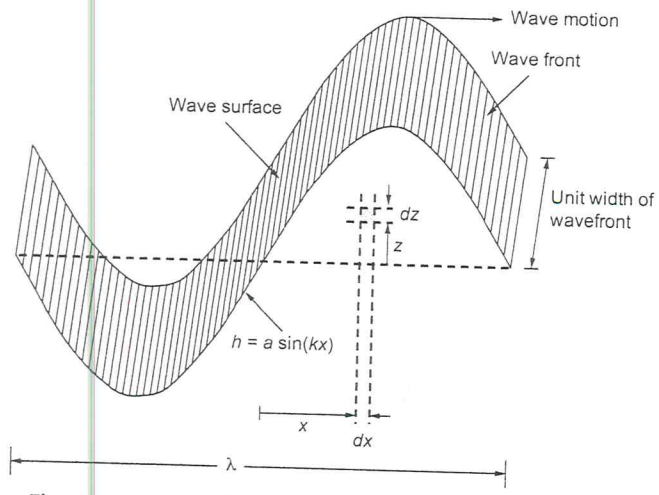


Fig. 10.10 *Wave surface of one wave length and unit width at any instant of time*

Example 10.2

A deep ocean wave of 2 m peak to peak appears at a period of 8 s. Find the wavelength, phase velocity and power associated with the wave. At this power rate, what is the average annual wave energy in MWh/m?.

Solution Given: Amplitude $a = 2/2 = 1$ m

Period, $T = 8$ s

Density of sea water may be assumed as, $\rho = 1025$ kg/m^3

Angular frequency can be calculated as

$\omega = 2\pi/T = 0.78539$ rad/s

From Eq. 10.3,

$$\lambda = \frac{2\pi g}{\omega^2} = 99.9238 \text{ m}$$

The phase velocity of the wave can be calculated from Eq. 10.5 as

$$v = \frac{g}{\omega} = 12.49 \text{ m/s.}$$

Power in wave can be calculated using Eq. 10.9

$$P = \frac{\rho g^2}{8\pi} a^2 T = 31.399 \quad \text{kW/m}$$

Average annual wave energy at the site = 31.399 × 8.76 = 275 MWh/m

10.2.2 Wave Energy Technology

Energy in the waves is harnessed basically in the form of mechanical energy using *wave energy converters*, also known as *wave devices* or *wave machines*. A wave device may be placed in the ocean in various possible situations and locations. The fluctuating mechanical energy obtained is modified/smoothed out to drive a generator. Wave energy devices may be classified in various ways. Depending upon the location of these devices, they can be classified as (i) off-shore or deep-water (water depth of 40 m or more) devices, and (ii) shoreline devices. The availability of wave power at deep ocean sites is three to eight times that of adjacent coastal sites. However, the cost of construction/installation, operation and power transmission is quite large. Shoreline devices on the other hand have the advantage of relatively easier maintenance and installation and they do not require deep-water moorings and long underwater cables. Depending upon the position with respect to sea level they are classified as (i) floating, (ii) submerged, and (iii) partly submerged devices. Submerged devices have the benefit of avoiding the worst storm conditions but have increased difficulties of maintenance.

Depending on the actuating motion used in capturing the wave power, these devices are classified as (i) heaving float type, (ii) pitching type, (iii) heaving and pitching float type, (iv) oscillating water column type, and (v) surge devices. For each of these types several designs have been developed and tested with many more still at the design stage. Some designs will be discussed here.

(i) Heaving Float Type A float (buoy) placed on the surface of water heaves up and down with waves due to the rise and fall of the water level. The resulting vertical motion is used to operate the piston of an air pump through linkage. The pump may be anchored or moored to the sea bed. Several float-operated air pumps are used to store energy in a compressed air storage. The compressed air is used to generate electricity through an air turbine coupled to a generator.

Power may also be extracted from a buoy by means of an internally suspended weight, with high inertia but free to swing. Energy is extracted from the differential motion of buoy and pendulum.

12. OTEC is characterised as having
    (a) high efficiency and low installation cost
    (b) low efficiency and high installation cost
    (c) low efficiency and low installation cost
    (d) high efficiency and high installation cost

13. In tropical regions, the ocean surface temperature may go as high as
    (a) 80°C (b) 40°C (c) 17°C (d) 27°C

14. Compared to an open-cycle system, a closed cycle OTEC system
    (a) has higher working pressure in boiler/turbine and lower specific volume of working fluid
    (b) has lower working pressure in boiler/turbine and higher specific volume of working fluid
    (c) has higher working pressure in boiler/turbine and higher specific volume of working fluid
    (d) has lower working pressure in boiler/turbine and lower specific volume of working fluid

11 Small Hydro Resouces

Introduction

The force of falling water has been mankind's important source of power and energy through the ages. Hydropower has been harnessed to do useful work—to grind grain, saw lumber and provide power to do other tasks. The Greeks used vertical-axis water wheels as early as 85 BC and horizontal-axis wheels from about 15 BC. The origins of water wheels can also be traced back to ancient Egypt, Persia and China where these were used for irrigation as well as grinding grain or flour. Hydropower was the only source of mechanical energy (other than wind) until the development of the steam engine in the nineteenth century. The early hydraulic units were relatively small and their outputs rarely exceeded a few hundred kilowatts.

Hydropower is the most established renewable resource for electricity generation. Large-scale hydropower is a well-established, mature and proven technology. However the concept of small hydro resources is recent and is expanding very fast.

In large-scale surveys and studies, the potential for small-scale generation from rivers has been greatly neglected due to techno-economic reasons. Recently, due to advancements in the design of low-head turbines, improvements in construction technology and availability of better control techniques, small hydro resources have also become viable. Environmental factors are also important, which cannot be judged by global surveys but only by evaluating local conditions. About 18% of potential large-scale hydropower sites have already been developed, but there is strong opposition from environmentalists for the development of the remaining sites. Small hydro resources are largely free from such environmental effects and therefore their potential is increasingly being utilised.

Small hydro plant (SHPs) projects include those installations that have low head (generally under 40 m) and small capacity. There is no international consensus on the definition of small hydropower. Different countries follow different norms, keeping the upper limit ranging from 5 to 50 MWe. In India, hydropower projects of ratings less than about 25 MWe are regarded as SHPs. They are considered as non-conventional as they have been conceived and built after the oil crisis of 1973. The major differences between a small and large hydro plants are that the former can be designed and built by local staff and smaller organisations using 'off-the-shelf' components or locally made machinery. It has standard designs for plant components, which are often not connected to grid and usually meant for local use. The latter, on the other hand, is grid connected and requires a tailor-made design for each particular scheme, and often have very expensive equipments and staff cost to maintain the grid.

Depending on the capacities, these plants are classified as micro (less than 100 kWe), mini (100 kWe–1 MWe) and small (1 MWe–25 MWe). These boundaries however, are not very

rigid. At the low end of the range, simplicity of design and control is usually essential for economic viability, even at the expense of efficiency of operation. However, at the high end of the range, the magnitude of the investment is likely to warrant fairly sophisticated protection and control devices. Micro-hydro schemes are used in remote areas where the grid does not exist. Typically, they provide power to just one rural industry or one rural community with power output as small as 200 W. Mini and small schemes sometimes make small contribution to national grid supplies.

The small/mini/micro schemes are further classified as (i) storage and (ii) run-of-the-river schemes. A storage scheme makes use of a dam to stop river flow, building up a reservoir of water behind the dam. The water is then released through turbines when power is needed. The advantage of this approach is that rainfall can accumulate during the wet season of the year and then release power during some or all of the drier periods of the year. A run-of-the-river scheme does not stop the river flow, but instead diverts a part of the flow into a channel and pipe and then through a turbine.

Micro-hydro schemes are almost always run-of-the-river type. The disadvantage of this approach is that water is not carried over from rainy to dry seasons of the year and power generation depends on the availability of flow. The advantages are that (i) the scheme can be built locally at low cost, and its simplicity gives rise to better long-term reliability, (ii) the environmental damage is negligible, as the river-flow pattern downstream of the plant is not affected, (iii) also there is no flooding upstream of the plant, and (iv) the scheme does not displace large numbers of people as large projects with big dams sometimes do.

11.1 ADVANTAGES AND DISADVANTAGES OF SMALL HYDRO SCHEMES

Advantages

(i) Hydroelectric energy is a continuously renewable energy source.
(ii) It is a much more concentrated energy resource than either wind or solar power.
(iii) Hydroelectric energy is non-polluting—no heat or noxious gases are released.
(iv) Hydroelectric energy has low operating and maintenance costs, it is essentially inflation proof.
(v) Hydroelectric energy technology is a proven technology that offers reliable and flexible operation.
(vi) Small hydro plants can be tailored to the needs of the end use market within the limits of water resources available.
(vii) It serves to enhance economic development and living standards, especially in remote areas with limited or no electricity at all.
(viii) For small hydro plants, the civil-engineering work does not need elaborate construction plans. Also, no expensive powerhouses or highly optimised electromechanical equipments are required.
(ix) It has a short gestation period.

(x) A small hydro plant requires few operating personnel, with some of the machinery capable of being operated entirely by remote control.
(xi) There is no need of long transmission lines because the output is consumed near the source.
(xii) High-performing electrical equipment (alternators, control circuits, battery storage, regulators, etc.) can be easily found in the market.
(xiii) The possibility of retrofits, and additional turbines and generators makes the upgrading of existing installations attractive.

Disadvantages

(i) Hydro systems, unlike solar components for example, do require some maintenance.
(ii) The quality of output of small power stations is not as good as that of bigger ones as these power plants are generally designed on the basis of short-term raw data. Thus, the ground conditions of operation are much different from those considered for the design.
(iii) The majority of SHPs are located in remote places and are not connected with the grid. Therefore, transmission of surplus power to other places is not possible. Therefore, during low-demand periods, they continue to operate at a low load factor that leads to the loss of power generation which in turn results in poor revenue collection.
(iv) In the absence of adequate hydrological and geological data, there are always uncertainties about their potential as a resource. Also, once commissioned, there is no surety of selling the electricity at a rate that is comparable to the outcome of the investment. Due to these reasons private developers avoid to have a stake in small hydro projects.
(v) The rotation of turbines can kill fishes, especially young fishes, swimming downstream.
(vi) Spilling of water over spillways can result in super saturation of water with gases from the air. The gas bubbles, absorbed into fish tissue, may cause damage and ultimately kill the fish.
(vii) Most hydroelectric facilities require construction of dams. Dams present a migratory barrier that can effect the free movement of fish species and their reproduction cycle. However, the effects upon stream ecology are minor compared to those caused by large hydroelectric facilities.
(viii) The existence of a reservoir can make the water become stratified, with warmer water collecting at the surface and cooler water lying at the bottom. In this way, the cold water is isolated from aeration and it loses its oxygen. Many species of fish cannot live in such environment due to low oxygen content and temperature.

11.2 LAYOUT OF A MICRO-HYDRO SCHEME

The layout of a typical micro-hydro scheme is shown in Fig. 11.1. The main components of the scheme are (i) diversion weir, (ii) water-conductor

system with regulating gates and spillways, (iii) desilting tank with spillway, (iv) headrace channel, (v) forebay tank with desilting basin and spillway, (vi) penstock, (vii) powerhouse, and (viii) tailrace channel.

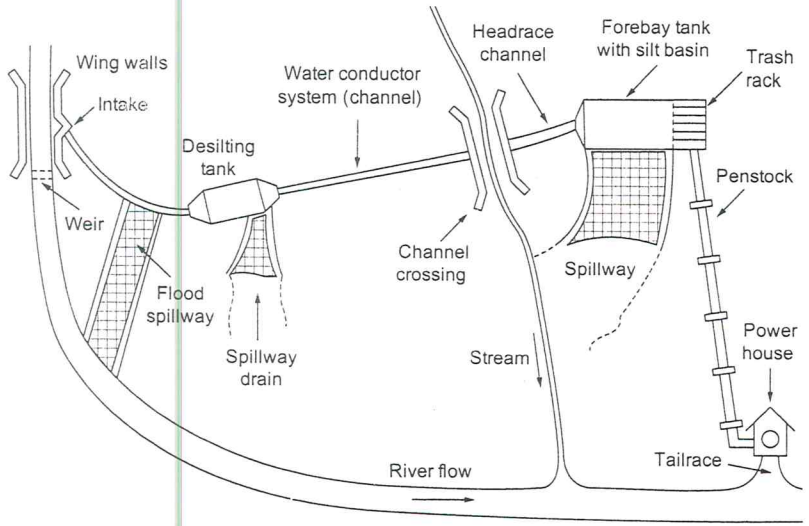


Fig. 11.1 *Typical layout of a microhydro power station*

11.2.1 Diversion Weir and Channel

A diversion weir is designed to divert and maintain constant flow in the channel for variable flow in the river through the year. If the channel overfills, damage will result. Special attention is required to save the channel during seasonal flooding. The intake structure regulates the flow. Further control or regulation is provided by spillways. The water-conductor system is a channel between weir and desilting tank and between the desilting tank to forebay. It should be designed to ensure least loss of head due to seepage, and the flow velocity should be adequate to prevent settling of silt. The most commonly used channel section is trapezoidal. The channel follows the contour of the hillside so as to preserve the elevation of the diverted water.

11.2.2 Desilting Tank

A desilting tank is usually provided in the initial reaches of water to trap the suspended silt load and pebbles, so as to minimise erosion damages to the turbine runner. Abrasive effects become more pronounced with increasing head. The size of the silt particles to be trapped for medium head turbines is 0.2 to 0.5 mm and that for high heads is 0.1 to 0.2 mm. The depth of a silt tank may be 1.5 to 4 m, and the horizontal flow velocity should not exceed 0.4 to 0.6 m/s. The deposits of silt tank are periodically flushed out to make room for further deposition.

11.2.3 Forebay, Penstock and Tailrace

A forebay is a temporary storage of water (pondage), to be finally utilised for energy generation. The storage size ranges from 2 minutes to 6 hours depending on the economic justifiability. Trash racks are also provided to prevent entry of trash, debris and ice. The flow velocity through a trash rack is kept at 0.6 to 0.9 m/s, so that there is no significant head loss. A penstock is a water conduit joining a forebay and a turbine. It should be sized such that frictional losses do not reduce the head unduly. A bell-mouth entry is provided to reduce the head loss and to ensure smooth entry of water. A tailrace is a simple water channel to transport discharge from the turbine back to the river with maximum flow of 1 m/s.

11.2.4 Powerhouse

***(a)* Speed Governor** The frequency and voltage of the generator output depends on the shaft speed. Voltage variations up to 7% are tolerable and may not adversely affect most of the loads. Frequency variations up to 5% above the rated value (but none below it) are considered as safe. In a small system, voltage and frequency may exceed these limits during switching operations for a short duration. Governors are used to control the speed. Traditional governors give high performance, but are too expensive to be justified in a micro-hydro plant (especially for ones having a below 10 kW rating). Non-conventional approaches are usually used to reduce the cost. The quality of control is poor but it can still be adequate to satisfy most common end users. In one such approach, the flow through the turbine is set at a constant value to keep the input power as constant. Therefore, the mechanical input to the generator remains constant. The load imposed on the generator is also kept fairly constant. This requires a ballast (stabilising) load across the generator to be increased or decreased accordingly as the user load varies. The generated energy that is not used productively is wasted in the ballast load (also known as dump load). An electronic load controller (ELC) is employed to perform this function. Thus, the electronic load controller ensures that the generator always supplies a constant electrical load. In this way, both the mechanical input and electrical output remain constant and therefore, the speed remains constant. In this approach, the part of the generated energy that is consumed in the ballast load is wasted. For run-of-the-river schemes, this is irrelevant as there is no provision for storage of unused water for later productive use.

(b) Turbine A suitable turbine is used to get mechanical power at the shaft from flowing stream of water. Various types of turbines and their characteristics are discussed in Sections 11.3 and 11.4.

(c) Generator A generator coupled with turbines gives electrical output from mechanical input. The details of various types of generators used in SHPs are given in Section 11.5.

12 Emerging Technologies

Introduction

Some newly emerging technologies are covered in this chapter. Fuel-cell and hydrogen-energy technologies are relatively new and in the initial stages of development. The principle of the fuel cell was discovered way back in 1838 by the German scientist Christian Friedrich Schönbein, and published in one of the scientific magazines of that time. Based on this work, the first fuel cell was demonstrated by the Welsh scientist Sir William Robert Grove in the February 1839. However, turning this idea into a practical means of energy conversion has proved to be elusive. Its widespread use is hindered mainly due to its high cost as compared to other available technologies. Many companies are working on techniques to reduce the cost in a variety of ways including reducing the amount of platinum needed in each individual cell. United Technologies Corporation's UTC Power subsidiary was the first company to manufacture and commercialise a large, stationary fuel-cell system for use as a co-generation power plant in hospitals, universities and large office buildings. UTC Power continues to market this fuel cell as the PureCell 200, a 200 kW system.

Hydrogen is an energy carrier, and not an energy source, because it is usually produced from other energy sources via petroleum combustion, wind power, or solar photovoltaic cells. Electrochemical extraction of energy from hydrogen via fuel cells is an especially clean method of meeting power requirements, but not an efficient one, due to the necessity of adding large amounts of energy to either water or hydrocarbon fuels in order to produce the hydrogen. A number of issues like production, delivery, storage, conversion and end use applications are involved in order to realise hydrogen economy.

12.1 FUEL CELL

A fuel cell is an electrochemical energy conversion device that continuously converts chemical energy of a fuel directly into electrical energy. Continuous operation requires supply of fuel and oxidant and removal of water vapour, spent fuel, spent oxidant, inert residue and heat. It is known as a cell because of some similarities with a primary cell. Like a conventional primary cell it also has two electrodes and an electrolyte between them and produces dc power. It is also a static power-conversion device. However, active materials are generally supplied from outside unlike a conventional cell where it is contained inside the cell. Fuel is supplied at the negative electrode, also known as fuel electrode or *anode* and the oxidant is supplied at positive electrode, also known as oxidant electrode or *cathode*. The only exhaust of a fuel cell, if pure hydrogen is used as

fuel (and pure oxygen as oxidant), is water vapour, which is not a pollutant. In case of a hydrocarbon fuel, carbon dioxide is also produced. If air is used as oxidant, nitrogen (spent air) is also produced in the exhaust. No other pollutant such as particulate matter, NO_x and SO_x are produced. Some amount of heat is also produced, which can be easily dissipated to the atmosphere or used locally for heating purposes. No cooling water is required unlike conventional thermal power-conversion devices where a substantial quantity of cooling water is required. As the conversion of chemical energy of fuel to electrical energy occurs directly without intermediate thermal stage, the efficiency of conversion is better and not limited by Carnot efficiency of thermal stage. The efficiency of a practical fuel cell may be around 50%. The average cell voltage is typically about 0.7 V (on rated load) and several cells may be connected in series to increase the voltage. The current depends on the electrode area and can be increased by connecting several cells in parallel. Thus modules of different sizes can be constructed by series–parallel connection of the required number of cells. A general large-scale use will require the development of a low-cost fuel cell with a reasonably long life.

The main advantages of a fuel cell are: (i) it is quiet in operation as it is a static device, (ii) it is less pollutant, (iii) its conversion efficiency is more due to direct single-stage energy conversion, (iv) fuel cell plant can be installed near the point of use, thus transmission and distribution losses are avoided, (v) no cooling water is needed as required in the condenser of a conventional steam plant. The heat generated can be easily removed and discharged to the atmosphere or used locally, (vi) because of modular nature, any voltage/current level can be realised and the capacity can be added later on as the demand grows, (vii) fuel-cell plants are compact and require less space, (viii) availability of choice from large number of possible fuels, (ix) can be used efficiently at part load from 50% to 100%, and (x) no charging is required.

12.1.1 Potential Applications

Once fuel cells of reasonably low cost and long life become available, they will be preferred in a large number of applications. Some of their potential applications are listed below:

1. Fuel cells can be effectively used for load leveling. When the generation exceeds the demand, excess generated energy can be converted and stored as hydrogen by electrolysis of water. During peak load time, when the demand exceeds the generation, the stored hydrogen would be used in fuel cells to meet additional demand.
2. A central station power plant using fuel cell is also possible using gasified coal as fuel. The efficiency of such a plant would be higher due to direct energy conversion as compared to conventional thermal plants. Thus coal will be used more efficiently with reduced emissions.

3. Fuel cells are also suited for dispersed generation. By locating the fuel cells near the load centre, transmission and distribution cost would be avoided/reduced, although there would be some cost for transporting the hydrogen.
4. To meet the demand of isolated sites such as construction sites, military camps and small village communities or hamlets, fuel cells are more suited than diesel generator sets.
5. For remote and inaccessible locations, fuel cell can be used unattended for a long period.
6. Emergency/auxiliary supply to critical loads such as hospitals, etc., can be better met using fuel cells as compared to diesel generator sets.
7. Fuel cells can also be used as a mobile power source in vehicles, submarines and spacecrafts. A hydrogen–oxygen alkali fuel cell has been used successfully in USA to provide electric power in shuttle spacecrafts such as Apollo.
8. Fuel cells are also proposed as a power source for propulsion of electric vehicles.
9. Fuel cells can be used to power portable electronic devices (e.g., mobile phones and other low-power appliances, especially those used in military) as substitute for primary or rechargeable batteries. Instead of waiting for several hours for recharging, a small cartridge of methanol can be replaced in the same way as an ink cartridge in a computer printer.

12.1.2 Classification of Fuel Cells

Fuel cells can be classified in several ways.

(a) Based on the Type of Electrolyte

(i) Phosphoric Acid Fuel Cell (PAFC)
(ii) Alkaline Fuel Cell (AFC)
(iii) Polymer Electrolytic Membrane Fuel Cell (PEMFC) or Solid Polymer Fuel Cell (SPFC) or Proton Exchange Membrane Fuel Cell (PEMFC)
(iv) Molten Carbonate Fuel Cell (MCFC)
(v) Solid Oxide Fuel Cell (SOFC)

(b) Based on the Types of the Fuel and Oxidant

(i) Hydrogen (pure)–Oxygen (pure) fuel cell
(ii) Hydrogen rich gas–air fuel cell
(iii) Hydrazine–Oxygen/hydrogen peroxide fuel cell
(iv) Ammonia–air fuel cell
(v) Synthesis gas–air fuel cell
(vi) Hydrocarbon (gas)–air fuel cell
(vii) Hydrocarbon (liquid)–air fuel cell

(c) Based on Operating Temperature

(i) Low temperature fuel cell (below 150°C)
(ii) Medium temperature fuel cell (150°C–250°C)
(iii) High temperature fuel cell (250°C–800°C)
(iv) Very high temperature fuel cell (800°C–1100°C)

(d) Based on Application

(i) Fuel cell for space applications
(ii) Fuel cell for vehicle propulsion
(iii) Fuel cell for submarines
(iv) Fuel cell for defense applications
(v) Fuel cell for commercial applications

(e) Based on the Chemical Nature of Electrolyte

(i) Acidic electrolyte type
(ii) Alkaline electrolyte type
(iii) Neutral electrolyte type

12.1.3 Phosphoric Acid Fuel Cell (PAFC)

PAFC was developed in the 1980s. The basic phosphoric acid fuel cell is shown in Fig. 12.1. It consists of two electrodes of porous conducting material (commonly nickel) to collect charge, with concentrated phosphoric acid filled between them, to work as an electrolyte. Pure hydrogen or a hydrogen-rich gas is supplied at the negative electrode and oxygen or air is supplied at the positive electrode. The pores provide an opportunity for the gas, electrolyte and electrode to come into contact for electrochemical reaction. The reaction is normally very slow and a catalyst is required in the electrode to accelerate the reaction.

Platinum serves as the best catalyst for both electrodes and used for premium fuel cells. In general, a less expensive material such as nickel (for negative electrode) and silver (for positive electrode) is used wherever possible. Thus, finely divided platinum or nickel/silver deposited on the outer surface of electrodes are used as catalyst. During the usage of the cell, the catalyst gradually loses its activity. This loss of activity is often attributed to 'poisoning' (inactivation) of the catalyst by the impurities (mostly sulphur compounds) in the fuel.

At the negative electrode, hydrogen gas is converted to hydrogen ions (H^+) and an equal number of electrons (e^-). Thus,

$$H_2 \longrightarrow 2H^+ + 2e^-$$

The electrons originating at the negative electrode flow through the external load to the positive electrode. Also, the H^+ ions migrate from the negative electrode